AGARD-CP-249

AD A063850
AGARD-CP-249

AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE

DDC FILE COPY

LEVEL

AGARD CONFERENCE PROCEEDINGS No. 249

Piloted Aircraft Environment Simulation Techniques

DDC
1979

DISTRIBUTION STATEMENT A
Approved for public release
Distribution Unlimited

NORTH ATLANTIC TREATY ORGANIZATION

DISTRIBUTION AND AVAILABILITY
ON BACK COVER

AGARD-CP-249

NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Conference Proceedings No.249

PILOTED AIRCRAFT ENVIRONMENT SIMULATION TECHNIQUES.

Papers presented at the Flight Mechanics Panel Specialists' Meeting on Piloted Aircraft Environment Simulation Techniques held in Brussels, Belgium, 24–27 April 1978.

THE MISSION OF AGARD

The mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

– Exchanging of scientific and technical information;

– Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

– Improving the co-operation among member nations in aerospace research and development;

– Providing scientific and technical advice and assistance to the North Atlantic Military Committee in the field of aerospace research and development;

– Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field;

– Providing assistance to member nations for the purpose of increasing their scientific and technical potential;

– Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community.

The highest authority within AGARD is the National Delegates Board consisting of officially appointed senior representatives from each member nation. The mission of AGARD is carried out through the Panels which are composed of experts appointed by the National Delegates, the Consultant and Exchange Programme and the Aerospace Applications Studies Programme. The results of AGARD work are reported to the member nations and the NATO Authorities through the AGARD series of publications of which this is one.

Participation in AGARD activities is by invitation only and is normally limited to citizens of the NATO nations.

The content of this publication has been reproduced directly from material supplied by AGARD or the authors.

ACCESSION for
NTIS White Section
DDC Buff Section
UNANNOUNCED
JUSTIFICATION
BY
DISTRIBUTION/AVAILABILITY CODES
Dist. AVAIL. and/or SPECIAL
A

Published October 1978

Copyright © AGARD 1978
All Rights Reserved

ISBN 92-835-0222-1

Printed by Technical Editing and Reproduction Ltd
Harford House, 7–9 Charlotte St, London, W1P 1HD

SUMMARY

A comprehensive Technical Evaluation of this meeting, written by Mr K.J.Staples, RAE Bedford, UK, appears in AGARD Advisory Report No.126. The following is the text of the Chairman's summary of the Round Table Discussion*:

In conclusion it can be stated that over the last 20 years or so, piloted flight simulation has gradually emerged as a recognized and widely accepted tool for aeronautical research and development while, in parallel, it has become a valuable training aid. Today's status has been achieved in the face of the fundamental criticism that, with a human pilot in the control loop, we are necessarily involved in deception and illusions; we try to make the pilot behave and react as though he were flying a real aircraft; and we expect him to suspend disbelief while doing so. The objective is simulation of the real world – not duplication.

The dictionary says that to simulate means to feign, to pretend, to sham, to trick, to deceive. Our deceptions require consideration of motion cues, visual cues, auditory cues, physiological, psychological, and proprioceptive cues, vestibular, graviceptor, and tactile cues including horseshoe-shaped imprints on the nether regions. And then it is asked "What is a cue?" Perhaps Sir Walter Scott was thinking of simulation when he wrote "Oh what a tangled web we weave, when first we practice to deceive".

The fundamental problem in the use of the piloted flight simulator is that the pilot is bound to be influenced by the qualities of the simulator itself. It is relatively easy to list the potential deficiencies in a representation of the real aircraft environment but virtually impossible to say what the effects of these deficiencies will be. Thus, while simulation equipment manufacturers strive to reduce these deficiencies, we cannot say with much certainty which are the critical features most in need of improvement.

On the "hardware" side, we have noted the imbalence between the development of motion and of visual systems. As we have said previously, our objective is *simulation* of the real world – not duplication. We can readily accept that duplication of motion cues is neither technologically nor economically feasible although, as has been pointed out, there is much emotion in motion. It is less obvious but nevertheless equally true that duplication of visual cues is currently also not technologically feasible.

The trend with motion systems seems to be toward better quality rather than bigger scale in the sense that we do not expect to need much larger amplitudes of motion than are currently available with the exception of special simulation problems such as terrain flight of helicopters. We expect instead to see improved smoothness, better frequency response and general removal of hysteresis, jerks, rumble, noise, back lash, and so forth.

With regard to the visual cues, much more research and development is required to remove the deficiencies of existing systems. The most obvious is the restricted field of view but there are practical prospects of major increases.

Each system claims some performance or cost advantage over others and it will be no easy task to choose the best system for one user's particular needs. It is to be hoped that more fundamental work will be done on the use of visual cues in the presence of motion so that the relative importance and benefit of this and the many other possible improvements to the simulated visual scene may be assessed. This also required a closer working relation between user and researcher. We need criteria by which to evaluate cue adequacy.

There is no question that simulation has been, and will continue to be, a quite invaluable tool. The piloted flight simulator is to the flight dynamicist what the wind tunnel is to the aerodynamicist. The emphasis on the control of development costs and operational training costs suggests that flight simulators will play an increasingly important role in the future. In the training field, we can expect continued and expanding acceptance of simulation as an alternative to flying training. On the civil side, we may expect more wide-spread use of simulation for conversion training and for practice of inherently hazardous manoeuvres. This trend can be expected to continue as long as simple economic considerations show a positive benefit and as long as certification authorities are satisfied as to the relevance of the training. Militarily, there seems little doubt that the pressure to reduce the cost of training and readiness will encourage more wide-spread use of simulation for any flight or mission phases where training can be shown to transfer reliably. In the long term, we can look forward to improved understanding of the relation between the physical characteristics of the simulated cockpit environment and the validity of the particular tasks which the pilot has to assess. Not only should this point the way to improved design of simulation facilities but also to more confident use of the results of exercises on existing facilities. Inevitably, further improvements in the technology will be expensive and compromises on the basis of cost effectiveness will have to be reached. The Flight Mechanics Panel will continue to play a guiding and co-ordinating role in this work as a major element of its technical activities for AGARD.

-A-

* Round Table Members: Dr I.C.Statler (Chairman), Prof. O.H.Gerlach, Prof. K.H.Doetsch, Mr A.G.Barnes, Mr D.R.Gum, Dr C.L.Kraft, Dr L.R.Young.

CONTENTS

CURRENT DEFICIENCIES IN SIMULATION FOR TRAINING

by
Colonel Charles D.Brown
United States Air Force
Tactical Air Warfare Center
(USAFTAWC)

First, let me say that I find it difficult to express to you exactly how pleased I am to be afforded the opportunity to meet with this august group and, more significantly, to have the chance to air some of my views on the subject of aircrew training devices and their utilization. Suffice it to say, I am extremely happy to be here. To me, the fact that a representative of the "user community" has been invited to open this session is highly significant. I interpret the invitation as an acknowledgement of the need to establish and foster extremely close working relationships between all of the individuals and agencies involved in our business. Only through an integrated effort can we achieve what I perceive to be our common goal, the efficient training of aircrews.

Before I launch into further discussion on the specific area I wish to address, I want to steal about 10 minutes of your time to give you an overview of the responsibilities of and functions performed by the organization which I represent.

At the risk of over-simplifying a not-so-simple set of circumstances, let me say that our organization, the Deputy Chief of Staff for Aircrew Training Devices, USAF Tactical Air Warfare Center, exists primarily for one reason. That is to provide a single, user oriented agency, which can track the entire simulator acqusition process, from the statement of the original operational requirement through the delivery and operational testing of the end product: The objective being to insure that the item requested is indeed the item delivered. Let me make it clear from the outset that we are not responsible for either procurement or design. The Air Force Systems Command and/or the Air Force Logistics Command fulfil those responsibilities. If I may, let me liken our position to that of an interpreter. As you are all well, and I'm sure often painfully aware, the acqusition process is, to a large degree, a series of translations. The initial requirement is stated in the pragmatic language of the operator, translated into the technical terms of the engineer, liberally sprinkled with the legalistic jargon of the various contracting offices, and so forth and so on. The danger, of course, lies in the fact that often something is lost with each translation.

Figure 1 illustrates so well the situation which often seems to exist, and of course, we should not forget what it was the user really wanted in the beginning. (Fig.2)

It is our task to try to eliminate, or at least minimize, the potential problems just displayed by providing a full-time program manager and simulator technicians who literally live with each new major tactical aircrew training device procurement or modification from inception through delivery and testing. We assist in developing the formal requirement, and the request for proposal. We are actively involved in source selection, preliminary and critical design reviews and acceptance testing, and to put the final touches to the process, we conduct the operational test and evaluation of the devices.

The major simulator modification we are currently working are shown in Figure 3. The visual system being added to the F-4E and A-7 simulators is a three-window hybrid of the McDonnell Douglas Vital IV, which I am sure is familiar to most of you. The Automated Adaptive Flight Training System is, as the name implies, a performance measurement device capable of automatically controlling problem presentation based upon student performance. The G-suit/G-seat modification is self explanatory. The visual system going on the F-111 is a four-window, three-channel system, but in this case it is the Link-Singer Digital Image Generation System.

The field of view of these visual systems is too restricted to allow us to train all required skills, but it will provide a much needed takeoff and landing capability, some training in low level navigation, and some visual weapons delivery training will be possible, especially in the F-111. It is a step in the right direction.

The new procurements which fall under our purview are shown in Figure 4. We have acquired and are currently conducting operational tests and evaluations on two simulators for the E-3A Airborne Warning and Control System (AWACS) aircraft. The first is the Redifon-produced flight simulator which features a dual window, single channel display system. The image is generated from a camera/model arrangement, and the cockpit is mounted on a six-degree-of-freedom motion system. In addition to the landing and takeoff presentation normally attributed to this type of system, an aerial refueling scenario is made available by substituting a scale model of the KC-135 tanker aircraft.

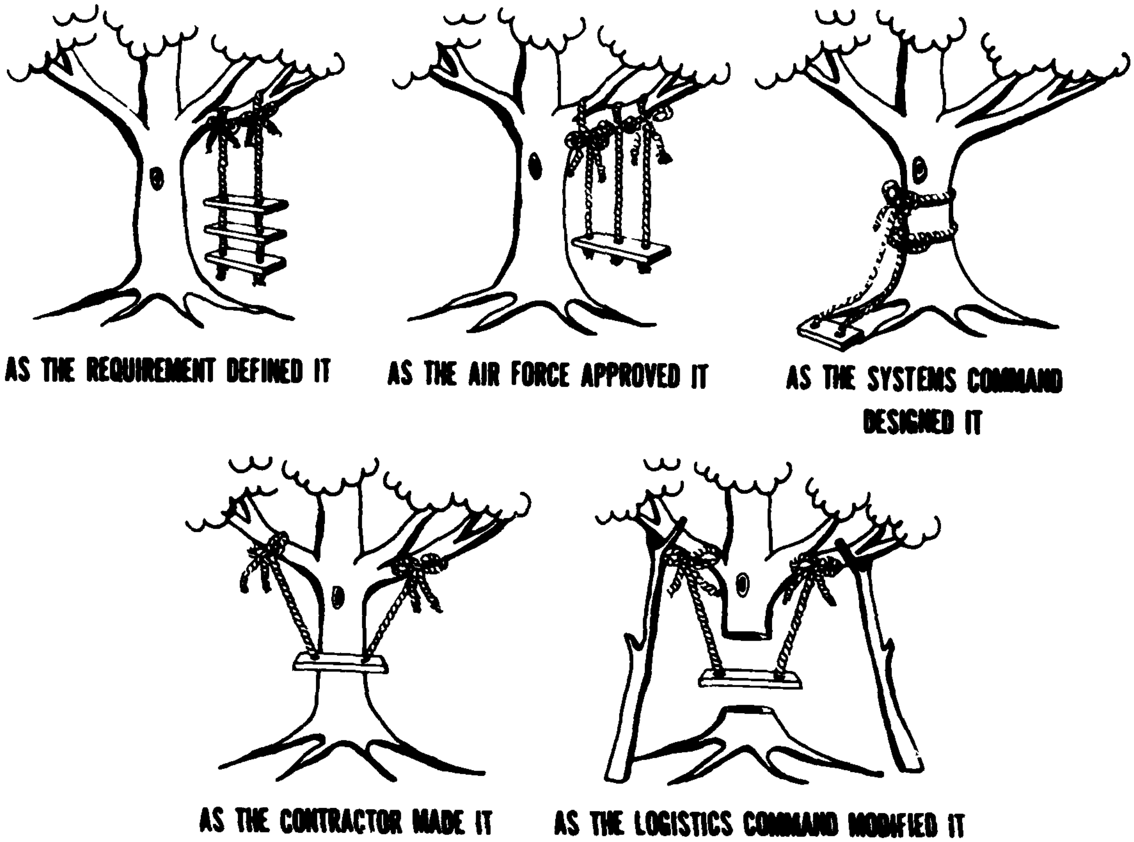


Figure 1

Figure 2

- F 4E
  - VISUAL SYSTEM
  - AUTOMATED ADAPTIVE FLIGHT TRAINING SYSTEM
  - G-SUIT G SEAT
- A-7
  - VISUAL SYSTEM
  - AUTOMATED ADAPTIVE FLIGHT TRAINING SYSTEM
- F-111
  - VISUAL SYSTEM

Figure 3

- E-3A (AWACS)
  - FLIGHT SIMULATOR
  - MISSION SIMULATOR
- F-15
  - FLIGHT SIMULATOR
  - AERIAL COMBAT PART TASK TRAINER
- A 10
  - OPERATIONAL FLIGHT TRAINER (OFT)
- F-16
  - OPERATIONAL FLIGHT TRAINER (OFT)

\+ PROJECT 2360 = A-10 WEAPONS SYSTEM TRAINER / F-16 WEAPONS SYSTEM TRAINER

Figure 4

The E-3A mission simulator, built by Boeing, is the primary device utilized to train the mission crew. These are the individuals who are not associated with the actual flying of the aircraft, but rather, the performance of the warning and control functions. This, of course, being the primary mission of the system. The mission crew portion of the simulator is a replica of the portion of the E-3A fuselage that contains the nine situation display consoles and the associated communications equipment to simulate control of the air battle. As I said earlier, this device is the primary medium for training the mission crew. The training required cannot be conducted in the aircraft itself, at least not on a day-to-day basis, due simply to the scenario which must be presented. I think that it is safe to say that this is the first time that the Tactical Air Command has had to rely so heavily upon a ground-based training device to train an airborne crew. It, however, is certainly only a "preview of coming attractions".

We are buying two simulators for the F-15, a flight simulator and what we term an Aerial Combat Part Task Trainer. The first five flight simulators have been delivered and we are well into the operational test and evaluation of the device. The F-15 flight simulator does not incorporate a visual system and although it does possess several advanced instructional features and a higher degree of fidelity than our older training devices, it cannot be considered as pressing the state-of-the-art. It is intended to be used primarily as an instrument and all weather intercept trainer. The cockpit is mounted on a six-degree-of-freedom motion platform.

The request for proposal on the Aerial Combat Part Task Trainer is being prepared now. This device, as the name implies, is not intended to allow training in any area other than the air-to-air environment. Each trainer will provide two interactive cockpits equipped with a full-field-of-view dome visual system. The trainer will allow its occupants to enage in a one-on-one aerial combat and a two-versus-one capability will be provided through the employment of an unmanned-synthesized-computer drive adversary. The first of these devices is scheduled for delivery in January 1981.

The A-10 and the F-16 Operational Flight Trainers are the two greatest challenges we have today. The first A-10 is scheduled for delivery in April 1979, and the F-16 in May 1980. We are taking a new approach with these simulators. What we ultimately want to obtain, in each case, is what we now term a Weapons Systems Trainer (the old term was Full Mission Simulator). Because the tactical fighter environment is primarily visually oriented, this calls for visual systems which provide fields of view which essentially duplicate that of the aircraft being simulated. Additionally, the visual scenes generated and presented must provide a wide range of ground features and targets (both static and moving) as well as airborne targets and threats. The problem we initially faced was simply that operational training requirements dictated that we could not delay the delivery of the two simulators for the period of time necessary to develop the required visual system. We decided to proceed with both procurements employing a "building block" approach. We ordered Operational Flight Trainers for each weapon system which, with some refinements, approximate the capabilities of the F-15 IFS I have previously described, but with growth potential to accept a full-field-of-view visual system. The first two devices, in each case, will be delivered with single window night visual systems and will be employed at the initial qualification training bases.

The remaining simulators will ultimately be modified through the addition of a visual system resulting from Project 2360. This is a competitive procurement wherein two selected contractors will each install full-field-of-view visual systems on two interactive A-10 simulators. We will then have a fly-off or, as some have termed it, a sim-off, between the two competing systems. We hope to have the results by late 1980. The intent is to install the final product on both the A-10 and F-16 simulators.

Enough of what we at TAWC do. I have taken these first few minutes to discuss what our organization does for two reasons.

First, the Tactical Air Warfare Center is a relatively new entry into the world of simulation and we need to advertise our product.

Secondly, and more importantly, it sets the stage for the remainder of my remarks and provides you with some knowledge of the environment which has shaped my views. One key fact which I would like for you to keep in mind is this: With the possible exception of the E-3A flight and mission simulators, the Tactical Air Command does not currently possess any Operational Flight Simulators which represent the current state-of-the-art.

That being the case, I am ill prepared to address "The Current Deficiencies in Simulation for Training" on a case-by-case, feature-by-feature basis. Rather, I would like to address the issue from more of a conceptual standpoint. Hence, I will emphasize the word *simulation* in its broadest sense.

Let me add one last qualifier. My operational and staff background centers almost exclusively in tactical fighter aviation; hence, the ideas I express must be viewed in that context.

Earlier, I defined our common goal as the efficient training of aircrews. Whether you agree with that or not, please accept that definition as a point of departure for the remainder of this presentation.

If we accept efficient training as our goal, then our objective must or should be to procure aircrew training devices which are effective, yet economical. Effective in the sense that they provide the means for reaching desired learning outcomes. Economical in terms of both investment and operating cost.

This assumes that we possess the requisite knowledge to specifically identify the desired learning outcomes (i.e., the skills, knowledge, and attitudes which the aircrew or aircrew members must develop).

Secondly, it assumes that we can determine through some means of performance measurement when and if the aircrew has attained the desired skill level.

(I have serious reservations about our ability to accomplish either of these functions just outlined in any but the most subjective manner – but that is an area to be discussed at another time and another place.)

Lastly, it assumes that we know what the *minimum* essential cue requirments for the training devices are. At last, my friends, we have reached the pivotal point of my presentation.

I can assure you that, at least within the command I represent, we know very little about the *minimum* cue requirements necessary to achieve our desired learning outcomes. This is not to say that our training devices are not (or cannot be) effective. It is a problem of economy, not effectiveness. We can, in essence, achieve the desired level of effectiveness by placing an order for a training device which totally replicates the characteristics of the weapons system in question. To the degree that the selected contractor can fill this order, the training effectiveness of the device should be as great as that of the aircraft itself. This approach may satisfy the individuals being trained and those responsible for conducting the training, but I rather suspect that the people that many of us work for (either directly or indirectly), the tax payer, would not be overly impressed with this solution.

Let me cite for you two relatively recent experiences we have had within our command which are either examples or indications of the fidelity overkill I have just suggested.

The first lies in the area of six-degree-of-freedom platform motion systems. In the summer of 1976 all of TAC's statements of new simulator requirements stated a need for such systems, even on those devices which were to be equipped with visual systems. Prior to that time our experience with training devices which incorporate visual systems had been extremely limited. We knew that we needed motion cueing of some sort, and because we were ignorant as to where the line should be drawn with regard to the source of this cueing, we asked for large displacement six-degree-of-freedom platform motion systems. (If a little is good, a lot must be better.) In the summer of 1976 we were well into the operational test and evaluation of the Simulator for Air-to-Air Combat (SAAC). This device combines six-degree-of freedom motion with a wide-field-of-view visual system. Although assessing the contribution of the motion system to training effectiveness was not one of the objectives of the test and evaluation (after all, it's intuitively obvious that it does contribute – right?). The people conducting the evaluation began to notice some things:

FIRST: Some subjects didn't like to have the motion system on. That didn't bother us. People don't like a lot of things that are good for them.

SECOND: Many subjects couldn't tell you whether the motion system was on or off. That too does not present a problem. People respond to many things they aren't aware of.

THIRD: Aircrew performance in the simulator did not seem to be affected by the presence or absence of motion. Well, that is a little troublesome; however, we don't train people to fly simulators. We train people in the simulator to fly airplanes.

FOURTH: There did not appear to be any discernible difference in the performance, *in the aircraft*, between those individuals trained with and without motion. Now that one cannot be explained away so easily.

I am the first to admit that this information was not collected in the most rigorous scientific manner, and I would be the last to offer it as proof of anything. It was enough, however, to spur a search for additional information.

At about the same time, the Air Force Human Resources Laboratory had prepared a briefing summarizing their research efforts which had examined the contributions made by platform motion systems to the training equation. Time does not allow us to dwell on all of their research and results. Suffice it to say, their conclusion paralleled what our experience had led us to suspect.

Paraphrased, that conclusion was basically this: At least for centreline thrust aircraft simulators, they could find no statistically valid indications that the six-degree-of-freedom motion systems examined provided positive contribution when the simulator was equipped with a visual system.

After carefully evaluating the information available to us, the Tactical Air Command made the decision that in the absence of any strong indication that six-degree-of-freedom motion systems were necessary for the conduct of effective simulator training, the only responsible position we could take was to no longer support their procurement on devices which were to be equipped with visual systems.

The issue was certainly not laid to rest by our decision, for believe me, there is no lack of emotion in the motion question. After a couple of months of debate, the United States Air Force Scientific Advisory Board (SAB) was requested to assess the motion question and to provide recommendations to the Air Staff as to the position which should be taken on the question of motion system provisions for the A-10 and F-16 simulators. The SAB formed an Ad Hoc Committee to examine the issue. After researching the available documentation, attending a series of meetings which spanned approximately a year, and assimilating the information presented to it in the form of briefings in numbers and from sources too numerous to mention, the committee reached its final conclusion. (Again, I take the liberty of paraphrasing.)

They concluded that a case could not be made for or against including platform motion in the specifications for the A-10 and F-16. They further offered the opinion that if the need for a platform motion system were defined at some future date, it would most probably be for a system far less sophisticated than the current six-degree-of-freedom systems. Both the A-10 and F-16 simulator will be procured without platform motion systems; however, they will retain the provision for adding motion at a later date should the need be validated.

The second case I wish to address is not a case of fidelity overkill, but rather an example of what can be accomplished with a relatively low fidelity device provided it possesses a visual capability. The Tactical Air Command was recently faced with one of our ever recurring problems. We initiated qualification training in the A-10 aircraft without having an A-10 simulator in the inventory. We were examining several alternatives for obtaining some interim simulator capability when the Air Force Human Resources Laboratory came to our rescue. They modified their Advanced Simulator for Pilot Training (ASPT) to a quasi A-10 configuration and allowed us to use it for A-10 training.

Earlier I made reference to a low fidelity device. I surely do not mean to imply that the ASPT itself is a low fidelity device. It is not. My low fidelity comment stems from the fact that the ASPT is a T-37 simulator with a side-by-side cockpit arrangement and the fact that the modification was performed "on a shoe string". For example, a very simple canopy bow and instrument panel were made and installed to form the single cockpit illusion and the T-37 flight dynamics were modified to "approach" A-10 performance characteristics.

Time will not allow me to go into all of the details regarding the training results achieved, but let me give you these bits of information.

The students who received ASPT training prior to flying the aircraft were all recent graduates of the undergraduate pilot training program. None had been previously qualified in fighter aircraft. The following data is based on the first 12 students who received simulator training. An average of five landing pattern attempts was required for ASPT-trained students to land the A-10 aircraft with no coaching. Qualified fighter pilots transitioning to the A-10 who did not receive the simulator training required an average of eight attempts to reach the same level.

More importantly, on their first time *ever* on a gunnery range, all but 4 of the 12 qualified in all events attempted (dive bomb, low angle bomb and strafe). The four who did not qualify in all events only failed in one. Those who have been exposed to tactical fighter aviation will certainly appreciate those results. For those not so fortunate, I can say that in my opinion it is phenomenal.

I realize that as the device is currently configured, it will not cover all aspects of A-10 training, but for initial qualification training it must force you to ask, "How much more benefit you would reap through fidelity refinement and, secondly, is it worth it?"

I think I can summarize the concern that I have been trying to express by saying that in my opinion we have been worshipping a false God. We have been kneeling to the God of Simulator Fidelity, when we should have been paying homage to the God of Training Effectiveness.

I don't condemn anyone, individually or organizationally. The trainer asks for high fidelity devices through ignorance. He doesn't know how much less than that he can accept and still perform his function. He is judged by the quality and number of aircrews produced for the force. He desperately needs to have the research community provide him with some much needed basic knowledge with regard to minimum cue requirements.

As for the researcher, he too, to a large degree is in a "cannot win" situation. First, although I do not profess to have the knowledge necessary to pass judgement in this area, it appears to me that he is seldom allocated the resources required to do a really creditable job, and when resources cuts come, he is often the first to feel the knife. Secondly, the conduct of the research required is highly dependent upon the commitment of operational resources. That is, aircraft and aircrews. Both are limited resources, and although the operator may be the first to ask for the answers the research will provide, he will, I assure you, be the last to want to give up those limited resources.

Now we come to the "other" category of individuals involved in the process of simulator acquisition. In this group, for the sake of time and convenience, I will lump the procurers, design engineers, and the producers. Let me say first that the degree to which the following observations are valid appear to me to be almost directly proportional to their remoteness from the actual training situation. The problem here, as I view it, is very likely one of human nature. It may be a shining example of the old "out of sight, out of mind" adage. They all know that the devices we are addressing are to be used to train aircrews, but they seldom if ever see them put to that use. Hence, they tend to make the transition from thinking of these beasts as training devices, to thinking of them as simulators.

Ladies and gentlemen, I would submit that one of the greatest mistakes we ever made was in allowing the term simulator to become a generic term for training devices. It implies too much.

Basically, there is not a requirement to build simulators for aircraft. The requirement is to build training devices for aircrews. Too often, in my view, the individuals in the "other" category become oriented to the simulation for simulation's sake position.

By now you must be saying to yourselves, "He diagnoses ills, but does he prescribe remedies?" The answer to that is yes, but only in a very broad sense at this point in time.

First we must establish a much closer working relationship between all agencies associated with the use, procurement, design and production of training devices. As I indicated earlier I see exchanges of views such as we are having here this week as a giant step forward in this area. Likewise, I believe the establishment of agencies, such as the one I represent, is another sign of progress.

Secondly, the individuals responsible for training and the researchers must jointly identify the specific areas where there are gaps in our knowledge. They must then develop a mutually supportable comprehensive plan which will allow them to gain the required knowledge. The plan must identify the specific tasks to be accomplished to reach their objectives and must establish the interrelationship between each of the tasks. This plan will serve two functions. It will obviously serve as a road map for achieving the objective, but perhaps more importantly, it will assist in articulating the need for the total research package to the keepers of the money. Hopefully then, when money cuts come, it will be seen that the whole research effort will collapse if one "keystone" is removed.

Next, when the actual research is complete, the researcher must take great pains to, and funny as it may sound, he may have to solicit support to do so, put the results into words that the operator can understand and use. Who knows how often the results of outstanding research have been totally ignored because the "mere mortal" could not comprehend the results.

Finally, for the "others", I'm afraid that I can offer no specific remedy other than recognizing that the disease exists, except perhaps to suggest to them that once a day, every day, they tell themselves – "My assignment is to build training devices, not necessarily simulators".

Simulating the Visual Approach and Landing.

A. G. Barnes
Chief Simulation Engineer
British Aerospace,
Aircraft Group
Warton Division
Warton Aerodrome,
Lancashire, PR4 1AX
United Kingdom

Summary

Are we likely to see a visual display system for landing approach which will satisfy both the airline captain and the ab-initio instructor? To answer this question, the paper takes a general view of the standards of simulation which are currently achieved in training and research simulators.

The approach and landing is sub-divided into separate phases - straight-in approach, curved approach, flare, and ground roll - and the piloting task is critically examined in each of them, with particular reference to the use of outside world visual cues. On the basis of this analysis, the merits and deficiences of existing simulators, as a means of providing the equivalent information, are then discussed.

Improvements to the overall simulation of the landing approach are more likely to emerge if a better understanding of the information which the pilot uses in each phase is available. This paper is an attempt to assemble some of the information pieces, and to relate them to the technology of simulation.

1. Introduction

The approach and landing is a critical phase of flight which requires skill and judgement on the part of the pilot. Such skill and judgement comes from prolonged experience and training. By representing the approach and landing task on a ground based simulator, valuable returns in terms of training costs and safety are potentially available. In the past, flight simulators have not succeeded in achieving a representation of the visual approach and landing to allow us fully to capitalise on these returns.

Measurements have been made of the simulator deficiencies in this area, to support pilot criticisms. Sink rate at touchdown has been one criterion of performance, and substantial differences between flight and simulator have been reported (Ref. 1) In spite of equipment improvements over the years, the criticisms of simulators in the landing phase have remained (References 2 and 3). The purposes of this paper are two-fold. First, to examine the current standards of equipment to simulate the visual approach and landing phases, and secondly to identify the parameters which influence the pilot's task in each of these phases.

2. The Current Systems

Almost without exception, electronic means of image generation and display are employed by current visual systems. Within this framework, the alternatives for producing the images are the TV camera looking at a model of the ground, or a digital computer (CGI). The display may be presented to the pilot on a TV monitor, or by a TV projector, or on a cursively-written CRT. The image may be collimated to infinity, or at a fixed distance on a screen.

These alternatives may be examined more closely by comparing six existing/projected visual display arrangements, on the basis of six factors which influence the success of the systems. The chosen factors are discussed below. A more complete catalog of factors relating to visual information may be seen in reference 4.

1. Field of View In simple terms, the wider the better, is a good criterion. Large elevation coverage is also desireable. $50^{\circ} \times 30^{\circ}$ a definite minimum for approach and landing, but the TV-model systems are not readily developed to provide more coverage. Laser TV should be better, and the CGI systems provide additional windows as required.

2. Textural Quality Ideally, the system should provide the high textural detail which is seen by the pilot during a typical approach - fields, trees, rivers, roads, houses, cows, cars, airport buildings, runway markings and other paraphernalia. The TV-model systems are able to provide most of these things, whereas the computer based systems rapidly reach a limit set by computing capacity and speed.

3. Resolution The limitation which raster TV imposes on the viewer's ability to resolve detail is well known. To match the capability of the eye, an improvement to current systems by roughly a factor of 10 is needed. The beam penetration tube used for night landing simulators is perhaps 2 or 3 times better than the raster systems, and laser TV offers further improvement.

4. Response The presence of a lag, dead-space, friction or non-linearity in the driving of the visual display is a potential source of piloting difficulty. The combination of aircraft characteristics and piloting task which are most affected by imperfect response are understood, but the simplest rule is to keep imperfections to a minimum. In some circumstances, no significant effect will be seen with as much as half second lag present; in others, a lag of 0.05 seconds will be noticed by the pilot. Often, the pilot is unaware that the source of a control problem is in the signals driving the visual display. Computer generated displays at least avoid the difficulties sometimes seen in opto-mechanical devices.

5. Flexibility For military aircraft training, and for research investigations, it is an advantage to use a visual display for different modes of flight: various take-off and landing situations, formation flying, weapon delivery, and navigation. In this respect, the CGI displays have a certain advantage over the TV/model systems, because changes are effected by software rather than hardware.

6. Range Several factors can limit the useful range of visual systems. One such limit is the depth of focus of an optical system on a camera; other causes of range limits are the physical size of a model, the scaling of an analog system, and the resolution of raster TV.

Two additional factors, installation and capital cost, are also listed. They neither add to, nor subtract from the piloting task, but they can have a strong influence on customer preference.

Table 1 allows an easy comparison of these factors, without attempting to put in the weighting term which a prospective customer would apply to each one. Other factors, such as reliability, and special effects are not considered, and even vary between systems in each group. The lesson from the table is that no one landing display has all the desireable features. In the following sections it is intended to examine the factors which are significant in the four phases of a landing, and to see whether any new requirements emerge.

3. The Straight Approach

3.1. Piloting Aspects

If no reference is made to flight instruments, the visual straight approach is a difficult manoeuvre, requiring fine judgement by the pilot. The glideslope information is the angular distance between the horizon and the glideslope origin (Figure 1); this must be compared with the angular position of the aircraft's velocity vector. Without a flight director, the pilot will normally estimate the position of the velocity vector by reference to an airframe datum, knowing from experience which datum to use, depending on aircraft weight and speed. He may even supplement this assumed datum by detecting the 'point of expansion' of the visual scene, although this cue is only detectable in the final stages of an approach. (Reference 5)

Further information is obtained from the perspective shape of the runway. Because the dimensions of the runway are roughly known, an estimation of height/range can be made; otherwise height information comes from the textural quality; and geographical features of the surrounding terrain. Pitch attitude information has a vital part to play. If the pilot wishes to make gradual changes in the approach trajectory, he will control speed with pitch attitude, and sink rate with power. More rapid changes can be achieved by reversing the control actions (speed with power, sink with attitude). The control strategy also depends on the handling qualities of the aircraft.

The higher the approach speed, and the larger the aircraft, the greater is the distance from the runway at which it is desireable to be established on the glideslope. In consequence, the judgement called for from the pilot is more difficult - judgement which requires the estimation of distance, speed, height, sink rate, and the perspective of the runway itself. A typical case is illustrated on Figure 2.

Assuming a height of 1000feet on a 3^{o} glideslope, the runway information is contained in a rectangle 3^{o} x 0.5^{o}, and a height change of 50 feet only changes the angle subtended by the threshold by 0.15^{o}. At this stage in the approach, reference has to be made to supplementary information concerning height, speed, rate of descent and glideslope. The pilot of the light aircraft has an easier task. Not only does he have more time to make these judgements (because of the lower speed); he also has an aircraft which is more easily established onto a new flight path. He is however, more vunerable to the effects of cross-wind, head-wind, wind shear, and turbulence.

The pilot's task laterally consists of maintaining a steady track over the ground. To do so, good bank and heading reference must be available. Drift due to cross-wind must be corrected for by heading adjustments.

3.2. Simulation Aspects

It can be inferred from 3.1. that even if the visual simulation were perfect, the pilot would still need to refer to information in the cockpit. The simulator should provide such information to the same standard as in the aircraft, and most simulators are able to do so.

With regard to the visual system, there is clearly an over-riding need for high resolution within a 10^{o} cone directly ahead of the aircraft. As the approach proceeds, the value of texture, to provide both speed and velocity vector information, increases. Associated with the high resolution is a need for pitch, roll, and heading information which is accurate to one or two minutes of arc, and without imperfections due to lags, thresholds, or steps.

Because the information is at long range, and because cross-reference between the outside-world and the cockpit instruments is essential, the visual display should be collimated at infinity, rather than projected onto a screen. For airline training, ground aids such as VASI and approach lighting must be represented, and the effects of cloud, mist, and fog should be simulated.

There is no obvious need for a field of view greater than 50^{o} unless it is considered that the ease of lateral control is influenced by having peripheral cues. There is an undoubted tendency for pilots to overcontrol in roll, on transition from instrument to visual flight, on existing visuals (both model/TV and CGI). It is a characteristic which pilots can learn to suppress: the source of the problem is not obvious, and the blame may not necessarily lie at the door of the visual system.

4. The Circuit/Curved Approach

4.1. Piloting Aspects

The student pilot has to master the circuit. First impressions are that there are too many interdependent quantities to be successfully controlled and adjusted simultaneously: speed, power setting, height, bank, turn rate, downwind position, R/T, checks, flap setting - and look out for other traffic. The secret, of course, it to never let large errors creep in. Early correction of any deviation is vital, and so over-obsession with any single variable can lead to trouble. The student's problem is to recognise the error, since the datum for error measurement, and the yardsticks for error, are only learned by example and experience. But with competence comes confidence, and most pilots find circuit flying a satisfying task and a nice measure of their ability. The ultimate in satisfaction, if not in safety, is the circuit in which cross-wind, downwind, base-leg and finals all merge, and we see a 'Spitfire' approach, turning continuously; the wings are levelled as the flare begins.

Apart from its aesthetic appeal, the visual circuit has several advantages over the straight approach. It can be flown, in the main, by reference to external visual cues, and in consequence, the pilot has much better opportunities to see (and avoid) other aircraft. The circuit may be joined safely without radar control, and in the case of jet fighters, efficient transition from high speed flights to touchdown is possible, by using the 'break' as a means of converting energy from a low pass down the runway in a clean configuration, into a good downwind position, in the landing configuration. A further advantage lies in the opportunities afforded at various key points in the circuit for the pilot to check for errors.

To examine the visual aspects of a typical circuit, it is useful to draw a panoramic view of the runway and horizon as seen by the pilot at different stages in the circuit. Figure 3 is such a diagram; the downwind leg is displaced from the runway by 10,000 feet, and the curved final approach might be appropriate to a fighter using 150 knots on finals. The circuit height is 1000 feet, the touchdown point is 1000 feet from the threshold, and the height at the threshold is 50 feet. An arbitrary cockpit cut-off line is also included.

The pilot's judgement of downwind position and offset from the runway comes from an assessment of the depression angle of the runway relative to the horizon. To make this assessment, height must be known, and height judgement will be greatly assisted by the textural quality of the ground. In particular, vertical features of known size (both natural and man-made) are useful. Airframe references also have a part to play - if the horizon is obscured, the wing can provide a good datum by which to judge where the runway should be located - provided errors are not corrected by bank angle adjustments! In the situation of figure 3, the runway is 5.3° below the horizon; a 1° error can result in a lateral off-set error of 2000 feet.

Two additional cues to achieving the correct lateral offset are:

1. the azimuth angle subtended by the runway itself, assuming that the runway length is known, and

2. the angular rate of change of ground features, such as the runway threshold.

To maintain the downwind track, good attitude and heading cues are essential; the early detection of drift due to cross-wind is also helpful. In this phase, the pilot's scan pattern will cover large angles in azimuth. The visual cue for initiation of the turn onto finals comes from a judgement of position relative to the end of the runway.

The pilot must then establish a rate of turn which will produce a tangential interception with the approach centre line. Initially, the turn will be based on the pilot's judgement of the downwind position, the speed, the crosswind. He will make a similar judgement based on flap setting, power setting, and speed to establish an appropriate rate of descent during the turn. As the turn continues, adjustment to tighten or slacken the turn will be necessary. One method, which pilots may use subconciously, is the <u>Assymtotic Approach</u>. Figure 4a shows the situation in plan. Figure 4b shows the view from the cockpit. Two angles, each measured relative to the runway heading, are of interest: the angle subtended by the end of the runway α, and the heading of the aircraft ψ. For a tangential approach path, $\psi = (1 + k)\alpha$, where k is an arbitrary factor. If k = 1, the path is circular, which if the speed is constant, implies constant bank angle. From the pilot's point of view, figure 4 b, he simply flies to keep the angle ψ twice as large as α.

On many occasions, it is desireable to complete the turn onto finals well before the runway threshold. In these cases the same principle will apply, except that the reference point will be along the extended runway centre line. Again, ground features, such as approach lighting, fields and roads, are needed to allow easy identification of the extended centre line.

4.2. Simulator Aspects

The obvious requirement for visual circuits as compared to the straight approach is the need for a wide field of view. We are now seeing display system which can provide something like 150° field of view in azimuth, and the customer can chose the area to be covered. Collimated images are essential, so that the relative position of windscreen and other aircraft structure to ground features is fully representative. The wing-tip, if visible, needs special attention to get the aspect of it geometrically correct; a scale model in the collimation optics is one solution.

The need for accurate angular location of ground features relative to the pilot's eye is also clear. Small angular errors represent large positional changes, and nothing could be more disconcerting to the pilot, if, as the display transfers from one window to the next, an apparent height or sideways translation occurs.

A further source of distortion, which is not often appreciated, comes from badly matched electronic generating and display elements. Essentially, the generator (perhaps a TV camera) provides X and Y shifts to the display (a raster TV tube). If an error in X shift from the camera is compensated on the display by a compensating Y shift, the picture can be geometrically correct until a roll input is made.

Mis-match errors of 10% can easily occur from this source; the effect is confusing to the pilot. Moreover, unless very careful setting up procedures have been followed after maintenance, errors from this source will not be found, because the pilot cannot diagnose the problem. The same mechanism also produces the illusion of lateral displacement.

Before the recent CGI developments, most visuals provided a field of view in azimuth of around 50° - woefully inadequate for flying a visual circuit. Nevertheless, they can be used to look at the last few degrees of the final turn, or to correct a track offset. Pilots new to the simulator find the simple task of aligning the aircraft with the runway centre line more difficult in the simulator than in the air. One possibility is that their awareness of the angular relationships involved is more acute in the air than in the simulator.

The recognition of ground features plays a part in the representation of circuit flying. There is a need for continuous recognition of geographical position, with an attendant emphasis on ground texture. The requirement for a wide field of view can be most easily satisfied by the use of a CGI display; unfortunately to provide the associated textural quality requires an excessively large computer at the present time. Systems are now becoming available which permit a visual circuit to be flown. The development of these systems over the next ten years to cover the complete spectrum of training, from the Cherokee to the Airbus, is full of opportunity.

5. The Flare

5.1. Piloting Aspects

The Flare is the manoeuvre by which the transition from trimmed flight on the glideslope to touchdown on the runway is achieved. It is a phase of flight that calls for skill and judgement. At an appropriate height, the pilot increases the normal acceleration on the aircraft, in order to rotate the flight path, and to reduce the sink rate. During the flare, power is reduced, the speed reduces-partly because of the reduced power, partly because of the change in flight path - and ideally the touchdown point, recommended touchdown speed, and near zero sink rate are all attained simultaneously. In practice, several factors cause occasional departures from the achievement of this ideal. These factors include the type of aircraft, the configuration, the type of approach, the approach speed, the time taken to flare, atmospheric conditions, ground effects and (some do say) chance.

It is difficult to lay down general rules concerning the flare. Compared to other phases of flight, it has been neglected by the analysts, partly because of the dynamic nature of the manoeuvre, and partly because of the lack of definition of the manner in which a pilot performs the flare. It can even be debated whether it is a closed-loop manoeuvre or a quasi-open loop manoeuvre. An early attempt at analysis considered one flare technique as an excited phugoid (figure 5) mathematically correct, but impossible from a piloting standpoint. New methods of analysis now point to ways of understanding the flare.

Pilots learn to flare by trial and error. The first essential judgement is that of range and height. Pilots of Tiger Moths were advised to flare when individual blades of grass could be resolved: a useful substantiation of perspective and other height cues. With larger, faster aircraft, the flare height is higher, and even if they landed on grass, it is likely that the flare height would need to be judged on range and height estimation alone. Once the flare is initiated, by a rearward stick movement, the pilot controls (or monitors) pitch rate (which determines the normal acceleration used in the flare), and as the nose rises, controls pitch attitude to avoid the over-flare. Height is also monitored, and adjusted by means of pitch attitude changes. Power adjustment is necessary to achieve the correct touchdown speed; if large errors occur, then power may also be used in flight path control.

Distinctions must be drawn between large and small aircraft, with respect to control in the flare manoeuvre. The first difference relates directly to size. The small aircraft is very responsive to control inputs, and requires continuous closed-loop control of attitude, speed and height. It is also responsive (embarrassingly so, at times) to turbulence. In contrast as size increases so the long response times of the large aircraft make pilot control in a closed-loop manner less and less rewarding. Turbulence has less effect. It is worth quoting the Chief Test Pilot of the CAA, on flaring the Boeing 747 (Reference 6). "A good average landing can be flown as simply as this: at 50 feet radio height and at V_{AT} make one small flare movement on the elevator: at 30 feet slowly close the throttle and merely resist any nose down pitch change with elevator, thereafter maintaining a substantially constant attitude; by about 10 feet, the power should be all off, ground effect is quite marked and reduces the rate of descent; a few seconds later there is a comforting rumble as the main gears run onto the ground".

A further distinction between the light aircraft and the commerical transport is in the complexity of the high lift devices which they each use. The simple flaps on typical light aircraft are in contrast to the triple slotted flaps on the 737 and 747. One effect, which influences handling in the flare, is the higher drag coefficient associated with the more efficient flaps. During the flare, some speed loss is necessary; in general the drag coefficients of larger aircraft are nicely matched to the flare manoeuvre; as the rotation of the flight path to the horizontal is achieved, so the speed has decayed to that desired for touch-down. In the case of light aircraft, even when the flare is complete, there is still flying speed; the necessary and often prolonged hold-off manoeuvre needs care and judgement. Reference 7 uses the terms "floaters" and "sinkers" to differentiate between aircraft in the flare. Development of these ideas leads rapidly into considerations of speed stability, and of control techniques outside the scope of this paper. A more complete description of the flare would also discuss the piloting problems raised by ground effect, crosswinds, wind-shear, and undercarriage design.

5.2. Simulation Aspects

Even the most ardent simulator enthusiast would not claim that we faithfully represent the flare in flight simulators. Measured sink rates at touchdown are invariably higher than those measured in flight trials, and most pilots would say that landing a simulator is a trick which has to be learned. Opinions vary as to where the deficiencies lie. A typical novice will be in trouble on flare initiation. The size of the runway appears to be smaller than in real life, and so flare initiation is late. Often, this mistake is followed by over-rotation, and severe over-control in pitch. There is an inability to appreciate pitch angle changes as readily as in the air, so that over corrections occur. Height and speed appreciation is also lacking, difficulties occur in recognising in the visual display the components of pitch, height, heading, and track which, together with speed and bank angle, determine the aspect at any one time.

Perhaps the biggest single deficiency of current visuals (and the most difficult one to remedy) is the recognition of range. No display system even promises to provide optics in which objects on the ground are at the correct focal distance, and yet there is no doubt that range estimation, from binocular vision and head movement, plays a vital part in the flare. Range estimation may also be influenced by atmospheric attenuation of the appearance of objects on the ground - in this respect, the lighting levels in simulators are way below those experienced in daylight landings.

The CGI displays do not suffer from the depth of field/focussing problem seen on model/TV systems, and their ability to provide peripheral cues during the flare may be of help to the pilot. But if the side-window displays are collimated, then any attempt to judge height by means of a downward glance through the side window will be thwarted, since an image which should be tens of feet away will be at infinity.

The part played by poor resolution in determining flare performance has still to be resolved. Pilots generally criticise the resolution of the images as seen on TV raster presentations; it is certain that their subjective impressions of the display will improve with improved resolution, and the key question is: will performance also improve? It is possible that with improved resolution, more textural detail will be seen which helps to identify the velocity vector of the aircraft. The position of the velocity vector is critical during the flare; on the other hand, as the flare is terminated, the cockpit structure invariably screens the location of the velocity vector from view.

Not enough attention has been given to the influence of display dynamics in simulation the flare. Although the basic aircraft modal frequencies are low, the control loops closed by the pilot have low damping and are close to instability at times. (The use of 'dither' has been linked with the pilot getting the best performance out of the system). In these situations any lag or time delay can have serious consequences, and systems like the TV/model which move large pieces of machinery around must be suspect in terms of dynamic performance. Most pilots would agree that in ideal conditions (a good approach, at the correct speed, and in calm air), the flare is not a difficult maneouvre. The simulator should have the capability to produce these ideal conditions, especially now that we have the accuracy of all-digital computation. Many simulators do not seem to have this capability, either due to computational inaccuracies, feel system deficiencies, servo thresholds and inadequate response. The malaise is not only associated with the visual displays, but perhaps the starting point is to ensure that the display is not a source of dynamic deficiencies.

Before we conclude that current simulation equipment cannot simulate the flare manoeuvre, we should look closely at the latest standards of Airline Training. Strong financial incentives have lead most Airlines to invest heavily on simulators, and the newer ones, using night or day CGI systems, are significantly better than any of the simulators currently being used for research. We have also seen that the piloting task in the flare is easier on the large transport aircraft than on the light aircraft. Moreover, at night, or in poor visibility, the pilots may use a partial flare. In these circumstances, adequate simulation of airline operation is possible. Confirmation comes from the news that two major US Airlines are close to obtaining FAA approval for type transition using simulators only (reference 8), without any loss of revenue time.

6. The Ground Roll

6.1. Piloting Aspects

A landing is not complete until the aircraft has come to a standstill. Each class of aircraft will have problems peculiar to that class; with a given class, individual types will be characterised by their behaviour on the ground. In consequence; a general discussion on how to complete the ground roll is inappropriate.

The larger, faster aircraft consume runway, so that stopping distance is the first consideration. Braking technique, and the use of thrust reversers (or parachutes) may be of most concern, coupled with runway conditions (water or ice) and crosswinds. Failures and assymetrics will provide the critical conditions.

The small light aircraft is less critical on distance, but will be more susceptible to crosswinds and gusts. The tail sitter is of special interest, because it is inherently unstable in the ground roll.

In terms of visual cues, the requirements are simpler than in the airborne case. There is a need for a good appreciation of speed, heading, drift, and position on the runway. The ability to detect small bank angles associated with the rolling moments from crosswinds, and to detect small pitching motions associated with the use of braking devices, is also important.

Perhaps the greatest danger in the ground roll is complacency. Most landings are carried out in conditions which are not critical, in terms of safety margins. When conditions are critical, however, the situation is also susceptible to random variation - much more so than in airborne flight. For example, runway surface conditions can vary over wide extremes. Aerodynamic forces and moments are not so well behaved as in flight, because flown patterns break down. Steering characteristics change with speed, wind conditions have more pronounced effects, and control limits are easily reached. In consequence, the pilot can be taken by surprise.

6.2. Simulation Aspects

The case for good simulation of ground roll is strong. Because the simulation of the flare is of dubious quality, the value of representing accurately the characteristics of the aircraft during ground roll is reduced, and only the large civil and military simulators pay attention to handling on the ground.

The standards currently achieved are open to improvement. The TV/model systems suffer from the small scale of the model which is needed to represent typical approach paths ('Range' factor of table 1). The runway surface appears to be too coarse, runway lights are too large, even the eye height of the pilot is often incorrect. The camera depth of focus limit is a further distraction.

The CGI systems are geometrically correct, and their wide angle capability together with smooth response, allow the pilot to recognise the changes in speed, heading, drift, roll and pitch which indicate when control inputs are required. Their main deficiency is their lack of textural detail.

In the ground roll, as in the flare, the inability of current display devices (collimated CRTs, or TV projectors) to represent objects in the visual field at their correct focal distance is most apparent. Estimation of the distance of objects is significantly different, compared to real life (reference 9).

In spite of these deficiencies, the important aspects of pilot control during ground roll can be represented in the simulator. To do so, attention must be given to the representation of the undercarriage geometry, springing and mechanical design, the braking system, the tyres and the runway surface. The computer modelling of these factors requires digital computing power which has only appeared in the last few years. The ability to demonstrate to pilots and engineers the critical cases of wet runway, cross-wind,brake failure, part-flap landing, and other emergencies is invaluable, for both pilot training and aircraft design, and increasing use of simulation of ground roll may be predicted with confidence.

7. Conclusions

Flight Simulators are in wide-spread use throughout the world for both training and research. They make a significant contribution to aviation design, development safety and economics. To make this contribution, complex equipments have evolved. The simulation of the landing approach is the most challenging of simulation requirements, and the visual aspects are the most difficult to reproduce.

Emerging from the study of the four phases of the landing is the conclusion that each phase puts a different emphasis on the display requirements. Also, the comparison of the features of existing visual display shows that any one system is good in some respects, but is deficient in others. Different users have different requirements - the display configuration best suited for an Airline Training Facility will be inappropriate for a University - based Research Simulator.

As with other fields, the future for image generation seems to lie with the digital computer - CGI systems will benefit considerably from the coming improvements in speed and capacity. Two outstanding problems remain on the display side:

1. High resolution, wide angle display devices, to permit full use to be made of the wide-field-of-view possibilities of CGI systems, are required.

2. Improved recognition of distance. Most current systems present the image of the outside world at a fixed distance. Means should be sought to represent objects in the visual field at the correct focal distance.

Neither of these problems has an obvious solution. On the other hand, twenty years ago, our current systems were not obvious.

8. References

8.1. R.A.E. Report TR 68116 "Difficulties with the Simulation of aircraft Landings.

B.D. Armstrong May 1968

8.2. NASA TN D-3971 "Determination of Flight Characteristics of Supersonic Transports during the Landing Approach with a Large Jet Transport In-Flight Simulator".

NASA Langley June 1967

8.3. AFFDL TR 75-41 "Low Visibility Landing Pilot Modelling Experiment and Data. Phase 1.

Wright-Patterson AFB April 1976

8.4. The Aeronautical Journal of the Royal Aeronautical Society. "Current Problems of Flight Simulators for Research".

K.J. Staples R.A.E., Bedford January 1978

8.5. RA.E. Report EL 1459 "A quantitative analysis of the ground indications seen by the pilot when using visual aids for landing in good and bad visibility".

E.S. Calvert 1949

8.6. ARB "Handling the Big Jets" 3rd Edition.

D.P. Davies December 1971

8.7. NASA CR 2517 "The Landing Flare: an Analysis and Flight Test Investigation".

E. Seckel May 1975

8.8. Aviation Week and ST. "Pilot Transitions Tested using Simulators Alone".

13th March 1978

8.9. AIAA Visual and Motion Simulation Conference. "Visual Space Perception on a Computer Graphics Night Visual Attachment".

E.D. Palmer, J. Petitt. NASA Ames. April 1976

Table 1

VISUAL DISPLAYS FOR APPROACH AND LANDING

GROUP / FACTOR	FIELD OF VIEW	TEXTURAL QUALITY	RESOLUTION	RESPONSE TO INPUTS	RANGE	FLEXIBILITY	INSTALLATION OVERHEAD 6)	CAPITAL COST
RASTER TV/MODEL	E 1)	B 3)	D	D	D	D	HIGH	MODERATE +
FILM/SERVO PROJECTOR	E	B	A	D	D	E	MODERATE	MODERATE
LASER TV/MODEL	C 2)	B	A	D	B	D	HIGH	HIGH
NIGHT CGI	C 2)	D 4)	B	B	B	D	LOW	MODERATE -
NIGHT CGI WITH RASTER INFILL	C 2)	C	B	B	B	D	LOW	MODERATE
DAY CGI	C 2)	D	C	B 5)	C	B	MODERATE -	HIGH
CONTACT ANALOG	C 2)	E	C	A	E	D	LOW -	LOW

SCALE: A B C D E

EXCELLENT ... BARELY ACCEPTABLE

Notes:
1. One window
2. Three window
3. Modelling limit
4. No credit for neon signs and firework displays
5. Subject to good cycle time
6. Space, power consumption

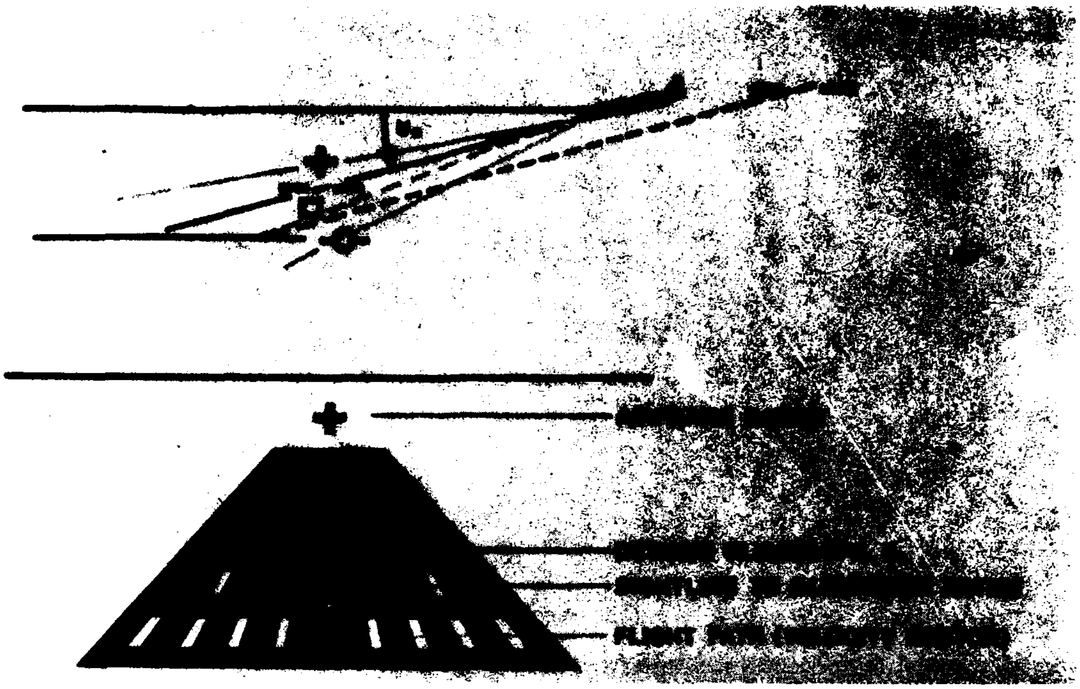


Figure 1.
Approach Geometry

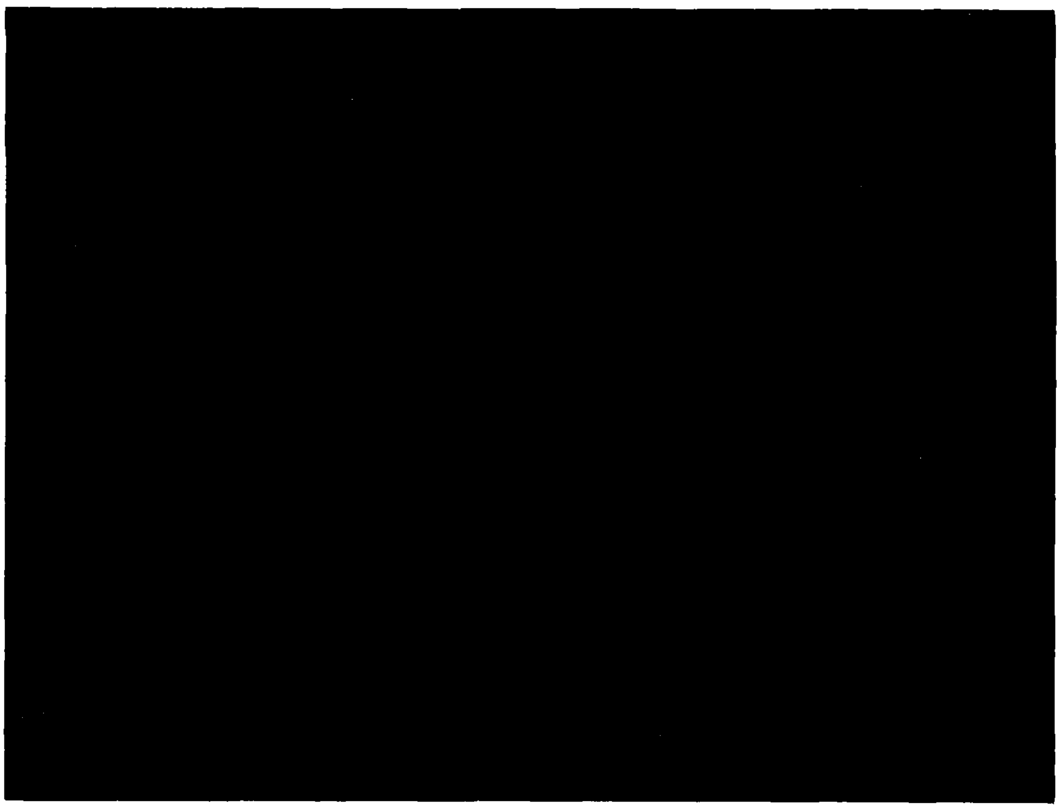


Figure 2.
Straight Approach

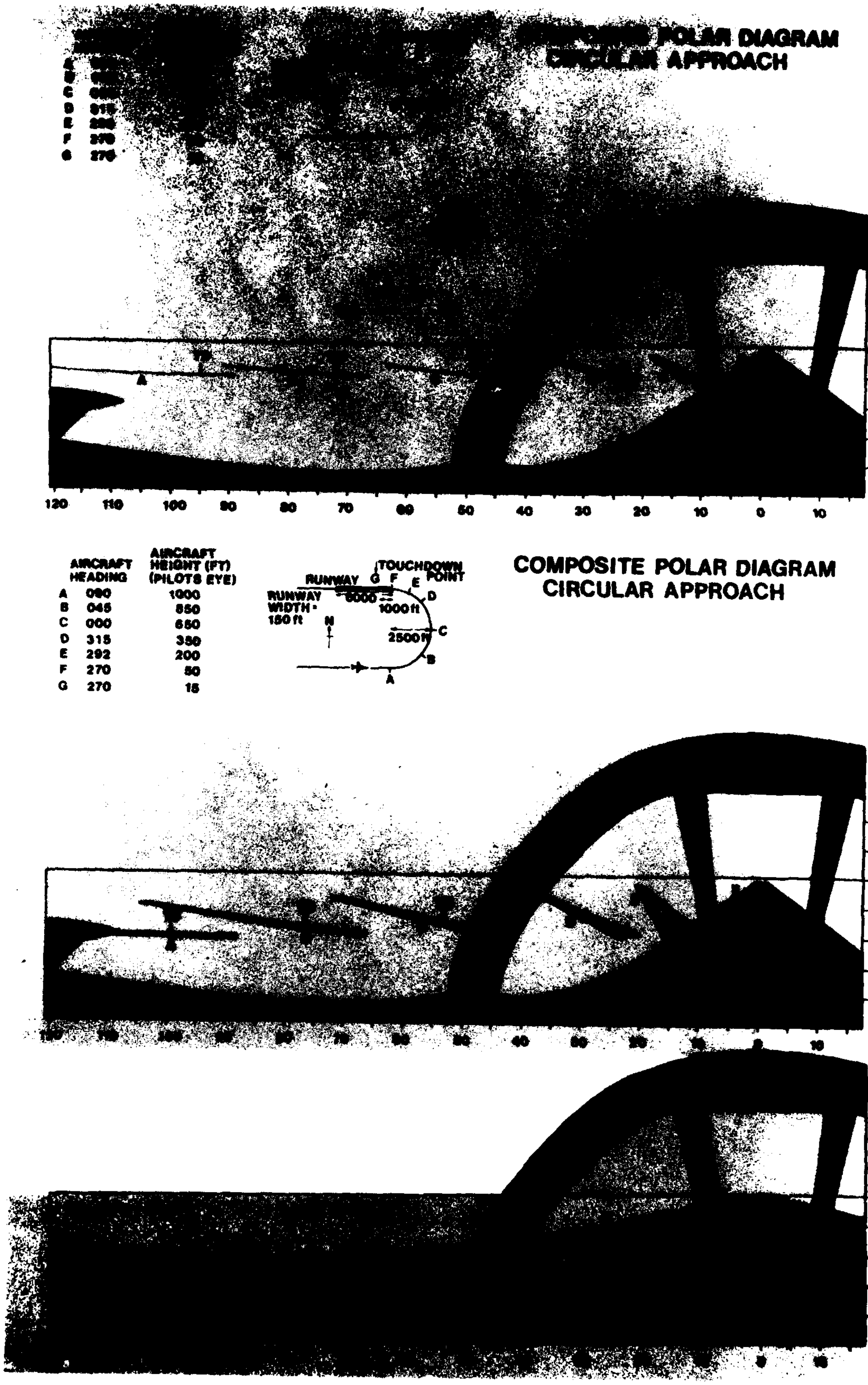


Figure 3 Polar Diagrams of Circuit

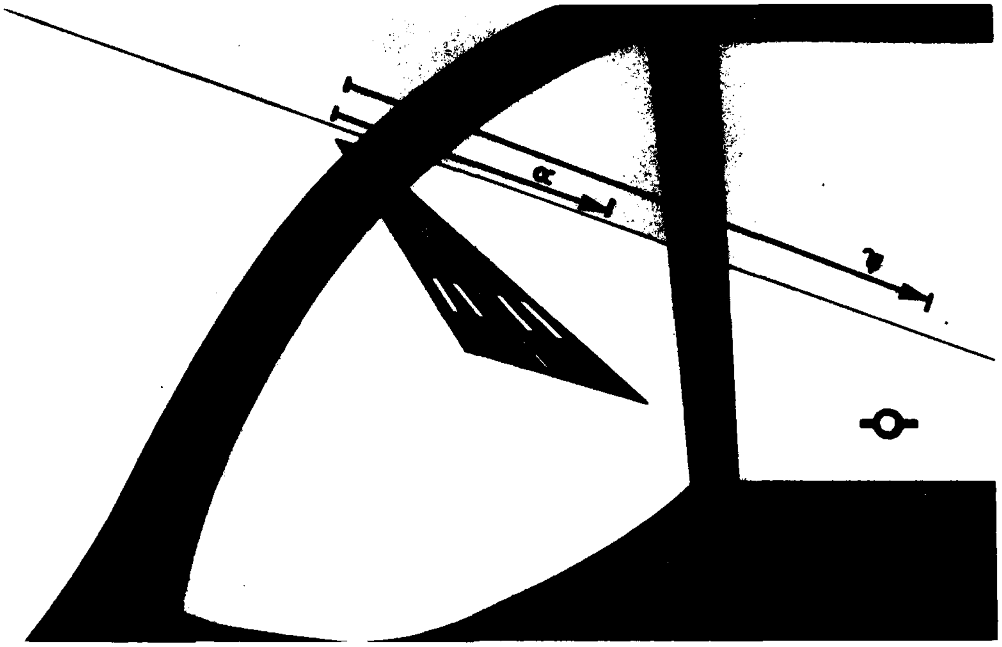


Figure 4a
Asymptotic Approach: Pilot's View

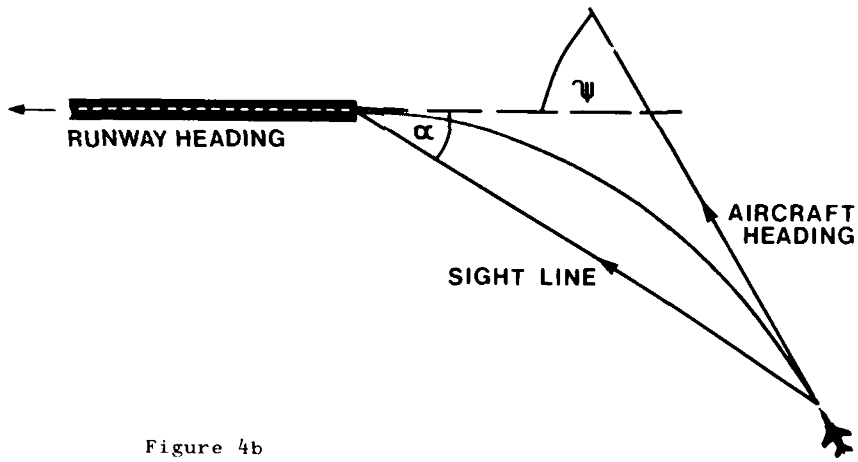


Figure 4b
Asymptotic Approach: Plan

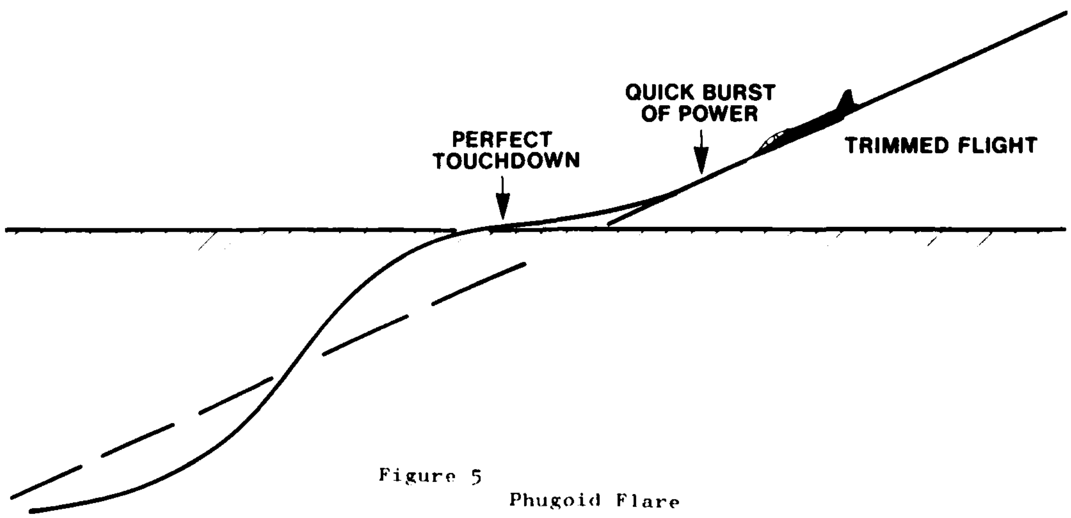


Figure 5
Phugoid Flare

VISUAL CRITERIA FOR OUT OF THE COCKPIT VISUAL SCENES

by
CONRAD L. KRAFT, Ph.D. - CREW SYSTEMS, BOEING AEROSPACE COMPANY
Seattle, Washington

LARRY W. SHAFFER - SYSTEMS ENGINEERING, GENERAL ELECTRIC COMPANY
Daytona Beach, Florida

INTRODUCTION

In 1973 a small committee of four men, representative of the disciplines of electronics, flight and vision, were asked to develop the criteria for a visual system for flight crew training in air transportation. This is a review of the visual criteria developed for this out of the cockpit visual scene generation. The date gives you an historical reference, however the visual criteria applied then apply today.

The available classes of visual systems in 1973 were three: film and anamorphic projection, closed circuit television and fixed terrain model, and computer generated image system. The last had the highest risk, but promised much greater flexibility, higher quality images and a day/night scene. These were the special requirements of the Boeing Commercial Airplane Company's Flight Crew Training organization. They were engaged in training people with extensive flight experience (20 to 30 thousand hours) and others that had as few as 150 hours of flight time.

VISUAL RESOLUTION

System resolution is almost always the first criterion mentioned in a specification for any visual system. However it is not necessarily the system resolution that is important; of importance is what is presented to the pilot at his eye reference point. The criterion for acceptance in this application was the visual angle, i.e., the angle subtended at the pilot's eye by the smallest element in the display. This is depicted in figure 1. Two objects of different sizes can represent the same visual angle on the retina of the eye if their position is represented at two different distances, as long as size is directly proportional to distance (figure 1). For night scenes, the ideal is to depict a point source of light, at some photopic brightness level, such that it would appear to be a true point source. If the visual simulation system could depict a point source at .8 of an arc minute at six foot lamberts, it would appear to be 1.25 arc minutes in size. At this luminance this would be a replica of the apparent size of any point source in the real world, regardless of its remoteness from the viewer in clear air. For the daytime scene, selection of a single value for acceptable resolution in the display was of necessity arbitrary in the absence of flight performance data. We chose the normative performance of pilots with the Landolt "C" as a target, and compared the resolution of one line and one element to their "clinical norm." At the time the Compuscene was developed, three arc minutes was the industrial capability of resolution of one line by one element.

EFFECT OF FIELD OF VIEW ON VISUAL RESOLUTION

For the 1000 line raster type display system with a full color capability, there are about 735 active TV lines vertically, and 880 elements horizontally. The visual resolution of these elements depends upon the field of view used in any single display. There are two very common sizes used today in visual systems, 30 X 40 degrees and 36 X 48 degrees. These two common fields of view are included in table 1, along with three other alternatives which span the field of view required for a resolution of .8 of an arc minute, to the 80 degree field of view which might be needed if the display surfaces were 12 pentagonal of a dodecahedron forming a sphere around the individual. To produce a system of .8 to one arc minute resolution, one would have to combine a number of 10 X 15 degree displays to make up the total visual field. From an engineering and economic point of view, this doesn't appear practical. On the other end of the scale, to use a 60 X 80 degree field of view means that you would have to use a 2000 scan line system to approximate the resolution that you would have with a 1000 line system and the 30 X 40 degree field of view. The common 36 X 48 degree field of view nearly fills the forward window of a 707, 727 or 737 aircraft. The resolution required by this degree of magnification of the RCA 25" tube would be 3 arc minutes vertically and 3.3 arc minutes horizontally. If one uses the 30 X 40 degree field of view, better resolution of 2.5 X 2.8 arc minutes is possible without changing the line scan system. General Electric's choice was to stay with the 30 X 40 degree field of view and provide the higher resolution.

SYSTEM RESOLUTION, VISUAL EFFICIENCY AND VISUAL ACUITY

Figure 2 illustrates the relationship among the simulator resolution, the visual efficiency and visual acuity. The abscissa in this graph is the visual angle in minutes of arc. The ordinate is Borish's term "visual efficiency in perception," and across the top is the familiar Snellen visual acuity scale. For a frame of reference, one minute of visual angle is equivalent to the 20/20 scale on the Snellen chart and this value is considered a clinical norm. Most pilots can resolve a Landolt "C" at 40 arc seconds or about two thirds of a minute. This may represent the ideal for a visual system. At 10 minutes of arc, the Snellen fraction is 20/200. Anyone with vision which cannot be corrected to better than 20/200, in the United States is considered clinically blind. Twenty/two hundred, or the inability to resolve the large E on the Snellen chart, also entitles one to apply for welfare. On the left of the graph, between one and five minutes of visual angle are the values that were included in table 1. The vertical and horizontal resolution of the Compuscene are included in the table which are equivalent to 20/40 and 20/60 on the visual acuity scale. There is still a way to go to reach the 20/20 equivalent of the ideal, but it is certainly a step forward from the practical 8.5 arc minute resolution of the fixed model/TV systems.

VISUAL RESOLUTION AND ELECTRONIC SMOOTHING

Visual system resolution as developed above does not consider any smoothing routine in the software. A number of visual anomalies occur as a function of the digital output of the computer interacting with the line scan aspects of the display. These anomalies take the visual form of flicker, scintillation, stroboscopic effects, and apparent motions such as changes in size, position, and relative spatial localization as well as shearing. The term aliasing as used by engineers covers these visual phenomena. To minimize or eliminate such phenomena the practice is to generate edge smoothing in the CGI system. Edge smoothing as an effective attenuator of some visual anomalies does alter system resolution in the following manner.

Figure 3 illustrates how horizontal edge smoothing works. On the upper left, the transition between element one and element two, a transition of color or luminance contrast, is unsmoothed. The smooth edge on the upper right incorporates a third element, a transition element of one half the color change or the brightness change. Therefore the transition from element one to element three is spread over a 5.6 arc minute section instead of 2.8, as in the non-smoothed edge. What this does, in effect is to reduce the resolution of the day scene from a 2.8 arc minute resolution to 5.6. It has a different interaction for the night scene representation of point sources. The 3 x 3 smoothing routine interacts in the following fashion: If the electron beam hits right of the center of the smoothing routine you get a point light source of 2.5 by 2.8 arc minutes, a size represented by one element by one line. This will occur 11% of the time. However, it is off in one dimension so that it includes a second element. Then you have 45% of the light sources represented as 2 x 2 elements or 5.0 by 5.6 arc minutes. Another 44% is represented by 3 elements where the beam is diagonally off the center of the smoothing routine and the point sources here are 7.5 x 8.4 arc minutes in size. Thus, resolution has an interaction with the smoothing routine in the CGI system. It is best to represent then that the resolution of the system varies for the night scene from 2.5 arc minutes to 8.4 arc minutes (see figure 2). And for the day scene, from 2.5 to 5.6 arc minutes. To exemplify this in terms of scene content, a 5.6 arc minute resolution would mean that if you had an 8-foot wide runway threshold mark with an equal space in between marks, as is used in Europe, the threshold marks would be resolvable from 4,900 feet or (1,494 meters).

Considering resolution or any other characteristic of the visual simulation in isolation will not yield an answer to "what resolution is required?" for air transport training or any other flight task. The question of what resolution is required for any specific flight training task is answerable only by applying research techniques to simulation evaluation wherein pilot performance is quantitatively measured. What resolution is required to provide the perception of motion in the periphery of the eye is very different from the resolution you need to read runway identification numbers.

LUMINANCE INTENSITY

A second very important aspect of image quality is the luminance level of the display. In a review of some 150 publications pertaining to research on luminance level and visual performance, the 11 listed in figure 4 were very pertinent. They are excellent pieces of research, with statistical treatment and insightful interpretation of the data. These reports dealt primarily with modulation transfer functions of the eye, modulation of the visual stimulus, target detection and visual acuity.

The original specification for the Compuscene was set at six foot-Lamberts as a minimum. This was to be measured in the central part of the display with one half of the raster lines active. The six-foot Lambert value was based on the data from the studies mentioned. For example, in figure 5, the effective luminance level on the modulation and spatial frequency thresholds for green light is shown. Note here that, when the retinal luminance becomes less than 100 Trolands, the visible spatial frequency in cycles per degree decreases more rapidly than it does at the higher luminances.

Dr. and Mrs. Blackwell's data of 1971 (figure 6) indicates that at six-foot Lamberts and above, lower visual contrasts will be visible and the magnitude of the difference between the 50 to 60 year-olds and the 20 to 30 year-olds will be minimized. From Boynton and Boss' 1971 data, figure 7, it appears that the detection of targets by their shape has a function below 5.8 foot-Lamberts which differs from that above. As can be seen in this graph of target detection as a function of luminance, above six foot-Lamberts performance tends to level off. These and other data made it desirable to aim for a six foot-Lambert central area of brightness in the Compuscene, a value that was achieved by General Electric. In addition GE achieved a loss of only 15% from the center to the extremes of the cathode ray tube display.

DISPLAY LEGIBILITY AT THREE ARC MINUTES RESOLUTION AND LUMINANCE OF SIX FOOT-LAMBERTS

The authors had the opportunity to test the resolution and luminance qualities of the Compuscene display in a Phase I Image Quality Acceptance Test conducted at Daytona Beach on the first completed display system. The purpose of this test was to measure the display's static and dynamic image quality against known legibility criteria. The procedure was to generate 20 alphanumeric symbols to include the numbers and the letters used as runway identification markings and those symbols with which these letters and numbers were most often confused. The 20 alphanumeric symbols were produced in a font that was like that of the Lincoln/Mitre Dot font modified to a 5 x 7 matrix (figure 8). The video signals to produce the characters were created by the point light generation capability of the visual system's image generator. The dot matrix characters were 16 arc minutes in height and 12 arc minutes in width.

The four individuals who participated as observers were all General Electric employees with a minimum of practice and familiarity with the Lincoln/Mitre font. Each observer was placed so that his eye location was in the region of the eye reference point of the virtual image display. The observers served in two sessions; one where the symbols were in motion at three degrees per second and another one where the symbols were static. The contrast polarity was positive with the symbol lighter than the homogeneous background. Each symbol was seen during a one second exposure, with four seconds between exposures. In the dynamic mode of presentation the set of symbols was shown in the lower right corner of the display. In the static mode the set was presented in the center. The results are those listed in table 2.

The conclusion was that the General Electric Compuscene visual system could produce a stationary and moving image of sufficient quality to provide 92% legibility of a central alphanumeric symbol such as a pilot would see on a distant runway. In a standard rate turn his reading accuracy would be lower, near 75%. The test itself gave evidence that the desired image quality had been attained. An unexpected benefit was discovered. The test itself could be a fast and practical tool for the assessment of electron gun convergence in triple gun systems. The legibility of the alphanumerics proved to be most sensitive to changes in convergence of the three electron guns.

VIRTUAL IMAGE DISPLAY

The computer-generated image could be displayed to the pilot in a number of ways. The image could be fed through a GE projector onto a reflective screen, as done in a Naval application, or a cathode ray tube could be positioned just forward of the windshield of the airplane, and viewed directly. The display could be a cathode ray tube visible to the pilot through a Farrand in-line infinity window. Or the cathode ray tube could be viewed as a virtual image through a combination of a beam splitter and mirror. The latter was used in the Compuscene for both visual and engineering reasons.

From a visual point of view, higher image quality was attainable with the beamsplitter and mirror system since losses due to the projection system and the reflective or translucent screen were eliminated. The second reason was that the virtual image system with the beamsplitter and mirror could also provide an infinity image as the emerging rays could be collimated to a distance greater than 10 meters. The principle advantage of an infinity image is that it gives the pilot a feeling of realism. Also from a training point of view, the pilot needs to change his visual accommodation from infinity to the instrument panel to the same extent as he would in flight operations.

VISUAL FOCUSING (ACCOMMODATION)

The accommodative or refocusing time differs for individual pilots as a function of age as shown in figure 9. For the 21 to 25 year old pilots, the mean accommodative time is somewhere around three and a half seconds . For the 51 to 55 year age group, the mean is somewhere around seven and a quarter seconds. Therefore as a function of different ages within flight crews, the amount of time consumed in changing focus from inside to outside and vice versa is differentially longer. In evaluating and training flight crews this should be part of the normal training. Time spent in visual focusing accumulates at different rates and reduces the time available for other aspects of the flying tasks.

The work of Drs. Clarence Larry and Charles Elworth also shows that visual accommodation time changes as a function of low and high illuminance (figure 10) and as a function of how long the person is engaged in the near distance task, with the length of time increasing the longer they work at the near task. The paradigm in the cockpit, of course, is the pilot's flying on instruments. Although the research data stops at four minutes figure 11, the actual time the pilots stay on instruments varies with the weather and the duration of the approach. In real-world operations this may be much longer than four minutes.

These visual accommodation delays may be compared with some operational time intervals. A CAT II approach where the airplane breaks out at 100 feet of altitude (by definition) and has a horizontal visual range of 1200 feet, a normally loaded 700 series airplane will take approximately fourteen seconds from that point to touchdown. If seven of those fourteen seconds are associated with less than complete refocusing to outside, this adds incomplete focus to the difficulty of the pilot seeing, as incomplete focus interacts with fog, haze and low luminance to reduce visual contrast. The use of the infinity virtual image display means that one can simulate the real world situation including the requirement to focus the eyes with its normal lags, along with attenuations and facilitations of the visual scene. Decision making as to landing or "going around" can be experienced and taught in the simulator with more complete visual reference.

INFINITY WINDOWS AND FIELD OF VIEW

Another advantage of the infinity windows is the fact they can be grouped in a horizontal arrangement to form larger fields of view. In the Compuscene application to the narrow bodied airplanes such as the 707, 727 and 737, a display was used for each of the forward windows, one in front of the Captain and one in front of the co-pilot. Then, with a head rotation of 60 degrees to the right for the co-pilot, there was the side window, and with head rotation for the Captain 60 degrees to the left there was a side window. This left a field of 20 degrees between the forward and side scenes not filled with an image. From the Captain's eye reference point, this arrangement means that he has moving stimulus in the peripheral field 80 degrees to the left and about 75 degrees to the right because he can see the image in the co-pilot's right-hand side window.

The 747 represented a different problem; its forward window is a much larger area than the other aircraft. General Electric's application here was that of juxtaposed displays. This combined two display elements in a fashion to provide the Captain a forward scene 20 degrees to the right and 54 degrees to the left. In addition, upon head rotation to the left 92 degrees the gaze was centered on the side window, another 30 degrees by 40 degrees display, giving the Captain a total field of view to the left of 112 degrees. The unfilled area between 54 degrees and 72 degrees is partially filled with a structural portion of the aircraft.

Each of these display systems use a 25", high-resolution, shadow mask CRT. The images from two of the CRT's are juxtaposed by means of modified 45° beamsplitter/spherical mirror optics. The CRT's are constructed from funnel and face plate elements used in commercial tubes to minimize cost. For this reason the CRT phosphor surface does not lie in the optics system focal surface and the location of the CRT and focal surface images are shown as transformed by the plane beamsplitter (figure 12). If the eye point is located in the center of the curvature of the spherical mirror, the correct image location on the CRT surface is the projection line through the eye point to the tangent image plane. In order to increase the instantaneous field of view, the eye reference point is located closer to the mirror than the center of curvature. The image correction that is possible with this type of infinity image kept the size difference between the right and left eye to be less than one percent. This avoids the visual discomfort of aniseikonia, the technical name for having retinal images of two different sizes. If the difference in right and left eye image size exceeds one percent, visual performance is attenuated. Concurrently the amount of visual discomfort generally reported is high and takes the form of general discomfort such as "drawing of the eyes" or headaches. Other distortions were restricted to two percent in the different portions of the visual field within plus or minus 15 degrees of the center of the image. The distortions beyond 15 degrees to the corners on the CRT were kept within three percent. The distortions were measured by placing a theodolite at the design eye reference point and measuring the actual angular distortion of a grid pattern.

An advantage of the side windows and the larger field of view, in addition to permitting training on circling approaches, is to provide pilots with strong relative motion cues available through the side windows. The two-factor theory of vision allocates the task of pattern recognition to the central part of vision or the foveal area. The peripheral part of the retina, the locus of a second factor, has as its primary purpose the orientation in space and perception of movement through space.

The peripheral part of vision does not depend upon a high-quality image. It is sensitive to relative motion and provides us with much of our orientation. Consider then the paradigm of the pilot making a long straight-in approach, where he is applying his central vision to the runway ahead. As he nears the ground the relative movements of the horizon and objects going by in the side windows give him an orientation of roll, and pitch and a relative speed. Some pilots use these peripheral cues to a greater extent than others. It is anticipated that future research, utilizing simulation as a method of measuring pilot performance, will show that at least two categories of pilots exist, divided by their relative use of these far peripheral visual cues. In addition to making such visual cues available by the presence of the side windows, there has been a concerted attempt to give texture and borders of sufficient size to provide relative motion perception in the periphery of the visual field.

The data bases used at Boeing by Flight Crew Training are patterned after real air fields, Grant County Airport (Moses Lake) in Central Washington, Boeing International Airport in Seattle and Yakima Airport in the southcentral part of Washington. In providing the Flight Crew Training personnel with the visual scene from Moses Lake, where there is a former B-52 runway, there was an insufficient number of edges to depict all of the hangars and support buildings which normally give the relative motion cues at this location. A deliberate, unrealistic scene differentiation of the fields on either side of the runway was attempted by using the point light source capability of the CGI system. Turning these lights off formed very small black surface areas in the color field. This technique, though attainable with a CGI system, was not useful to the pilots visually. The point sources ranged from 2.5 to 9.0 arc minutes in diameter. These are too small to be seen in the far peripheral visual field. Visual acuity 30 to 70 degrees off the visual axis requires an object at least 30 times larger than one in central vision if it is to be seen with equal probability. Therefore such small black dots could be seen from a distance in central vision but as the airplane approaches touchdown these dots are not visible in the peripheral portion of the eye. The explanation lies in the pilot's maintaining fixation on the runway. This makes the small black dots subthreshold and therefore not visible through the side windows during the flare and touchdown. In the absence of research data, we assumed that if these dots were not reported at the cognitive level, they were not contributing to the discrimination of speed and relative height. The solution chosen was to present some interlocking diamond-shaped non-real-world fields of the size and contrast that could be perceived in this off-axis area of the retina. They did not need to be high contrast. They could be assigned priority which would make them available only as the airplane approached the area of the airfield. This is an instance where non-real-world images can be introduced to provide specific visual information that is needed to perform a task.

ACCEPTABLE VISUAL LAGS

Before we leave the subject of relative motion entirely, we should deal with the lags that a visual system might have. Dr. Gerald Westheimer determined that about 2 percent of the population could experience lags shorter than 125 milliseconds and none of this population could perceive lags that were shorter than 100 milliseconds. The General Electric Compuscene theoretically has about 70 milliseconds of visual lag, and in the two years use of the Compuscene, no complaints have been received from the instructors or the students that they perceive any lag in the visual display.

COLOR AND THE CGI SYSTEM

The inclusion of a three gun color system whereby color primaries can be generated, provides us with a visual system that can produce a multitude of different colors. There is a natural tendency to make the colors very saturated in the CGI systems. There are two marked disadvantages to this tendency beyond that of making the scene appear very cartoonish. In the real world there are very few scenes that have high saturation, so to make the scene appear like it does in the real world, most of the colors should be quite desaturated, that is, have a good deal of white mixed in with hue. Two visual factors are involved which make the desaturated imagery much preferred. Since all systems have a limited number of edges available, the surface of a field pattern in the scene is often represented by a homogeneous color. A color which is homogeneous takes on the aspect of what is called a film color. It represents a surface localized only by its boundaries. Another way of stating this is that if one looks down a short cardboard tube at a homogeneous color, the perception is that the color exists at the far end of the tube and not in space beyond the edge of that tube. In the aircraft simulation application the film color will become a curtain-like surface. If a field is sufficiently large that it fills the aircraft windscreen, the borders then become the windscreen borders, and the field becomes a curtain-like color at the windscreen surface, because there is no detail in the infinity image to bring about focus at an appropriate distance.

The second aspect is that not all people localize colors in space in the same order of spatial position. The human eye is not completely color corrected. The quality of this incompleteness differs from individual to individual. Research to date (figure 13) has shown that about one half the population sees the long-wavelength colors as being nearer them than the short-wavelength colors. In other words, all things being equal, such people will see red, orange, yellow, green, and blue in that order from near to far. The other half of the population inverts this. The amount of this relative displacement of colors in space appears to be normally distributed.

The greatest magnitude of perceived displacement occurs when the colors are represented as saturated. Thus, if saturated colors are used in simulation, the perception of visual space will be distorted away from the normally perceived world. However, if the desaturated colors are used, this phenomenon is avoided in proportion to the desaturation.

The selection of visual criteria for a CGI system still depends on research done for other purposes, or it is an arbitrary selection in some respect or another. If we make minimal requirements for visual simulation for training and transfer to flight, can we prove the validity of our choices? Is the visual information sufficient for the pilot to learn what he must learn for later successful performance in the airplane?

ASSESSMENT OF VISUAL CRITERIA

The direct method of measurement is to use pilot performance as a dependent measure, a group of pilots as a measuring tool to gain generalization, and scientific experimental controls in a simulation to gain reliability. We have partially accomplished this in experiments designed to ascertain whether pilots could make a visual approach and landing without flight instrument data from altimetry and/or glide slope indication, and to compare such performances to those that were made with such flight instrumentation present.

Two duplicate experiments (figure 14) were conducted, one with eight qualified pilots who flew the 737 simulator. The second experiment was with another eight qualified pilots who flew the same experimental plan in the 727 simulator.

Using a digital printer we recorded the flight performance data from the host computer of the simulator. Recorded were 1) rate of descent at touchdown, 2) altitude and azimuth at the middle marker (five tenths of a mile from touchdown), 3) deviation of touchdown point from the intersection of the electronic glide slope, and 4) deviation in air speed from the theoretical optimum.

Instructor opinions and notes, and pilots' protocols and comments were two subjective quantifications. The pilots were all very experienced instructor pilots who had varying degrees of recency in terms of flying the simulators, but all were fully qualified and were currently engaged in training pilots.

We made the situation more difficult putting a 20-knot crosswind coming from 99 degrees to the right of the approach path. This wind dropped to 10 knots at 4880 feet from glide slope intersection with the runway, and then again dropped to zero at 50 foot of altitude. This provided two very abrupt windshears, which tended to drive the airplanes off to the right when the wind subsided. We wished to compare the average performance of these pilots flying on instruments to touchdown compared with what the visual scene would contribute in terms of improving this performance.

We were interested in whether the visual scene alone would provide the same approach, flare and touchdown performance as with the scene supplemented by the glide slope flight instruments. The experimental plan was a 2 x 2 x 2 design; two levels of visibility, high or low, two levels of "time of day," i.e., a day scene and a night scene, and two levels of information sources, visual scene only and visual scene with the instrumentation of the glide slope. It was felt then that the visual scene-with-glide slope performance would serve as a basis for comparing the visual scene only. If similar information is provided by the visual scene, these two performances should match, at least within statistical limits. All approaches were made without altitude information being displayed in the cockpit.

Figure 15 is a depiction of the approach altitude as a function of distance. The "T" represents the theoretical altitude at each of the distances designated. The "V plus GS" represents the values that the pilots actually generated when they had the visual scene and the glide slope available to them. The "V" in the middle group represents the actual altitudes they flew when they were flying with the visual scene only. You will notice that from 4.7 miles out to 2 miles there is almost no difference at all in these averages. However, inside of two miles with the visual scene above, altitude gets somewhat lower. At the .5 and .3 nautical mile distances, these values become statistically significant.

The explanation is an interesting one; as demonstrated in Table 3, the interaction between time of day and visibility is the contributing agent here. When visibility is good or intermediate and pilots are flying to the day scene, they perform equally well as a function of altitude. The day performance is matched by that for the night approaches with intermediate visibility. However, it is the night scene with good visibility where the pilots fly low. These good visibility night approaches contributed the shift in the mean for the visual approaches.

If some information were missing from the visual scene to produce this result one would expect the night-limited visibility condition also to be affected. Reexamination of these data indicate a higher probability that when the visibility was high the pilots disregarded the experimental instruction to stay on the electronic glide slope, instead transitioning to the equivalent of a visual 2.5 degrees glide slope. The electronic glide slope is higher, intersecting 1840 feet down the runway while the visual reference is at 1000 feet from the runway threshold.

These data therefore are supportive of the conclusion that the General Electric Compuscene has been providing sufficient visual information for experienced pilots to make night and day approaches to instrumented runways as depicted on the Compuscene.

POINT LIGHT SIZES AND FLIGHT PERFORMANCE

Earlier in our discussion we mentioned that none of the CGI systems could generate point sources of light sufficiently small to represent the real world light sizes. In figure 16, one will observe that on the left at 100 foot distance, the actual four-inch light on the side of the runway should represent about 11.3 arc minutes in size. If the CGI system changes point light size as a function of distance as in the real world, at 1000 feet they should be about 1.25 arc minutes in size and it would decrease normally to about 12 arc seconds at 10,000 feet. However, on the retina of the eye the spread function maintains the size at about 1.25 arc minutes. None of the current visual systems reviewed meet this requirement completely. The General Electric system does have an increase in size of these lights as a function of distances inside 1000 feet, but for lights beyond 1000 feet they remain too large. In this graph the dotted line that begins at 11.3 and breaks away from the solid line between the 500 and 1000 foot of distance is the General Electric Compuscene curve. The experimental question asked was: Would these non-real-world light sizes influence pilot performance on their approach and landing with night scenes? It was observed that the runway edge lights tended to appear as though they were going uphill the further away they were from the threshold.

An experimental study was done with static imagery in which we compared pilots' perception of their height and distance as a function of 1) the texture of the runway by itself, 2) the lights on the edges of the runway by themselves, and 3) the runway edge lights and texture combined. The results indicated that whenever the runway edge lights were present the pilots overestimated their altitude at all the distances out to 4.7 miles, the furthest distance we tested. It was therefore assumed that, since the pilots overestimate their altitude on the static imagery they would generate a approach which would be below the 2.5 degree glide slope. General Electric worked out a software change by which the light size was partially compensated for by a decrease in illuminance with distance, over and above a normal decay of luminance as a function of atmosphere and distance. This was incorporated into the Moses Lake data base and placed on a disc. On the same disc but with a different code, was the original data base with equal luminance lights. This difference in light intensity was the main independent variable of the study.

The second independent variable was the appearance of the runway texture, at three levels. At the first level the runway texture became visible to the pilot only after he had passed over the threshold lights and was 892 feet from the glide slope intersection with the runway. At the second level the texture became visible at 2208 feet from the glide slope intercept of 368 feet before reaching the runway threshold. At the third level the runway texture became visible at 5257 feet, or 3417 feet before reaching the runway. The visible range of the texture interacts with the runway edge lights' size and luminances to affect altitude on visual approaches figure 17. With equal luminous intensity of runway edge lights, the pilots fly lower on night approaches only when the runway texture is not visible or appears very late in the approach. If the runway texture is available at an approach distance of 5257 feet or more, the influence of equal runway edge luminance appears to be countered.

In the absence of runway texture, CGI lights with equal luminance provide a visual scene in which the far end of the runway appears to be higher than the nearer lights and under these circumstances the pilot flew lower, making the runway plane look flatter. These data are in agreement with earlier studies done with other simulation techniques. On the other hand, the approaches made to the scene with the attenuated luminances to compensate for the excessive size of the runway edge lights were actually resulted in higher altitudes over the threshold of the runway. In transferring this data to the real world the approaches to the scene with the attenuated luminances would be very similar to the real world situation and the transfer of training from this to the real world should be more positive.

SUMMARY

Visual criteria in the design of computer generated images may in part be available from clinical and experimental literature. The specific results reported here point the way to visual system evaluation. The final data must come from controlled experiments with simulators fitted with visual systems, using experienced pilots, quantitative readouts and statistical analysis. These investigations can provide in addition to reliable and valid data, a measure of the relationship between cost and effectiveness of training.

REFERENCES

1. Blackwell, H. R. Brightness discrimination data for the specification of quality of illumination, Illum. Engr., Vol. 47, 1952, pp. 602-609.

2. Blackwell, H. R. The evaluation of interior lighting on the basis of visual criteria. Appl. Optics, Vol. 6, 1967, pp. 1443-1467.

3. Blackwell, O. M. and Blackwell, H. R. Visual performance data for 156 normal observers of various ages. J. Illum. Engr. Soc., Vol. 61, 1971, pp. 3-13.

4. Boynton, R. M. and Boss, D. E. The effect of background luminance and contrast upon visual search performance. Illum. Engr., Vol. 66, 1971, pp. 173-186.

5. Daitch, J. M. and Green, D. G., Contrast sensitivity of the human peripheral retina, Vision Research, Vol. 9, pp. 947-952, 1969.

6. DePalma, J. J. and Lowry, E. M. Sine-wave response of the visual system. II. Sine-wave and square-wave contrast sensitivity. J. Opt. Soc. Am., Vol. 52, 1962, pp. 328-335.

7. Larry, C. and Elworth, C. L. The effects of pilot age, lighting and heads down time on visual accommodation, D162-10378-1, T.N., The Boeing Company, 1971.

8. Patel, A. S. Spatial resolution by the human visual system. The effect of mean retinal illuminance. J. Opt. Soc. Am., Vol. 56, 1966, pp. 689-694.

9. Schober, H. A. W. and Hilz, R. Contrast sensitivity of the human eye for square-wave gratings. J. Opt. Soc. Am., Vol. 55, 1965, pp. 1086-1091.

10. Shlaer, S. The relation between visual acuity and illumination. J. Gen. Physiol., Vol. 21, 1937, pp. 165-188.

11. Sloan, L. L., Measurement of visual acuity. Arch. Ophthal., 1951, 45, 704-725.

12. Spencer, D. E. Out-of-focus photometry, J. Opt. Soc. Am., Vol. 55, 1965, pp. 396-403.

13. Van Nes, F. L. and Bouman, M. A. Spatial modulation transfer in the human eye. J. Opt. Soc. Am., Vol. 57, 1967, pp. 401-406.

14. Westheimer, G. Eye movement responses to a horizontally moving visual stimulus. AMA Arch. Ophthal., Vol. 52, 1954, pp. 932-941.

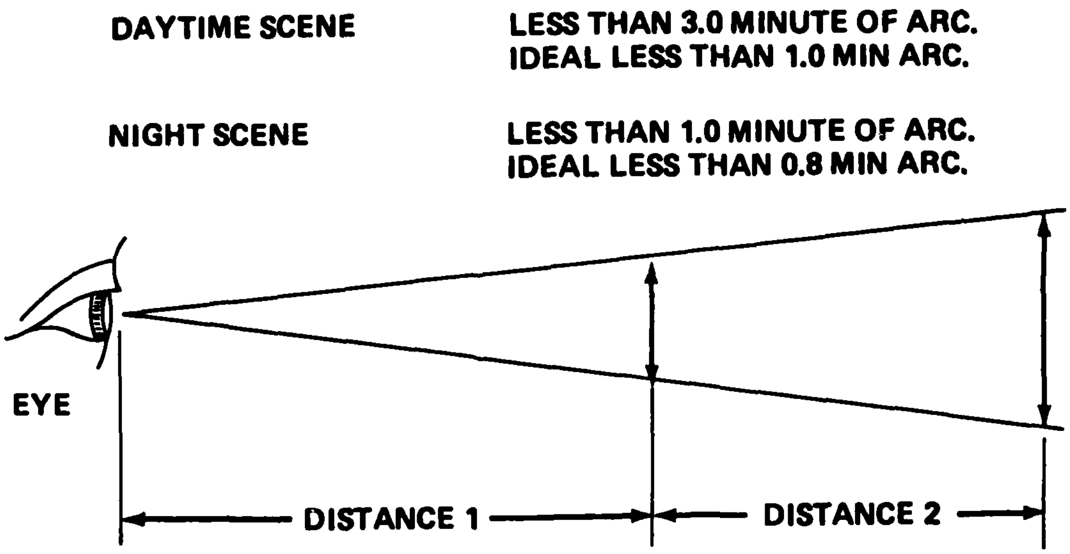


Fig.1 Visual resolution desired in simulation

TABLE 1

Interrelationship of Visual Resolution and Field of View for a 1000 Line Visual System

FIELD OF VIEW (IN DEGREES)			VISUAL RESOLUTION (IN ARC MINUTES)		
VERTICAL		HORIZONTAL	VERTICAL		HORIZONTAL
10	X	15	0.8	X	1.0
15	X	20	1.2	X	1.4
30	X	40	2.5	X	2.8
36	X	48	3.0	X	3.3
60	X	80	4.9	X	5.5

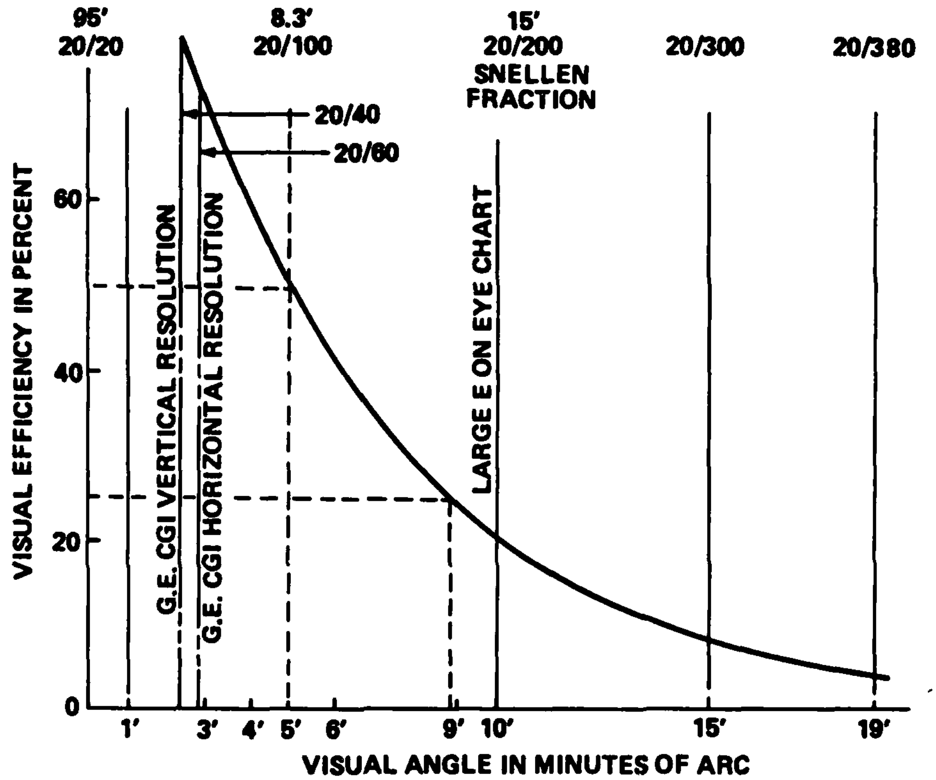


Fig.2 The relationship among simulator resolution, visual efficiency and visual acuity

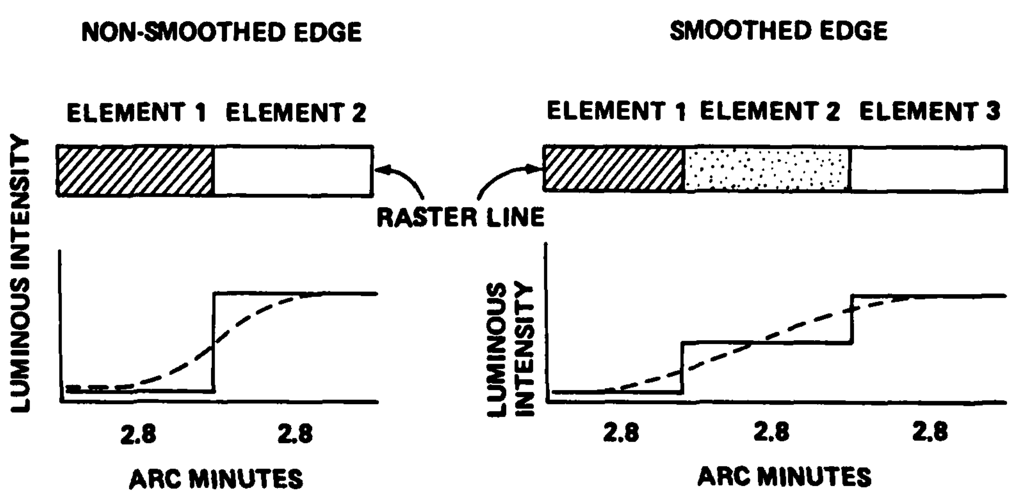


Fig.3 The effect of smoothing on resolution of edges

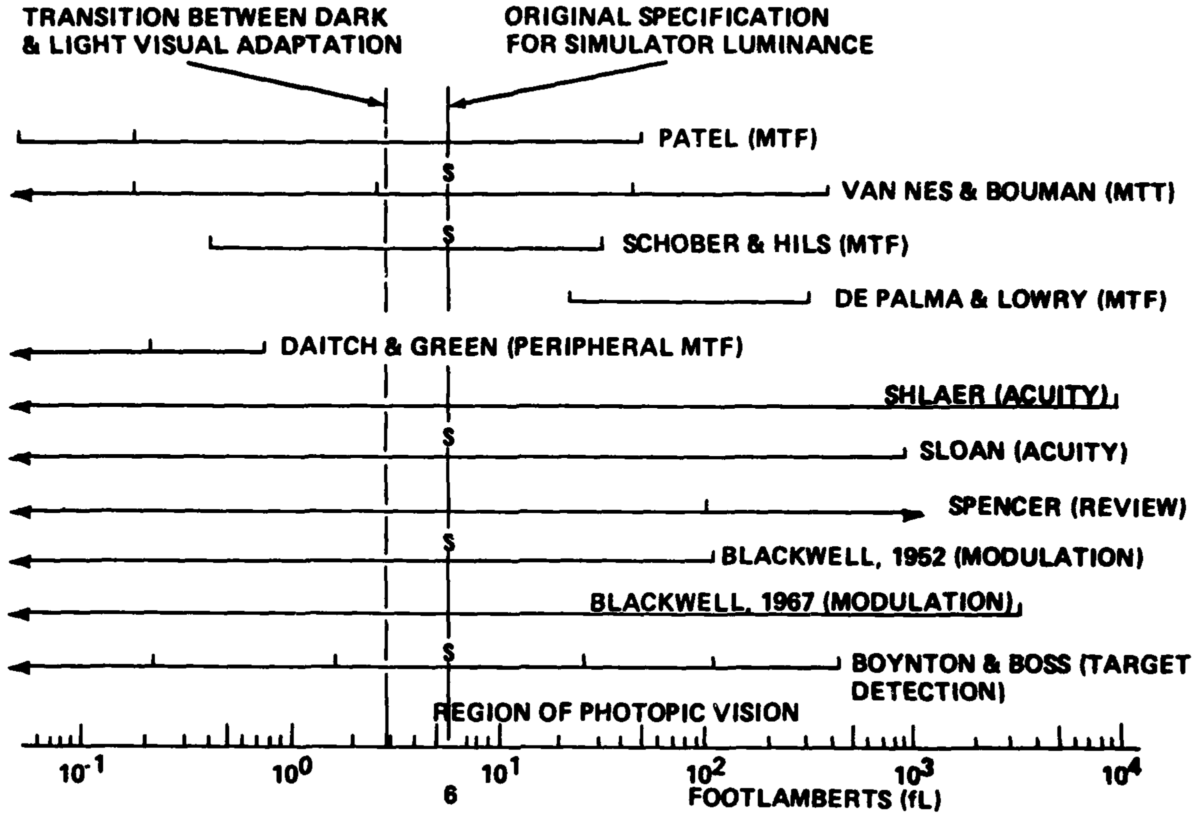


Fig.4 Illumination levels at which visual performance was measured

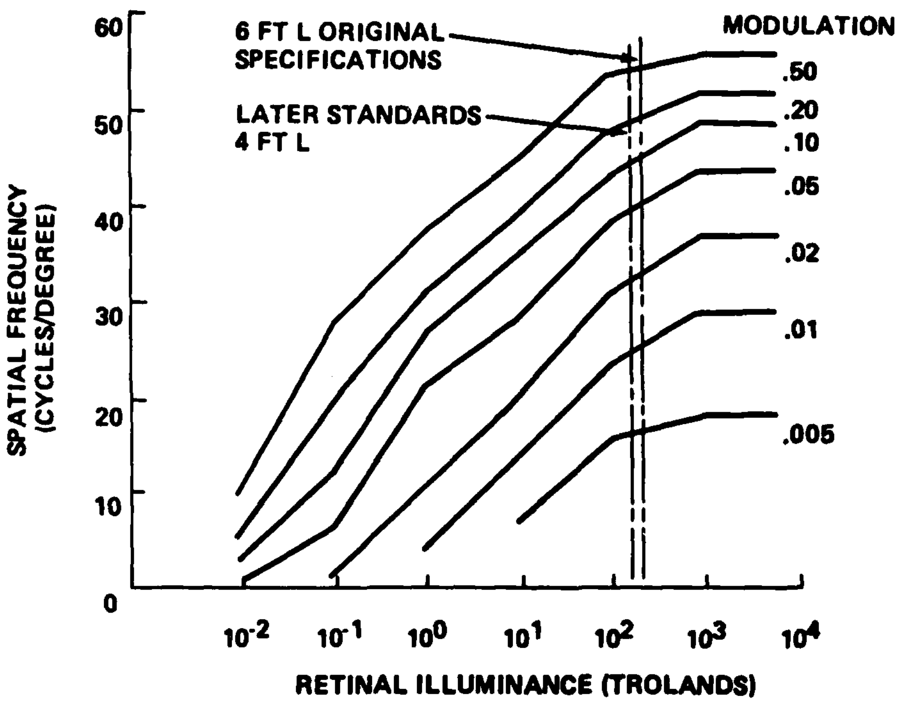


Fig.5 Effect of illuminance level on modulation and spatial frequency threshold for green light (Van Nes and Bouman, 1967)

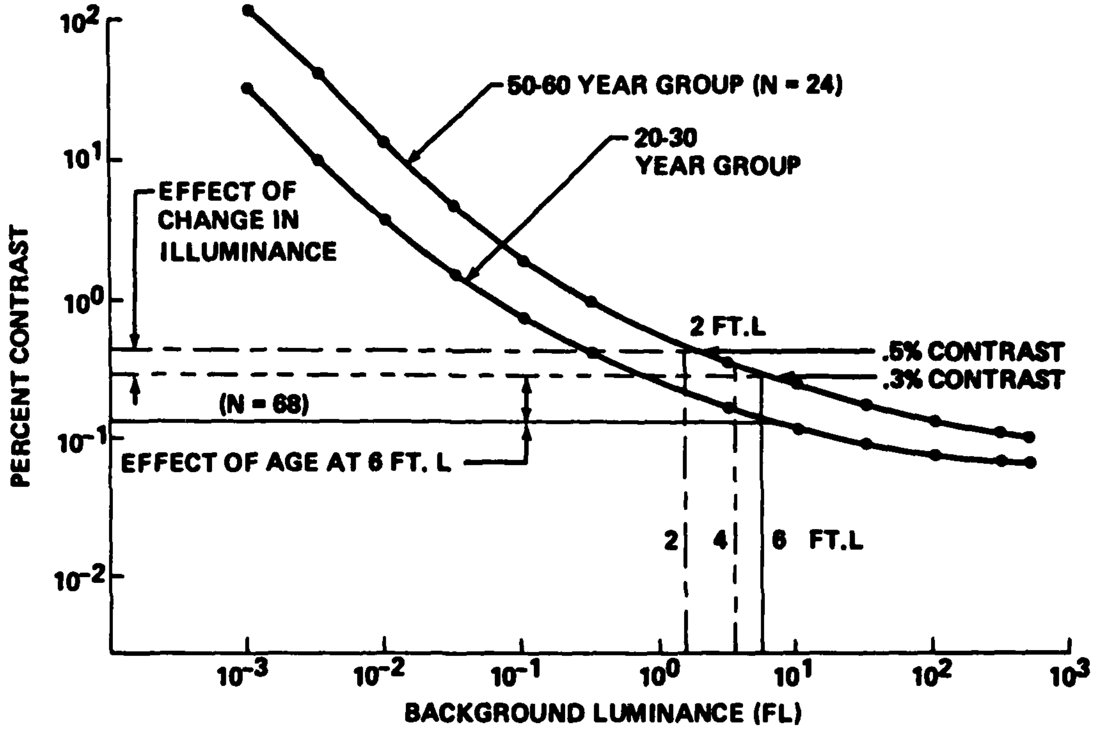


Fig.6 Effect of background luminance on contrast threshold for two age groups (Blackwell & Blackwell, 1971)

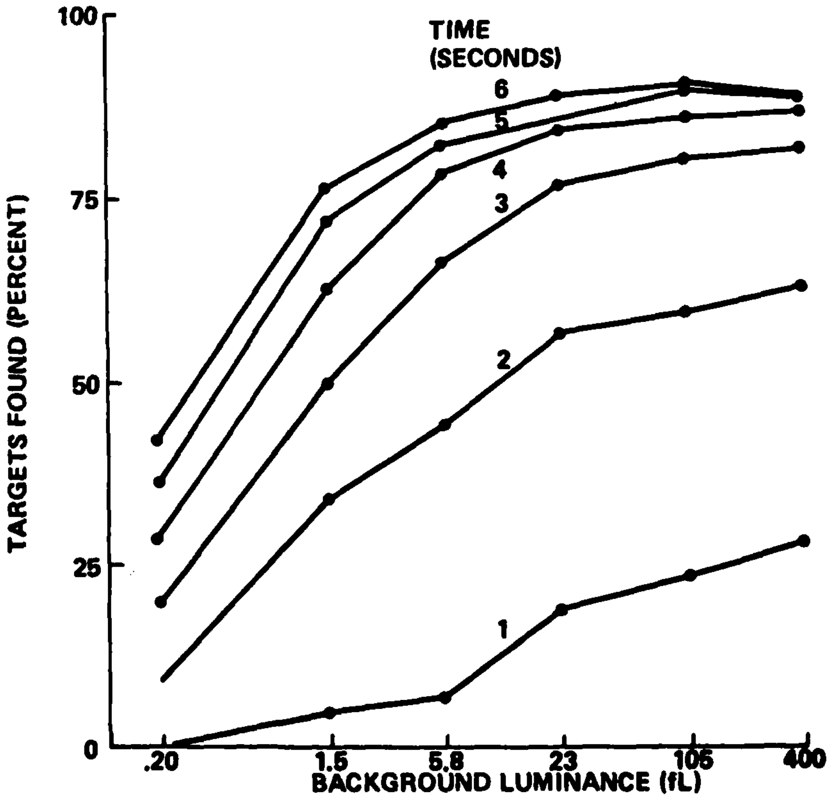


Fig.7 Effect of luminance on detection at various times after display appeared (Boynton and Boss, 1971)

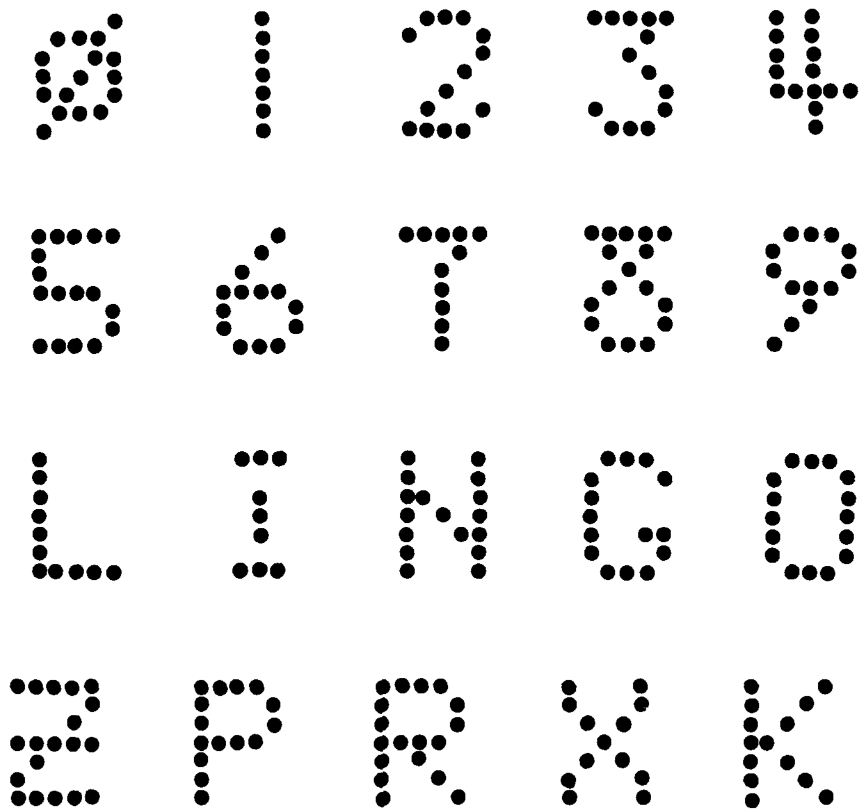


Fig.8 5 x 7 dot matrix pattern for characters – phase 1 image quality test

TABLE 2

Distribution of Errors in Reading Alphanumeric Symbols on the GE/CGI Display System

DISPLAY CONDITION	OBSERVER				TOTAL ERRORS	PERCENT CORRECT	CRITERIA
	1	2	3	4			
STATIC/CENTRAL	3	4	1	5	13	92%	90%
DYNAMIC/ PERIPHERAL	10	13	10	7	40	75%	75%

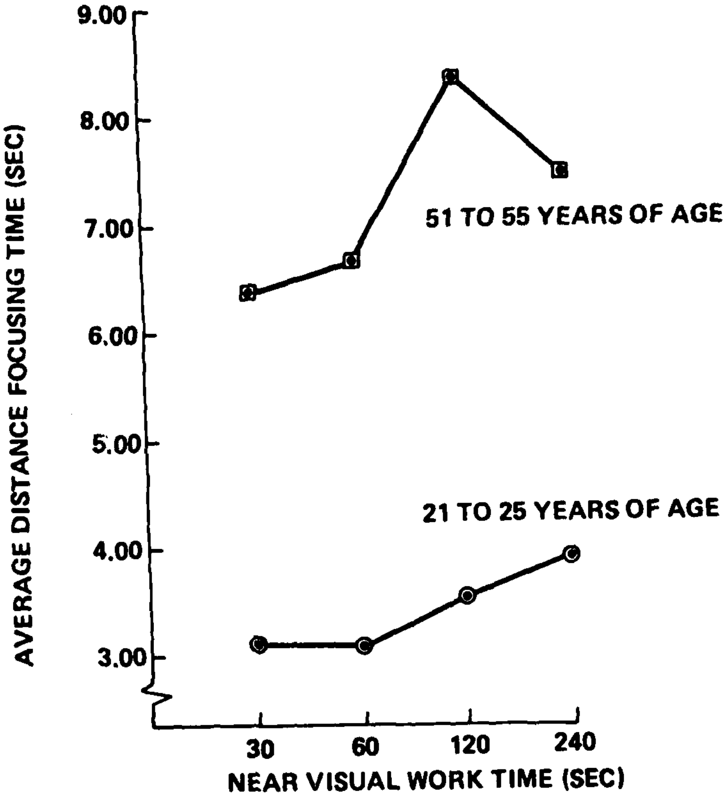


Fig.9 Near to far visual focus as a function of age

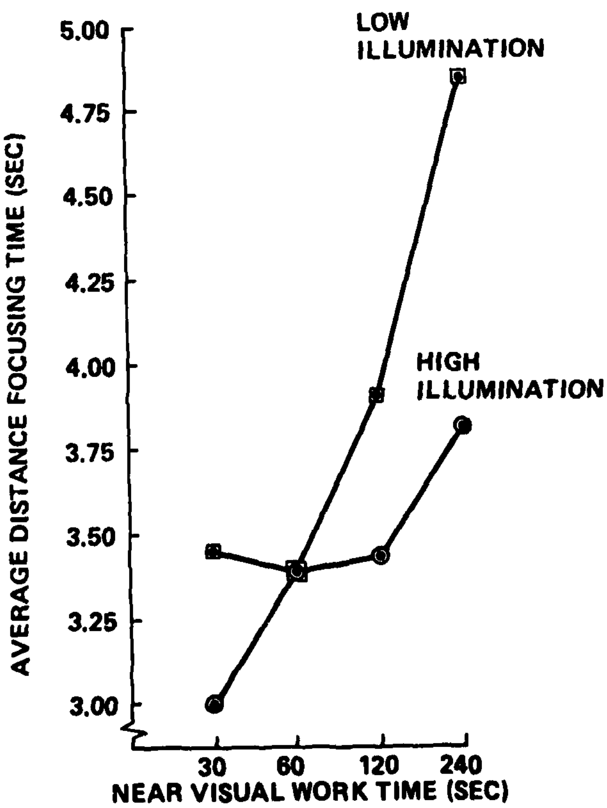


Fig.10 Near to far visual focus as a function of illuminance

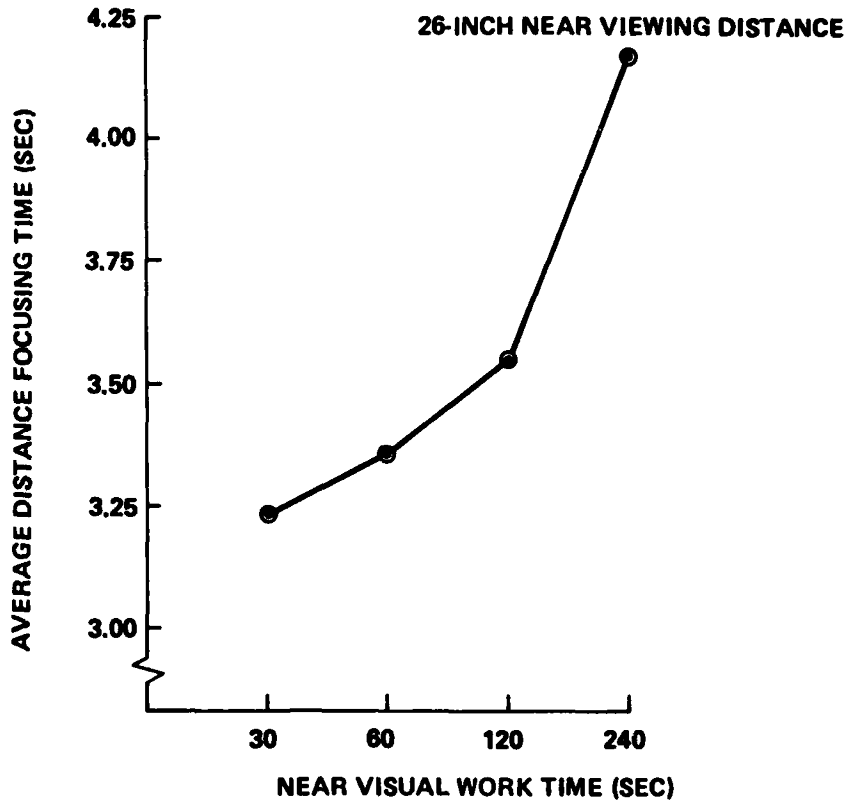


Fig.11 Near to far visual focus as a function of near worktime

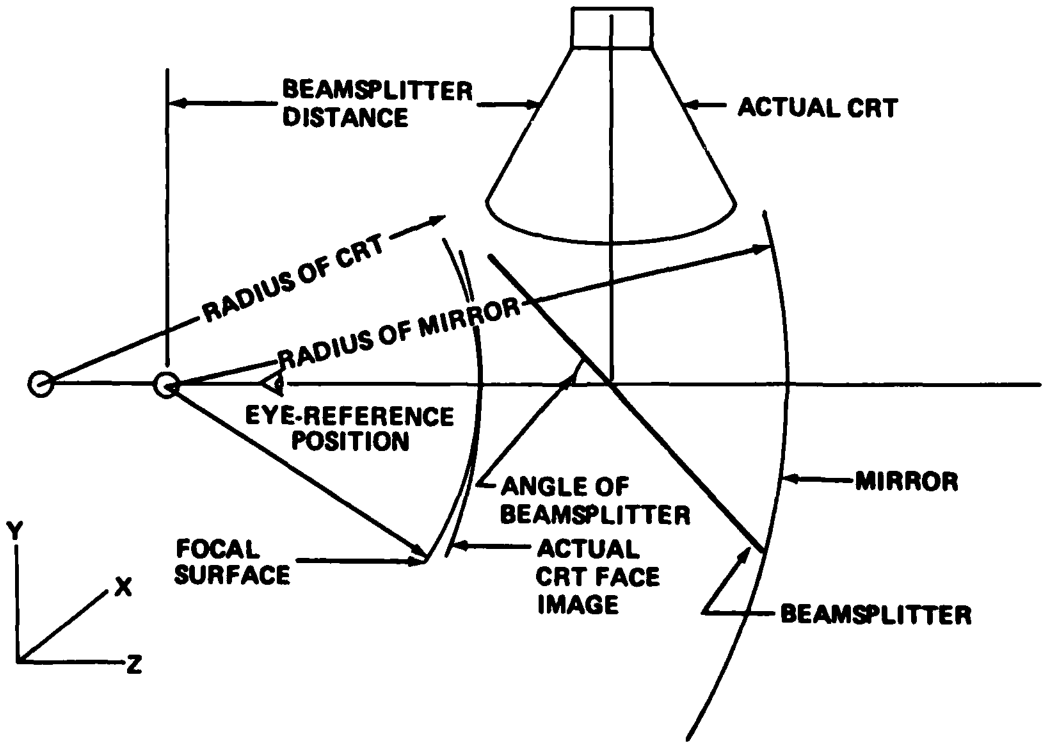


Fig.12 Virtual image display optical schematic showing input parameters

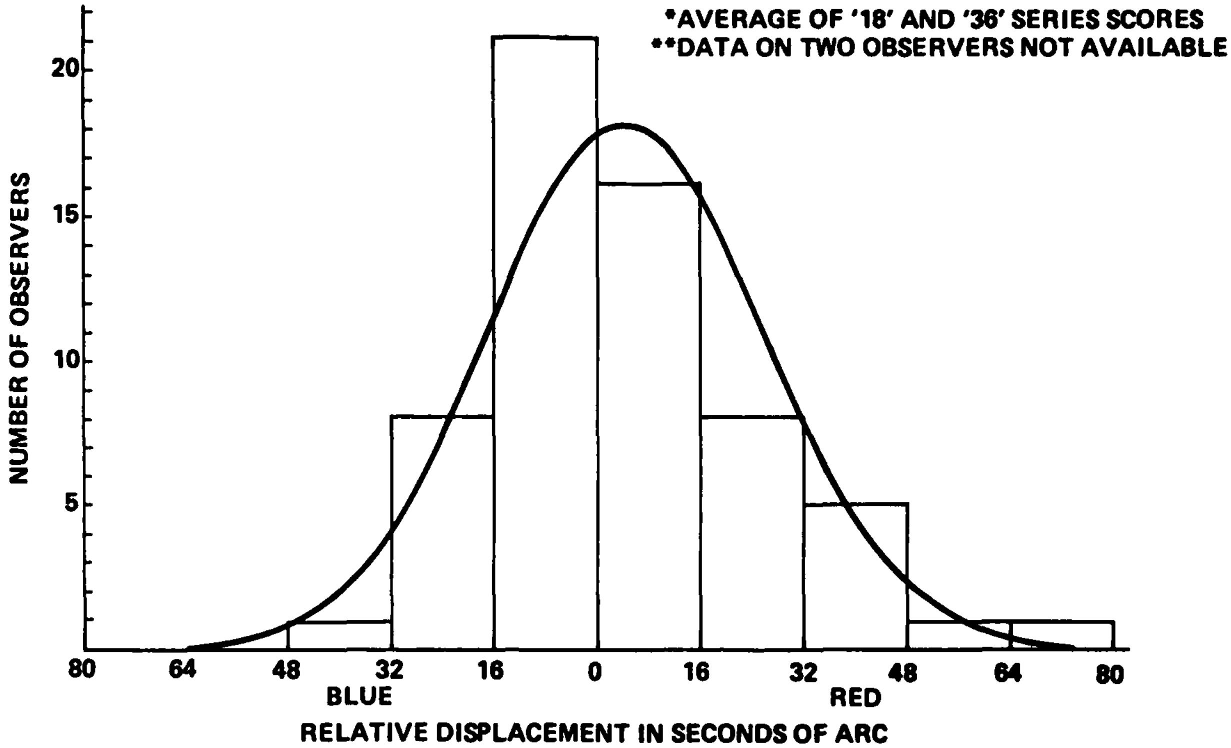


Fig.13 Histogram and normalized curve of chromostereopsis scores* for 61 observers**

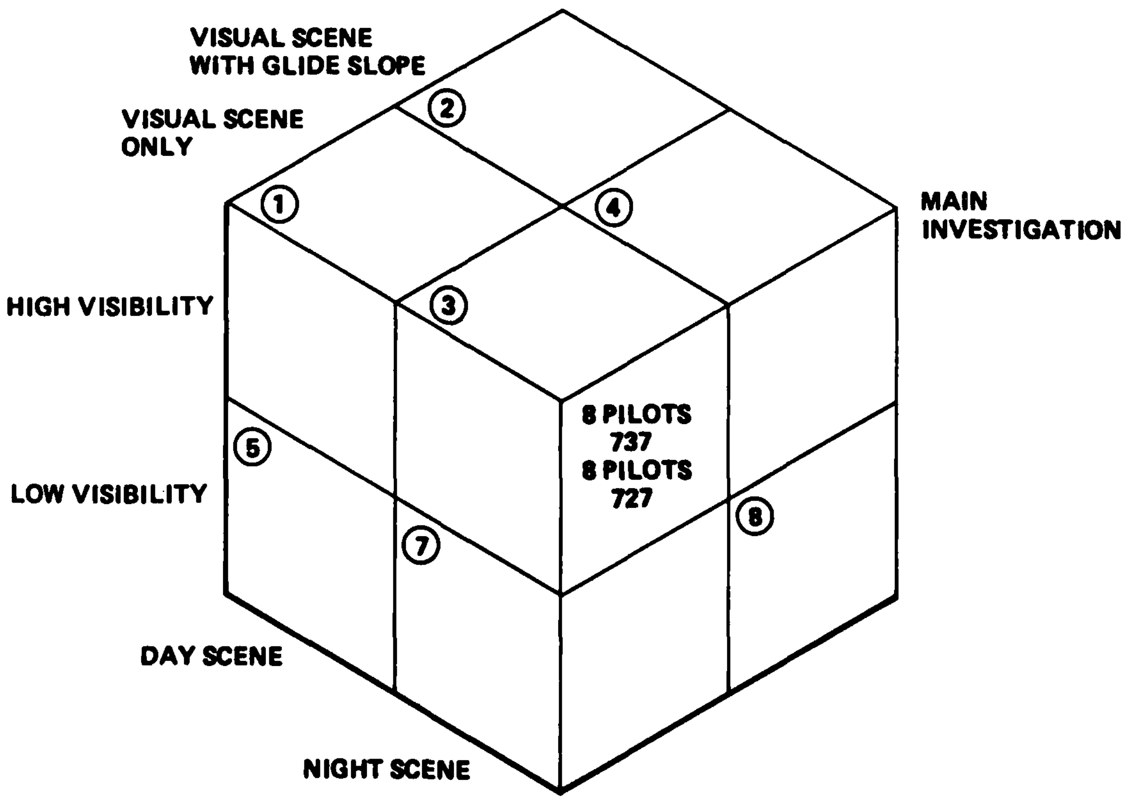


Fig.14 The plan for performance evaluation

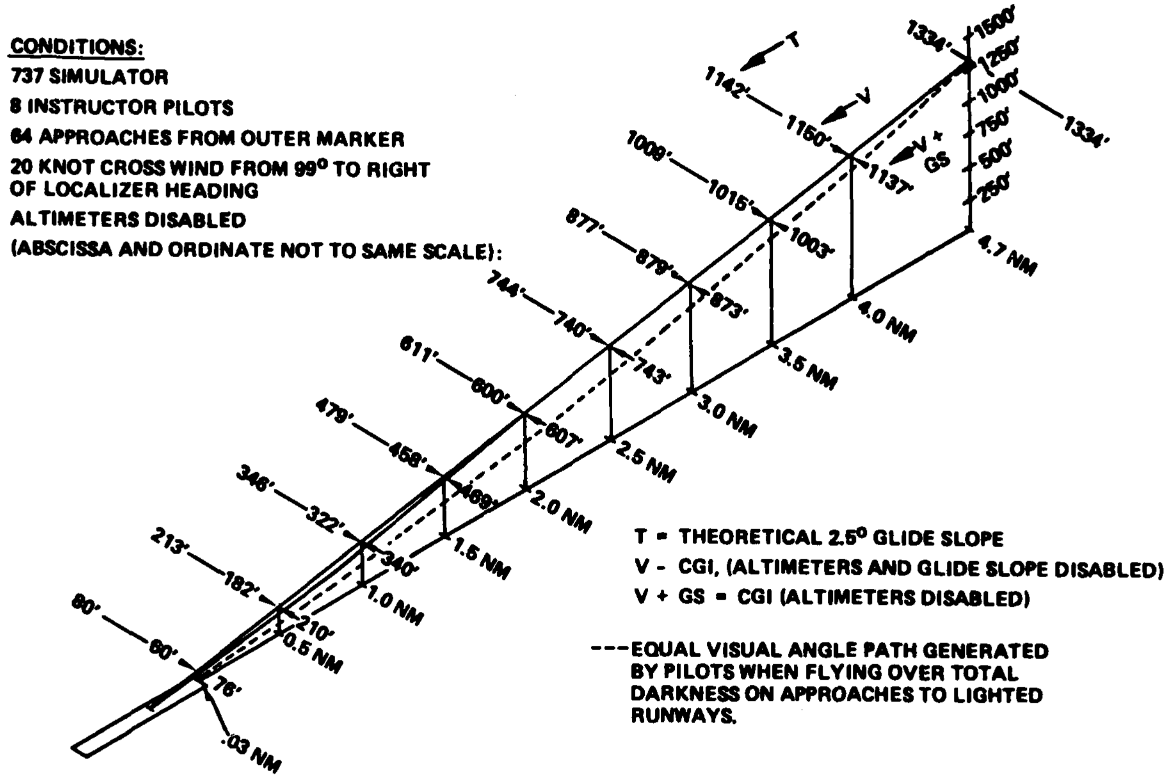


Fig.15 Approach altitude as a function of distance

TABLE 3

Pilot Performance with 737 Simulator Analysis at 0.6 nm from Glide Slope Origin Just Before Middle Marker (Wind Shear 20 to 10 knots)

DISPLAY	ONLY VISION	GLIDE SLOPE + VISION	
ALTITUDE AT 0.6 NM	210.9 FT	235.4 FT	P < .05*

TIME OF DAY X VISIBILITY

ALTITUDE AT 0.6 NM	VISIBILITY GOOD	VISIBILITY INTERMEDIATE	
DAY	224.5 FT	225.2 FT	P < .05*
NIGHT	209.8 FT	233.1 FT	

VISIBILITY	GOOD	INTERMEDIATE	
SPEED	127.9 KNOTS	130.4 KNOTS	P < .01**
TIME	1.88 MIN.	1.866 MIN.	P < .10
DESCENT RATE	9.05 FT/MIN.	10.29 FT/MIN.	P < .10
AZIMUTH	55.1 FT LEFT	68.8 FT LEFT	P < .05*

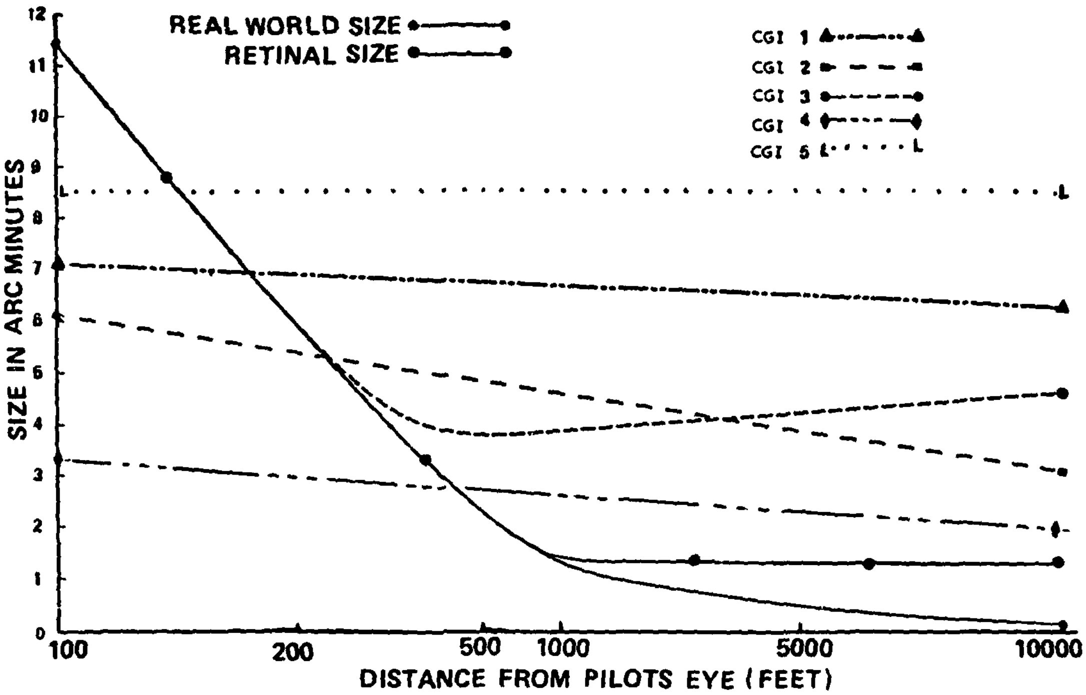


Fig.16 Representation of light sizes in night scene

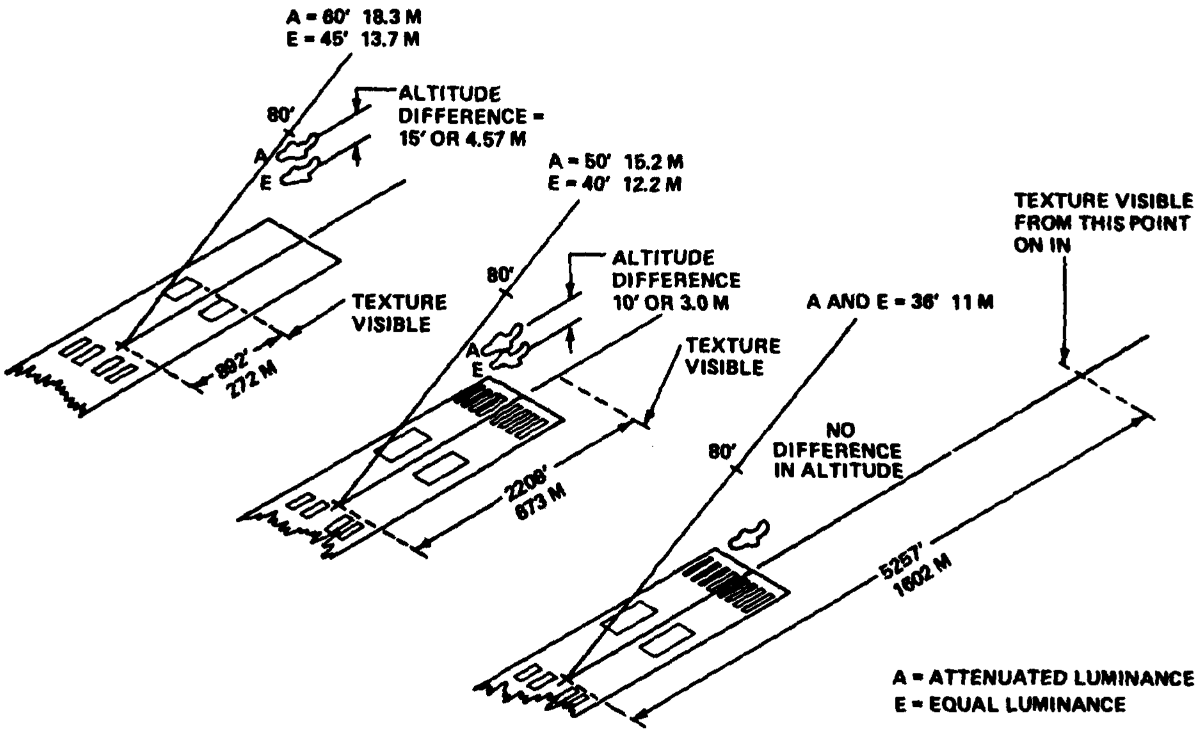


Fig.17 Height over threshold on night approaches as a function of luminance distribution and visibility range of texture

MISSION ENVIRONMENT SIMULATION FOR ARMY ROTORCRAFT DEVELOPMENT—REQUIREMENTS AND CAPABILITIES

David L. Key, Billy L. Odneal, and John B. Sinacori
Aeromechanics Laboratory, U.S. Army Aviation R&D Command
Ames Research Center, Moffett Field, California 94035, U.S.A.

SUMMARY

The helicopter is naturally a ground contact machine par excellence, and its mission use in Army aviation is more characteristic of a flying jeep or tank than of an airplane. This puts the Army aviator in an environment rich in detail both from the ground and from the atmosphere. Terrain features, both natural and man-made, visibility factors of weather and darkness, and atmospheric characteristics of wind, turbulence, and ground effect all have to be represented to the helicopter pilot in significant detail to provide a meaningful simulation.

The Aeromechanics Laboratory of the U.S. Army Aviation R&D Command (AVRADCOM) is engaged in developing a simulation capability to support aviation system development and system integration. This effort is being performed jointly with NASA at the Ames Research Center. Existing facilities at the Ames Research Center have been used to develop motion system requirements. Although these are particularly severe due to the high maneuverability required in the terrain flying environment, they can be adequately achieved by upgrading the NASA Vertical Motion System presently under development. Adequate simulation of the visual environment will be much more difficult to achieve. The rich and varied detail visible in terrain flight must be presented by a wide field-of-view system with much detail and high resolution. The rotary-wing R&D simulator must have great versatility for easy change of cab configurations and the capability to accommodate a two or three man crew. Basic specifications for an adequate visual display have been developed and are compared in this report with current and forecasted techniques for image generation and presentation. Results of a study performed to determine the feasibility of meeting these requirements using the current technology of TV camera-model image generation and projected display is discussed and an assessment of the possibility that computer generated imagery (CGI) can achieve the desired level of detail is presented.

1. ARMY MISSION ENVIRONMENTAL FACTORS

1.1 Atypical Mission

The U.S. Army must be prepared to fight anywhere in the world, under all types of meteorological conditions, and against weaponry systems ranging from the highly sophisticated to the most primitive. For the helicopter to contribute under these conditions—and under these parameters of employment—the Army must know exactly what is required of the helicopter and the crew that will operate it. One of the best means of accomplishing this is through the use of flight simulators. The U.S. Army has flight simulators to assist in the training of new aviators and in maintaining proficiency. Until very recently, the Army did not have a research and development flight simulation capability that could be used to assist in the development of helicopters to operate under these various conditions. We must examine effectiveness on all battlefields and in all meteorological conditions against the various types of weaponry that will be used. The key is survivability, and the Army attains survivability for the helicopter (on the modern high-intensity battlefield) by using terrain flight. Terrain flight itself is nothing more than staying out of the visual, optical, or electronic acquisition means of the enemy's weaponry system (Figs. 1 and 2).

At the longer ranges—say in the corps area—the helicopter should be able to operate at altitudes up to 1500 m but generally at low levels maintaining both speed and altitude. As it approaches the battlefield, it must descend to what is called contour flight; that is, to vary its altitude but maintain its airspeed as it flies along the contours of the earth. When it reaches the battalion rear area, it must drop down as low as possible, varying altitude and airspeed while using any natural shielding of vegetation or terrain to keep from being acquired by the enemy. This is called nap-of-the-earth flight (NOE). Terrain flying is the term used to cover these three conditions of flight at lower and lower altitudes. With this in mind, let us take an imaginary, and perhaps not typical, Army aviation scenario which we can use as a vehicle to define our simulation requirements.

It was decided to reinforce a river crossing and to move up tube artillery to aid in fire support. A hilltop fire position for this had been found about 3 km from the bridge site. Air re-supply would be the only means of putting the guns in position. After a small air assault had seized the hill top and secured the position, it was decided to implace one platoon of 105-mm howitzers to support the river crossing forces. The artillery pieces were to be airlifted from the corps rear area. Three utility aircraft (UH-60A's) of the 180th Aviation Assault Company were directed to move the tubes, ammunition, and the crews to these positions. It was necessary to fly low-level up to the division rear and then fly contour and nap-of-the-earth to reach the selected position. Because of the enemy situation and lack of detailed information along the selected routes, two aeroscout teams from Troop D, 2nd Sdn, 22nd Armored Div., were tasked to provide air route reconnaissance for the utility aircraft. On the day of the operation there was about 200-ft ceiling (with light drizzle and fog) over the entire corps area and the enemy front-line defense area; visibility was about 500 m. The three UH-60A helicopters reported to the corps artillery unit, picked up two 105 tubes, their ammunition and gun crews, and flew by low-level flight in IMC to the division holding area where they were joined by the four attack and two scout aircraft.

Figure 3 shows a profile and schematic of the entire mission. It also shows the flight route from the corps artillery unit to the division holding area through the forward edge of the battle area (FEBA) to the fire support base. It includes the primary and the alternate routes. Also shown are the various points at which the aircraft changed flight modes; for example, low-level flight from the corps rear area to the division holding area, contour flight up to the front-line battalion rear areas, followed by the NOE flight from there up to the fire support base. The makeup of the flight was two observation helicopters and two attack helicopters about 3,000 m or one terrain feature ahead of the three lift ships.

Following and overflying the three lift ships were the other two attack helicopters. The lead aeroscout teams moved along the selected route using the "bounding overwatch" technique of movement. As the scouts moved to a new position, they called the attack helicopters forward. When the attack team moved, the scout helicopters provided overwatch protection for them. The task force departed the division holding area on schedule, and the flight through the FEBA was uneventful until a point was reached about 5 km from the fire support base. There, the pilot of the lead OH-58 received, from its APR-39 radar warning device, information that he was being taken under radar surveillance by a ZSU-23-4-type antiaircraft weapon. He immediately took evasive action and broadcast a warning over his radio. All of the aircraft were told to hold their positions. The two scouts then tried to visually locate the ZSU-23-4. It was decided that the attack helicopters would take these weapons under attack and try to eliminate the threat. The attack order was given and the scout aircraft determined the best firing position and brought up their two attack helicopters to make the attack. In the meantime, the lift ships were maintaining their positions. They could do this either by hovering or, if in terrain that permitted it, by setting their load on the ground while continuing to hover until the threat was eliminated. The two attack helicopters in the rear provided security for them. The scouts in the meantime, were searching for the ZSU-23-4's and selecting sites to launch the attack by their TOW-equipped AH-1S attack aircraft. One ZSU-23-4 was located, and a firing position selected. The AH-1S's moved into position and took the ZSU-23-4 under attack. As he had a very difficult firing position, the AH-1S pilot decided that he must perform an evasive maneuver during the time of flight of his missile. He decided to use the inverted V ("$\wedge$") maneuver in which he climbs and moves laterally at the same time. He tries to use a 200-m/min rate of climb and a lateral acceleration of 0.25 g, climbing about 25-30 m and then descending at 200 m/min while continuing his lateral flight. The threat was eliminated and the task force continued on its flight route. When arriving in the river crossing area, the ground commander cleared it to proceed to the fire support base. By this time the early morning low ceilings and fog had cleared enough so that the fire support base was under VMC. The lift ships were required to make a pinnacle approach into a rather confined area. While they were emplacing the two tubes, the ammunition, and the gun crews, the aeroscout teams were asked to provide a reconnaissance for the ground commander. During this reconnaissance one of the scout helicopter pilots reported that he saw a flight of three helicopters approaching from the enemy rear area. Upon observing these helicopters, he determined that they were the MIL-MI-24 "Hind" aircraft. The air task force commander decided to engage these Hinds with the AH-1S helicopters that provided security for the lift ships. These aircraft proceeded to the location of the Hinds to engage them in air-to-air combat using their 20-mm turret-mounted weapons and 6.9-cm rockets. They took up ambush positions and successfully destroyed the three Hinds. One of the Hinds engaged one of the AH-1S's in a one-on-one combat for a limited time until the other AH-1S came up and destroyed it. The air task force having successfully emplaced the gun tubes and protected the lift ships, was then released by the ground commander.

Using the typical mission as our base we can define some of the problems that could be studied using the simulator. We have selected six primary flight problems. The first would be to determine the appropriate flight envelope and handling qualities required to fly IMC with external loads. This kind of flight is very demanding for the lead pilot because he has to maintain control of the aircraft under very stringent parameters of attitude, airspeed, altitude, and heading. If the flight is in formation, the other aircraft have even more critical control tasks. The pilots can be affected by turbulence, load oscillations with resulting PIO's, vertigo, low intervisibility, climbs, descents, and turns. The second flight problem relates to the contour portion of the flight. Here, the aircraft must maintain their airspeed while following the contours of the terrain. Again, oscillations by the loads and resulting PIO's and overcontrolling by the pilots need to be examined. Control difficulty can be increased if formation flight were also a prerequisite. The third problem occurs when the aircraft are engaged in nap-of-the-earth flight. Each must maneuver around and between obstacles, and navigate, communicate, and proceed with the mission, while maintaining awareness of threat weapons. The problem is the definition of helicopter characteristics that permit this. The most stringent task, again, occurs for the lift ships with their external loads. Besides the other NOE requirements, the lift ship must keep the load clear of obstacles—the ground, etc.—and not excite oscillations. The fourth problem is the determination of appropriate evasive maneuvers for the scout and attack helicopters which have to break lock or minimize kill probability while engaging the threat. The helicopter characteristics required for performing these maneuvers must be better defined. The fifth flight problem relates to the pinnacle approach and confined area emplacement of the external loads—the 105-mm howitzers. This is a very demanding piloting task because of turbulence, wind shears, low visibility, partial ground effect, and cross wind. Handling qualities and performance capabilities need to be defined for these maneuvers. The last flight phase is associated with air-to-air combat and the necessity for better understanding of the maneuver requirements. These are just a few of the problems that need to be investigated.

1.2 Environmental Factors

This section will briefly enumerate some of the external environmental factors that have to be simulated adequately in order to produce a realistic pilot workload environment in helicopter terrain flight operations.

1.2.1 Wind, Turbulence and Ground Effect

Turbulence is an important factor in any simulation. In low-speed flight near the ground, steady-wind and wind shear are also very important. Pilots find that terrain features such as draws, intersections, and ridges can induce large changes in wind magnitude, usually in unpredictable ways. Somehow we have to determine what a reasonable wind structure is, and if there really is a large variation with terrain, then simulate sufficient variability to satisfy the pilot's expectation of unexpectedness.

NOE flying requires sustained operation in a region around hover defined by speeds of 35-knot sidewards and rearwards, and about 60-knot forwards, at altitudes up to one rotor diameter. At these heights the downwash impacts the ground and spreads out. The upwind part of the outflow is rolled up to form a vortex, and as the flight or wind speed increases the vortex gets closer to, and eventually passes under, the helicopter. This effect is illustrated in the sketches of Fig. 4, which is reproduced from Ref. 1.

There are many effects apparent to the pilot due to this vortex: large lateral trim changes; changes in power required; general aircraft unsteadiness; and weapon launch inaccuracies. Many of these factors will have to be better understood and systematically modeled for meaningful simulations of this environment. A sequel to the work reported in Ref. 1 is presently being performed by Boeing Vertol under contract to AVRADCOM and should provide a useful addition to the required background.

1.2.2 Visibility

The hypothetical mission described in Sec. 1 has many elements that strain our current helicopter capabilities and involve very high pilot workload. This is true even in daylight under ceiling and visibility conditions as good as 300 ft and 1000 m. In Ref. 2, LTC Watts presented an analysis of weather to be expected in Europe. This is summarized in Table 1. Clearly, over an average year, the visibility and lighting will be worse than condition 1 for 47% of the time. Some capability currently exists to operate into condition 2 (Ref. 3) but very high pilot workload is involved and there is a need for many pilot aids such as radar altimeters, navigation aids, and a vision aid such as light intensification (e.g., low light level television (LLLTV), goggles) or thermal imaging devices (forward looking infrared (FLIR)). There is also obviously a trade to be made between better displays and augmented stability and control characteristics. The required aids and augmentation schemes become even more important and potentially complex and expensive if we are to operate into conditions 3 and 4. To better understand the tradeoffs involved it is essential that we be able to simulate the range of visibility conditions listed.

TABLE 1. AVERAGE ENVIRONMENTAL CONDITIONS FOR MID-EUROPE (FROM REF. 2)

No.	Lighting	Ceiling, ft AGL	Visibility, m	Time existing, averaged over 1 year, %
1	Daylight	>300	>1000	53
2	Night; 1/2 moon or better; any degree of cloud cover	>500	>4000	13
3	Night; 1/4 to 1/2 moon	>300 <4/8 cover	>2000	2
4	Night; less than 1/4 moon; any cloud cover			26

It should be noted that realistic simulation of reduced visibility should include patchiness which is a frequent killer of unwary helicopter pilots. This may be caused by a sudden patch of fog that eliminates all visual cues and induces vertigo.

Other effects desired for improved realism are rotor shadow and vegetation movement to help the pilot judge his clearances, and weapon flashes under simulated darkness.

1.2.3 Other Considerations

There are many cockpit internal environmental factors that affect the overall design and, hence, the techniques used to provide external cue simulation. These will not be discussed, but include:

1. Vibration of instrument panels, cockpit seats, and controls, but not of the visual display
2. Unencumbered subject head, eye, shoulder, and upper body to facilitate ready access for observations and recording
3. Crew-station layout flexibility to permit two- or three-man crews and side-by-side, tandem, or staggered seating
4. Convenient, quick change of subjects with no special fitting or calibration requirements

2. USES OF AN R&D SIMULATOR

Simulators can be used to train better pilots or to develop better helicopters. It is the latter application that is of interest in this paper, and the following section will outline these uses and show how they affect the desired simulator characteristics.

The uses of an engineering R&D flight simulator extend through the life of an aviation system from development of the technology data base, from which design criteria and specifications can be developed, through all stages of system development; from conceptual and system integration studies during initial design, to product improvement efforts long after the aircraft has entered service. Table 2 outlines some of these uses.

R&D — Studies of man-machine research can be performed to develop a data base on cockpit control/displays, mission performance, and workload. Such a technology base will allow sensible choices to be made during conceptual system synthesis and allow our handling qualities specifications to be improved.

TABLE 2. OVERVIEW OF TASKS

Technology data base	R&D • Man-machine research • Cockpit control/displays • Mission performance/workload • Criteria/specifications	Smart Buyer
System development	PM support • Conceptual studies • Total system integration • Competitive proposal evaluations • Product improvement studies	Smart Buyer; Efficient system development
System development	Contractor support • Design development • Flight test planning/familiarization • Envelope definition/expansion	Efficient system development

PM Support — Simulation can be used to support the Program Manager (PM) during the conceptual phase, and to perform design studies and total system integration evaluations. It can also be a powerful tool for competitive proposal evaluation and PIP studies late in the life cycle.

Contractor Support — Helicopter contractors need access to a high-fidelity simulator to get maximum confidence early in their design phase. This would supplement work on their relatively primitive in-house facilities. As the prototype approaches flight test, there is a need to plan the detailed test maneuvers and familiarize the pilot with the aircraft's handling qualities and systems. Investigation of dangerous maneuvers, such as autorotation and envelope expansion, should also be investigated on the simulator prior to flight. To summarize, judicious use of simulation gives us two benefits:

- It allows us to be a "smart buyer"; that is, it gives us the ability to choose between the many alternative approaches and combinations of equipment, so that we may buy systems that perform the missions we want yet do not have unnecessary frills
- It allows us to support the development of the chosen system hardware

Evolvement of the R&D simulation during the course of the system development provides, as a fallout, an accurate mathematical model for use in subsequent training simulators.

2.1 Impact on R&D Simulator Requirements

The uses outlined above all have potential effect on an aircraft design. Wrong answers can lead to dangerous or unnecessary design features. For example, a failure-effect study may indicate unsafe transients and unacceptable post-failure controllability so that a redundant fail-operate system is required. If this is not an accurate assessment, the increased cost and complexity may have been unnecessary. A primary characteristic required of an R&D simulator must therefore be high dynamic fidelity so that the handling quality assessments can be taken at face value, not merely as indicating trends. Major contributors to dynamic fidelity are the mathematical model accuracy, the motion system response, and the visual display.

A second important characteristic required is versatility: the ability to change the simulation easily from one type to another, and to perform the corresponding wide range of maneuvers. Helicopters of interest to the Army range from small, lightweight types, such as scout (OH-6A) through utility (Blackhawk) and attack (AAH), to medium and heavy lift such as CH-47, CH-54, and HLH. Research configurations such as rotor systems research aircraft (RSRA) and advancing blade concept (ABC) and XV-15 also have to be covered. The maneuvers performed by these helicopters range from the high-agility flying of NOE, to sedate instrument approaches or precision hover. These requirements for versatility affect the mathematical modeling capability, both in capacity and ease of reprogramming, motion system performance, and the cab-visual display interface. Cab size, shape, and interior layout must be easily changed and be able to accommodate cabs that are large or small, and wide or narrow, including tandem or side-by-side seating. It is also desired to accommodate two crew members, with the pilot having high fidelity motion and visual cues. The second crew member can have degraded fidelity in motion and visual cues, since he will not perform the primary aircraft control function. However, he should have reasonable motion, and sufficient visual information to be aware of the flight situation.

The requirements on visual and motion design and performance characteristics that these overall features imply are discussed in the following section.

3. SIMULATOR VISUAL AND MOTION REQUIREMENTS

In this section, we will illustrate the methods used to determine some of the more important simulator motion and visual system requirements. The rationale used and the assumptions adopted will also be highlighted. It is stressed here that the objective is to translate the combat environment into engineering terms suitable for specifying simulation hardware.

The important questions here are: What combinations of tasks and research problems create the critical specifications for the motion and visual systems? What are these critical specifications (i.e., those considered to have a high impact on hardware cost and complexity)?

We are answering these questions as part of the preliminary definition phase of the research facility development.

3.1 The Important Parameters

The parameters that appear to drive hardware cost and complexity are briefly described below. They are detailed more fully later.

1. Visual System
   - Field-of-view
   - Field-of-view location; that is, placement of the field center relative to helicopter body axes
   - Resolution/contrast (including color)/luminance; that is, the parameters that govern detectability, recognition capability, and image quality
   - Dynamic performance, thresholds, and all factors affecting image quality during periods of movement
   - Level of detail; that is, the features of the simulated area presented to the crew members
2. Motion (platform device)
   - Maximum angular and translational excursions, velocities, and accelerations
   - Minimum values of the above, or threshold levels
   - Dynamic performance; that is, bandwidth, phase distortion, etc.

It is also obvious that the critical visual and motion requirements will occur during simulation of good visibility conditions since the pilots will take advantage of the available visibility to perform vigorous maneuvering.

3.2 Some Probable Worst Cases

The results of the effort thus far have indicated several cases where critical visual and motion requirements occur. They are:

1. Abrupt direction reversal of a scout helicopter to evade an antiaircraft weapon (critical motion platform excursion requirement)
2. Precision hover of a utility helicopter with external loads (critical motion platform threshold requirement)
3. NOE flight of a scout helicopter where rapid attitude and thrust changes are used to avoid obstacles while maintaining a low altitude and high speed (critical motion platform dynamic performance requirement
4. Air-to-air combat using a one-on-one strategy (critical visual field-of-view requirement)

Abrupt Reversal

Imagine a scout helicopter flying the mission described earlier. At the point in the flight where a scout pilot discovers they are being tracked by a radar-directed antiaircraft weapon, the pilot in command looks out the right window and sees the weapon just over the hill forming the canyon from which they have just emerged. The weapon is close (about 1000 m) and since the flatland ahead is devoid of cover, the pilot decides to reverse course back behind the hill. The initial speed is 60 knots so the maneuver selected is a "wingover" type that should reverse course in a few seconds.

The nose is pulled up abruptly to about 45° and the helicopter rolled to about a 60° bank to the right. The nose is continually "pulled around" until the heading change and bank each reaches 90°. Just before this attitude is reached, full power is applied and a fuselage yaw to the right is begun that results in the helicopter pointing nearly straight down with a reversed heading. From here the nose is pulled up and a rapid acceleration initiated back to cover. The initial speed of 60 knots has been reversed while the helicopter traversed about 70 m forward and arched upward about 30 m. The whole maneuver required about 8 sec, and it is expected that full control travels and full power would be used.

The above maneuver represents the worst case from the viewpoint of motion platform excursion requirements. An idealized time history of this maneuver is shown in Fig. 5.

3.3 Motion (Platform) Requirements Definition

It is generally agreed that motion simulation is required to obtain the full potential pilot performance and that it is also necessary for engineering research and development simulation. In a more general sense, motion simulation is required when:

1. Expected motions are above human sensory or indifference thresholds

   and
2. Within the sensory frequency range; that is, above 0.2-0.5 rad/sec
3. If full pilot performance (e.g., tracking) is desired
4. Or when a degree of face validity or realism is required to gain pilot acceptance of the total simulation.

The maneuver, tasks and research objectives anticipated for the facility all comprise conditions that impose the above constraints. For these reasons motion simulation is required and will be specified from the following.

A widely accepted methodology for motion simulation does not presently exist. However, some concepts are emerging that are based on reproducing to some degree the motion sensations of the pilot. The properties of this sensory process are not perfect and advantage of it may be taken in order to reduce required simulator motions. Specifically, washout can be made compatible with sensory washouts so as to produce motion sensations in the simulator that are close to those of flight. Just how close is of course the central question.

The criteria adopted for these requirements reflect this view and are the result of researcher opinion supported by very limited test data. In essence, the criteria relate the maximum allowable distortion of angular velocity and apparent force in the simulator relative to that of the simulated aircraft. This distortion is "looked at" at a discrete frequency of 1 rad/sec, the frequency where rotational sensing is best and close to the frequency range where sensory washout is placed.

3.3.1 Maximum Excursions, Velocities and Accelerations

The point-to-point flight maneuvers used during NOE simulations (Ref. 4) were analyzed to define the platform excursion requirements. This was done by taking the resulting flight maneuvers from this simulation and playing them (off-line) through a drive logic set up to represent the six-degrees-of-freedom drive logic of an advanced simulator. The computer on which this method was implemented was then instructed to search out and retrieve the maximum positions, velocities, and accelerations of all six-degrees-of-freedom.

The fidelity of motion "recovery" set up on the drive logic is described in Fig. 6 in terms of phase distortion and amplitude of the simulator "recovered" motion (at a frequency of 1 rad/sec, the frequency at which the vestibular phase shift is zero) relative to that in the simulated helicopter cockpit. (Recovered motions mean the angular velocity and specific forces components that would be observed in the simulator.) The motion parameters compared were the three components each of angular velocity and apparent force.

Figure 6 shows the fidelity boundaries adopted and selected operating points for each axis.

The fidelity criteria were hypothesized by the authors and R. S. Bray, Ames Research Center, following a pooling of thought among Ames researchers on the effect of washout on fidelity. Experiments at NASA on the Flight Simulator for Advanced Aircraft and by the Air Force on single-axis (roll) devices have given limited results that support these fidelity criteria. Because smaller amplitude tasks will utilize less than the maximum requirements, nonlinear drive logic is planned to vary the gains and washout frequencies in order to obtain as much fidelity as possible with lower amplitude tasks. The results of the analysis are given in Table 3. Here, the maximum position, velocity, and acceleration of each axis as collected by the computer are shown. The requirement is for all axes to produce these quantities simultaneously; for example, all velocities must be producible simultaneously.

TABLE 3. MOTION (PLATFORM) REQUIREMENTS FOR CRITICAL TERRAIN FLIGHT MANEUVERS

	Parameter		
Axis	Position, rad, m	Velocity, rad/sec, m/sec	Acceleration, rad/sec^2, m/sec^2
Yaw	±0.4	±0.6	±1.0
Pitch	±0.3	±0.5	±1.0
Roll	±0.3	±0.5	±1.0
Surge	±1.3	±1.3	±3
Sway	±3	±2.6	±3
Heave	+7, -14	+8, -11	+14, -12

Notes: The requirement is for simultaneous operation.
The rotational gimbal order is yaw, pitch, roll.
Translational axes are orthogonal; plus is forward, right, and down.

The reversal maneuver described earlier has also been analyzed in a preliminary fashion and found to require slightly larger excursions than the point-to-point flight cases; hence, its description earlier as the worst case.

The simultaneous requirement is amplified by Table 4. Here, the position of each axis, at the instant one reached a maximum, is presented. The data are from a typical maneuver case and the optimized drive logic. The significance of the data is that when one axis is at a maximum, some of the others are at large values also.

The need is not for a perfect simultaneous requirement but something less. The precise definition of this for a particular motion drive needs an analysis in which the taped maneuvers are played through the optimized drive logic and hardware model with the appropriate constraints.

TABLE 4. EXAMPLES OF SIMULTANEOUS EXCURSIONS

Axis at maximum position	Simultaneous axis position, % maximum					
	ϕ Roll	θ Pitch	ψ Yaw	X Surge	Y Sway	Z Heave
ϕ	100	0	31	0	92	73
θ	60	100	6	83	46	14
ψ	67	22	100	28	54	41
X	33	33	19	100	0	59
Y	87	33	38	83	100	77
Z	47	33	0	56	69	100

3.3.2 Thresholds

The requirement to allow precision hover with external loads means that helicopter attitude motions are typically ±1°, ±2°/sec, and ±4°/sec², Ref. 5. These values are above the human threshold by a factor of 2 to 10 depending on one's threshold data interpretation. Considering the wide variability of human threshold data it is reasonable to use approximate human thresholds as design objectives.

Human rotational and translational thresholds have been measured by Hosman and Van der Vaart (Ref. 6) using a hydraulic motion base with hydrostatic bearings. Their results show the angular motion thresholds to be frequency dependent and all values to be a function of pilot task loading. The values adopted are approximations to these data and are shown in Table 5. Corresponding sinusoidal angular position and angular acceleration are also tabulated. The use of such data for specifying threshold performance insures a smooth device devoid of the bumps and jerks so characteristic of platform motion systems.

TABLE 5. MOTION PLATFORM THRESHOLDS

Angular			Linear Acceleration
Position	Velocity	Acceleration	
$\frac{0.2}{\omega}$ deg	0.2 deg/sec	$0.2\,\omega$ deg/sec^2	0.01 g
ω in rad/sec			

3.3.3 Dynamic Performance

The speed of response or dynamic response of the motion base should be chosen on the basis of the fastest commands it must follow. If one knew the highest frequency at which a helicopter could ever be maneuvered, a motion platform actuator natural frequency 7 to 10 times greater with adequate damping will result in good following performance. This is because such a system produces a phase lag of only a few degrees which in turn translates to a negligible effect on pilot and helicopter performance.

The frequencies associated with hard reversals are about 1 rad/sec (complete reversal, or one cycle in about 6 sec). This would lead to a critical frequency of 7 to 10 rad/sec, a modest requirement. It turns out, however, that roll reversals during high-performance NOE flight can occur at frequencies of up to 3 rad/sec, hence the requirement for a critical frequency of at least 20 rad/sec.

Such high-frequency maneuvering occurs only when handling qualities are such that pilot and helicopter performance is high.

The point is illustrated by the experimental results of Fig. 7. These were obtained by the authors, using the roll axis of a wide field-of-view simulator. This is a plot of the effective pilot time delay for a critical task as a function of the roll actuators' natural frequency. The actuators' dynamics were represented by a linear second-order system of 0.7 damping ratio and variable natural frequency.

It is seen that little effect on pilot time delay exists for natural frequencies of 19 rad/sec or higher. The tasks used for these tests were critical in that they required the pilot to control increasingly divergent roll axis dynamics until loss of control was observed. The time delay estimate is based on the level of divergence at the instant control was lost. The criterion of 19 rad/sec or higher, therefore, represents the required actuator response for a simulation in which the pilot is the limiting factor.

The worst (or fastest) case anticipated involves a task in which pilot and helicopter performance is high. These are cases where rapid maneuvering is required and the control configuration allows it. From this viewpoint the tasks are nearly critical ones where helicopter rigid-body frequencies approach 3 rad/sec. To insure good following dynamics under the worst possible case, the 20 rad/sec for the motion actuator natural frequency is specified. With this, maneuvers approaching the critical ones described will be adequately followed by the hardware.

3.4 Definition of Visual System Requirements

3.4.1 Field-of-View

Maneuvering during air-to-air combat operations obviously dictates the critical (widest) field-of-view requirement. During one-on-one combat the adversary helicopter can rapidly traverse to nearly any part of the top hemisphere of the field of view. Besides the usual arena of air combat, helicopters present some interesting possibilities because of the way they fly. Conventional fighter aircraft point by rolling and pitching. The pitching comes about from the large normal force, thrust being used to help adjust speed. Helicopters, on the other hand, can point more easily by simply adjusting the rotor thrust. At the low speeds at which they fly, they are capable of rapid yaw, and with proper design can perform some aerobatic maneuvers.

Two modes of air-to-air combat can be imagined. The first takes place at low speeds and is essentially a contest between helicopters attempting to yaw rapidly so as to achieve an orientation favorable for firing guns or missiles. This may be termed the "quick draw" regime and probably will be the favored tactic below a speed of 60 knots.

Above this speed, the relative velocities, inherent stability, and kinetic energy of the combatants will make some maneuvers attractive. For example, following a surprise close passage of adversaries in opposite directions, neither has the initial advantage (all other factors being equal). If one starts a hard 2.5-g level turn, the other could consider initiating a similar turn to maintain the neutral situation. However, if the latter were to perform a 2.5-g loop, he would, at the top, have further options of varying bank in order to reach a firing position. Calculations have shown the loop to have about a 1-sec advantage over the level turn. The 2.5-g level turn reverses pointing in about 6 sec, but the loop accomplishes it in about 5 sec. These and other maneuvers considered require a continuous field-of-view of at least 2π sr (the upper hemisphere) and probably closer to 3π sr due to the necessity of looking downward along the sides and front of the cockpit during hover operations.

3.4.2 Field-of-View Location

In conventional high-altitude air combat, the adversaries attitude and location relative to the attacker's body axes comprise the primary information required. The horizon and earth are secondary in the hierarchy of preferred cues. This is due to the high lift (6+ g) maintained during most of the engagement, causing the aircraft's track to depend mostly on the integrated effects of the lift vector, gravity (hence horizon) having a smaller influence. Simulation hardware therefore need only provide a good quality image of the adversary and a low-quality image of the ground.

With helicopter air combat, this is not true. The low-speed, low-altitude, and low-thrust/weight capability of these machines makes combat near the ground more attractive due to enhanced concealment. This means that a high-resolution wide-field display of the adversary and the ground is required. For NOE point-to-point flying and hover operations, however, a smaller area display will suffice. For example, studies of obstacle avoidance during NOE flight yields a requirement for a horizon-stabilized 120°-wide by 60°-high area centered at a point directly forward.

This requirement results when one calculates the azimuth of a point 3 sec ahead during turning or sidestepping level flight. The value of 3 sec is considered the minimum preview time for obstacle avoidance. What this means is that a display must be wide enough to show obstacles at least 3 sec ahead in the projected flight path during turns or sidestepping. For example, a 2-g level turn (60° bank angle) requires that objects 3 sec ahead be visible at an azimuth of 60° for a speed of 50 knots. It also means that the display might have to be horizon-stabilized if the vertical field is small (40° or less) or else the 3 sec point (or objects) will lie out of the field.

These considerations lead to an NOE field-of-view requirement of about 120° horizontally by 60° vertically that is horizon-stabilized in roll. Such a display can be centered directly forward. Hover at 15 m altitude during a difficult low-visibility pinnacle approach requires a field of 40° by 50° centered downwards about 45° and to the side and rear.

3.4.3 Resolution/Contrast (and Color)/Luminance

Because these parameters are interrelated from the viewpoint of human performance, they are treated together. The ability to show fine detail is an unmistakable way of defining image quality. It would seem that a moderate degradation in our visual resolving power would result in a moderate loss of performance in accomplishing tasks requiring visual cues. This is not the case. A visual acuity of 3 arc-min (about 20/60 vision) will not result in a third of the performance (e.g., the speed at which a NOE course could be flown at a specified mean altitude) obtainable with 20/20 vision even though objects must be three times closer to be recognized or detected. This quality of the seeing mechanism results in relaxed requirements for uncorrected vision associated with many roles (such as pilots) and points up the fact that rarely in our lives do we really need the fine resolving power of our eyes.

The combat environment, it would seem, presses on this ability because of the necessity to detect and recognize potential targets that, because of their distance, subtend small angles. Detection and recognition events, however, can be artificially induced and therefore are not requisites for this simulation facility. What then dictates this requirement? To help form this judgment, a list of familiar object-situations is presented below together with their subtended angles:

- 1.8-m-wide helicopter at 3000 m: 2.3 arc-min
- 0.3-m-wide gun flash at 3000 m: 0.4 arc-min
- 2.54-cm tree branch at 16.4 m: 5.7 arc-min
- 10-cm fence post at 100 m: 3.8 arc-min
- 2-mm wire at 100 m: 0.08 arc-min

With sufficient contrast, all of the above objects may be easily seen by the normal unaided eye. If a visual system resolution of about 3 arc-min were to be used for advanced helicopter research, most of the object-situations listed would not be revealed. While it is difficult to deny that performance sufficient to detect all of these objects in a combat environment is required, it is difficult to justify such visual performance for a research facility, because all of the objects listed that are smaller than 3 arc-min may be arbitrarily brought closer or made larger <u>without compromising the ability to answer research</u>

questions. For example, such a research facility can be used to answer the question, "How fast can a particular helicopter travel and still avoid wires that suddenly appear in its path?" The matter of detection distance can be controlled in such research in order to gain the real insights into the agility required.

The choice of resolution of 3 arc-min or better appears reasonable from the points of view of expected pilot performance, pilot acceptance (face validity), and hardware constraints. It is stressed that this is the best (lowest) resolution required. Most simulations can be performed with much less, provided large familiar objects are included to enhance the pilot's range judgment ability.

The detection performance of the human eye is given in Fig. 8 from Ref. 7, in terms of threshold contrast, background luminance, and target size. The target for these tests was a circular gray dish on a darker background. The probable operating envelope of the research facility visual system is also shown for a minimum resolution of 3 arc-min. The dimension into the paper represents the inverse of resolution and, therefore, can be used to describe spatial frequency. This also permits the operating envelope to be described in terms of the modulation transfer function, although the boundaries shown do not reflect this. Most earth features have contrasts between 0.03 and 1. The probable worst point is the high-brightness, low-contrast one at design resolution. It is seen that for the range of brightness shown, color is not always needed.

3.4.4 Dynamic Performance

The specification of simulator visual system dynamic performance is relatively straightforward if there are no delays due to computation. Unfortunately, there are significant computation-induced delays and we are currently studying the allowable tolerances.

If servosystem dynamics (considering that the display system uses servos) are set to those of a 25 rad/sec second-order lag of 0.7 damping ratio, the time delay in response to a sinusoidal command of varying frequency is nearly constant at 56 msec. If a reasonable total time delay of about 100 msec is to be maintained, then the computational delay (generally about 3/2 X the frame time) must not exceed 44 msec. This yields a maximum frame time of about 30 msec.

Additional considerations are required if computer-generated imagery is used as part of the visual system. Because of peculiar effects with such systems, the treatment of required dynamics will need more study. When objects are slewed on the retina at angular velocities of 1 rad/sec or more, the resolution decrease is not more than one-half the static value. It would seem reasonable, therefore, not to allow the resolution to degrade beyond one-third of its static value for an image angular velocity of 80°/sec; a value considered to be the maximum angular rate of any object due to rotation of the helicopter.

4. ASSESSMENT OF VISUAL SYSTEM LOW-RISK TECHNOLOGY

In looking at the techniques of providing the pilot a visual representation of the outside world, it is convenient to divide the discussion into techniques for image generation (IG) and techniques for image presentation (IP). Table 6 lists some of the possibilities for each. Generally, it is possible to combine any IG technique with any IP technique if the initial design is compatible with the intended application and is developed accordingly.

TABLE 6. EXAMPLES OF IMAGE GENERATION AND PRESENTATION

Function	Type	Examples
Image generation	CGI	MCDEC VITAL III, IV - Navy Airlines GE COMPUSCENE - Boeing
	TV camera-model	Link VISULINK - Army
	Laser scanning	Redifon - Under development
Image presentation	Real image Projectors	 Redifon DUOVIEW Northrop WAVS - USAF
	Matrix	Liquid crystal or light emitting diode - future
	Virtual image	CRT Discrete windows or mosaic

There are many characteristics that have to be defined to comprehensively describe the performance of a visual system. Table 7 lists some of the parameters defining image generation performance for camera model techniques and CGI techniques, and includes some performance numbers that are about the limits of current technology. Similarly, Table 8 compares primary parameters for image presentation by projection and CRT.

This section will discuss the possibility of meeting desired values for three of the characteristics which have a first-order effect on the design and cost: field-of-view, resolution and detail. The advantages and disadvantages of different approaches, as they affect the ability to simulate Army missions will also be discussed.

TABLE 7. IMAGE GENERATION PERFORMANCE

	Image generation	
Parameter	TV camera-model scale 1:250/1:500	CGI
Field-of-view, deg	60 vertical, 120 horizontal	4 channels of 30 vertical x 40 horizontal
Resolution: Limiting center	9	
arc min/OLP edge	11	3
Depth of field at 11 arc min/OLP or better	Probe limited (focus @ 62 m) 30 m to ∞	Unlimited
Detail	Very high - from model	Low - potentially 8000 edges
Refresh rate per sec	30	30
Lag (through display)		0.063 sec
Position accuracy, deg	0.3	N.A.
Gaming area, n. mi.^{2}	6	Unlimited
Simulated aircraft limitations		
Min. eye height, m	1.5/3	Unlimited
Horizontal clearance, m	5/10 at eye height	Unlimited
Excursions θ, ϕ, ψ, deg	±90 Unlimited Unlimited	
Velocities V, q, p, r, knot, deg/sec	250/500 ±60 ±100 ±100	
Accelerations $\dot{V}$, $\dot{q}$, $\dot{p}$, $\dot{r}$, g, deg/sec^2	3/6 ±100 ±150 ±100	
Miscellaneous		
Moving targets	No, unless superimposed CGI	Yes
Threat weapon effects	" " " "	Yes

TABLE 8. IMAGE PRESENTATION PERFORMANCE

	Image presentation	
Parameter	Projector	CRT
Field-of-view		
Detailed, deg	180 x 60	Four windows @ 30 x 48
Background, deg	240 x 160	N.A.
Scene field rotation (roll), deg	±45	N.A.
Pilot viewing volume (<10° error)	±0.5 m	±0.15 m
Luminance, m-L	2.5	1.8
Contrast	10:1	20:1
Refresh rate, Hz	30	30

4.1 Image Generation

4.1.1 TV Camera-Model Techniques

Of the three first-order factors — field-of-view, resolution, and detail — it is scene detail that is the easiest feature to achieve in camera model systems. A terrain board can be constructed with very high detail, even with quite small scales (1000:1). For example, Fig. 9 shows detail of an NOE terrain board at Ames Research Center; the scale is 400:1.

For a given size of model board, small scale is required to maximize gaming area, but optical probe clearance and depth of focus put lower limits on scale, and these limits are particularly severe in probes with wide field-of-view. For example, in a study performed for AVRADCOM by the Northrop Corporation (Ref. 8) a Ferrand 140° probe was used as a design base. A sketch of its profile is shown in Fig. 10. The absolute minimum height is about 0.5 cm; this translates to 1.5 m eye height with a scale of 250:1. A smaller, but quite usable model scale such as 1000:1 gives a minimum eye height of 6 m, which is considerably greater than that of a pilot in an Army OH-6A, or Blackhawk on the ground. The wide side profile also limits clearance of approach to obstacles to about 6 m at eye level for 1000:1 model scales. These clearances have to be increased significantly from the physical minimum to provide a practical means of "crash" protection. For example, a Northrop concept using computer terrain mapping to trigger an automatic retract mechanism, requires clearance of 4.8 cm horizontally (12 m at 250:1) and 8.9 mm (2.2 m at 250:1) vertically for a flight condition of 120 knots horizontally and 15.2 m/sec vertically downward.

In applying the wide angle probe, it was decided that to obtain reasonable resolution through the TV chain the 140° field would have to be divided into three fields of 42° by 60°. Limiting resolution for such a system of probe and TV cameras is then estimated to be as shown in Fig. 11. Further degradation in resolution can be expected due to registration errors in the projection of independent red, blue, and green, and due to the probe depth of field as shown in Fig. 12. If the probe is focused at 60 mm (15 m at 250:1) the scene will have resolution, from the probe, better than 6.7 arc-min per optical line pair (arc-min/OLP) from 51 to 72 mm (12.8 to 18 m) and will degrade below 20 arc-min/OLP closer than 45 mm (11.25 m) and further than 105 mm (26.3 m).

Scheimpflug tilt correction will significantly extend this depth of field for a flat surface. Fig. 13 compares the resolution variation for a tilt-corrected and uncorrected probe. Also indicated is the effect this would have on a 15 m tree at 60 m range (250:1 scale).

For missions involving terrain flight, where it is important to see close three-dimensional objects, these limitations are probably the most restricted aspect of camera-model technology.

As there seems to be a trend away from camera-model systems toward CGI, it follows that we are unlikely to see advances in conventional camera-model technology that will result in a dramatic improvement in resolution or field-of-view. The basic decision to be made then is whether the advantage of high detail compensates fðr deficiencies in resolution, field-of-view, and eye height. The alternative is to move to CGI with its exactly opposite virtues. Before discussing CGI, it must be mentioned that some unconventional camera-model techniques are under study which may modify this situation (cf. paper by Driskell in this conference).

4.1.2 Computer Generated Imagery (CGI)

With CGI, the field-of-view and resolution are limited only by the price one may be prepared to pay for the necessary computation capacity. The present practical problem is providing sufficient scene detail over a large area. Available techniques can achieve a highly detailed scene such as shown in Fig. 14 which contains 1500 edges. The problem is to develop techniques that will allow the density of detail to increase as features, such as hillsides, are approached, so that scene content is maintained at some sufficiently nigh level to provide the necessary cues to the pilot. Fig. 15 shows how the present situation runs out of detail as the ground is approached. Fig. 16 shows a test terrain derived by Singer-Link under contract to the AVRADCOM to investigate what minimum scene detail and object realism a pilot will accept. Arranged in the flat valley, the scene shown provides adequate detail for precise low-altitude maneuvering; facets on the square-section posts, and angular rocks, became quite distinct at short range, and provide a good textural cue. Several test pilots were asked to evaluate their ability to maneuver in this area and they judged the cues and realism to be adequate. The next step must be to extend these kinds of scattered objects over non-planar areas such as on hills.

Resolution with CGI is primarily a function of the IP system with which it interfaces. A 1000-line color system gives effectively 900 lines resolution. If such a system is used for a field of 60°, the resolution would be 4.0 arc min/TV line pair, clearly a very desirable resolution.

Field-of-view can be extended by coupling more channels of IG; for example, the 120° by 60° field discussed in the camera model technology section could be derived from three channels of 40° by 60° CGI.

4.2 Image Presentation

Several significant advantages result from the fact that in a projected display the IP hardware is structurally independent of the cab. These are: (1) versatility of cab shape; (2) size and pilot location; (3) ease of cab change; (4) the ability to move the area of detailed scene presentation so that it always covers the most likely area of interest; and (5) the ability to vibrate the cab independently of the out-the-window display.

Versatility is illustrated by the arrangement developed in the Northrop study (Ref. 8) performed for AVRADCOM (Fig. 17). The constraints were that the pilot should be able to see down 30° and back 120° without supporting structure intruding into the field. The cab shapes to be accommodated were to be at least 2-m wide with a side profile as shown in Fig. 17. Occlusion of the projected picture by cab overhead structure for this size cab was investigated and is shown in Fig. 18 superimposed on the pilot's field-of-view on an OH-6A (Ref. 2). Using triad projection for red/blue/green, blue can be placed at the bottom; only this color is then lost in small areas of the ground terrain, and this is not considered a significant penalty. The range of cab shapes that can be accomodated without further interference should be considerable, but very wide cabs such as the Blackhawk's will cause problems. A second aspect of versatility is related to pilot location. Clearly only one point (the center of the dome) can be presented with accurate visual cues. However, the display will be readily visible to a second crew member and, though distorted, should be adequate for studying many "copilot" tasks. Virtual image CRT displays cannot match this capability.

The second advantage of a projected display is that, with careful design, it is possible to roll the displayed field to keep the area of interest within the available field. Earlier it was shown that a criterion based on the pilot being able to see ahead at least 3.0 sec during a turn results in a field-of-view of about ±60° in azimuth for a coordinated 60° banked turn at 50 knots. However, with a visual field of say ±30° by ±60° fixed relative to the cockpit, the 3-sec point vanishes at slightly greater than 30° bank angle, not at 60°. Figure 19 shows this effect. A projected display that can be rolled to keep the horizon in the center of the field retains the full benefit of the ±30° by ±60° field. Also shown on Fig. 19 is an outline of the transparent areas for the pilot in an AH-1G. The upper window frame can be seen to obscure a significant part of the rotated scene, but it must be remembered that this structure is close to the pilot's head so slight movements of his head allow him to easily see around it. This ability to see around the window frames is of course not possible with virtual image displays.

A display formed by a mosaic of CRT, like the U.S. Air Force's ASPT at Williams AFB, Arizona can be used to generate a rolled display in the manner described above. However, even that display system cannot present a visual scene to two crew members simultaneously.

With current projectors there are significant penalties to pay for the advantages described: the hardware is more expensive and complex than that of collimated CRT displays and the resolution is poorer. The resolution loss from misregistration of the red/blue/green may be particularly important in color projection systems. Second-order factors, such as brightness, are also likely to be inferior to those obtainable with a CRT. However, it is expected that the inherent advantages will result in continued development of such real-image displays, whether using projection or eventually through matrices of LED or LCD.

5. CONCLUSIONS

Army missions impose special requirements on environmental simulation. Flight at very low altitudes is in an environment rich in detail from the ground and from the atmosphere. Performance of high-agility maneuvers requires the highly detailed out-of-the-window display to be presented over a wide field-of-view.

The Army must solve several difficult problems in order to maximize its helicopter effectiveness against existing threats; simulation can greatly aid this. Use of a simulator for aircraft system development necessitates high dynamic fidelity for all components, and especially the expensive components providing the visual display, motion cues, and mathematical modeling.

Motion system platform fidelity requirements were hypothesized and verified with some limited experimental testing. The resulting levels of excursions, velocities, and accelerations should be achievable with the planned modifications to the NASA Ames Vertical Motion System.

Visual display requirements for Army mission simulation are the most critical environmental simulation limitation. Hypothesized desirable performance levels for field-of-view, detail, resolution, and dynamic response are unlikely to be realized in the near future. TV camera-model techniques of image generation can give adequate detail, but field-of-view is limited to modest size and resolution is marginal. Computer-generated imagery does have greater field-of-view and resolution capabilities, and the recent rapid advances suggest that acceptable detail will soon be achieved.

It is not clear at this time what image presentation system may be adequate for future multi-crew needs. Candidate systems are those based on improved projection, laser scanning and solid-state light emitting diodes.

REFERENCES

1. Sheridan, P.F. and Wiesner, W.: Aerodynamics of Helicopter Flight Near the Ground. American Helicopter Society paper, May 1977, pp. 77.33-04.

2. Watts, LTC A.C.D.: Army Helicopter Operations at Night and in Adverse Weather. Proceedings of the 1st European Rotorcraft and Powered Lift Aircraft Forum, September 1975, Southampton, England.

3. Odneal, B.L.: Effect of Nap-of-the-Earth Requirements on Aircrew Performance During Night Attack Helicopter Operations. AGARD Conference on Guidance and Control of V/STOL Aircraft and Helicopters at Night and in Poor Visibility, Stuttgart, May 1974.

4. Chen, R.T.N. and Talbot, P.: An Exploratory Investigation of the Effects of Large Variations in Rotor System Dynamics Design Parameters on Helicopter Handling Characteristics in NOE Flight. American Helicopter Society paper, May 1977, pp. 77.33-41.

5. Sinacori, J.B.: V/STOL Ground Based Simulation Techniques. USAAVLABS TR 67-55, 1967.

6. Hosman, R.J.A.W. and Van der Vaart, J.C.: Thresholds of Motion Perception Measured in Flight Simulator. U of Delft Memo M248, 1976.

7. Bioastronautics Data Book, NASA SP 3006, 2nd edition.

8. Northrop Corporation: Feasibility Study for Helicopter V/STOL Wide Angle Simulator Image Generation and Display System. Final Report NOR 77-102, October 1977.

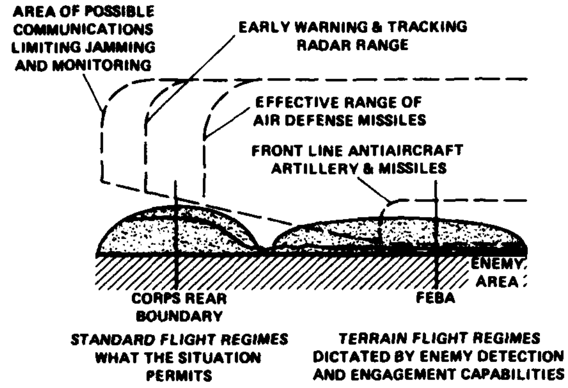


Fig. 1. Threat portrayal on high threat battlefield.

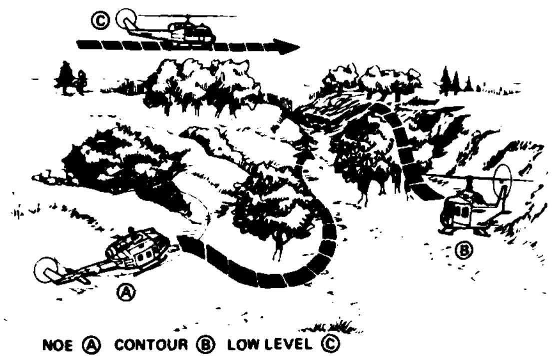


Fig. 2. Terrain flying regimes.

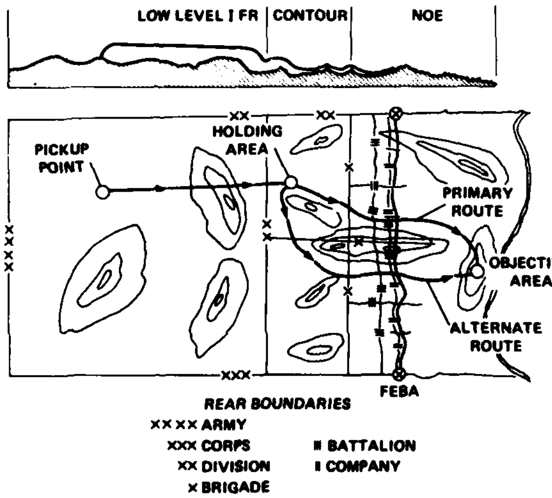


Fig. 3. Mission profile.

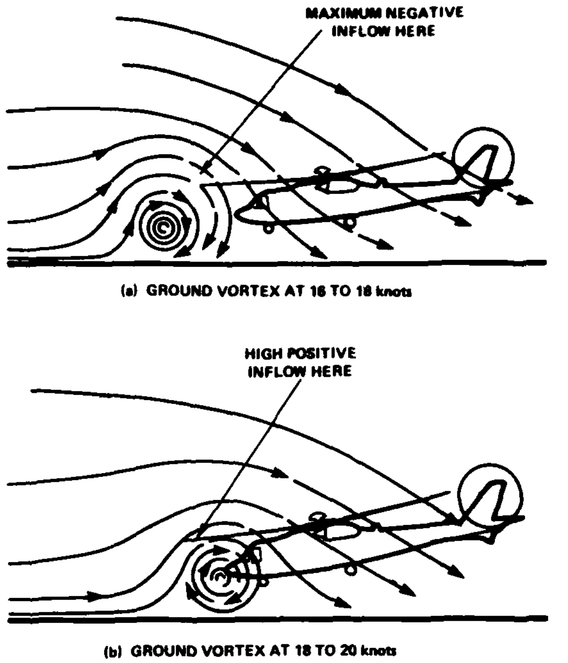


Fig. 4. Helicopter ground vortex interaction (from Ref. 1).

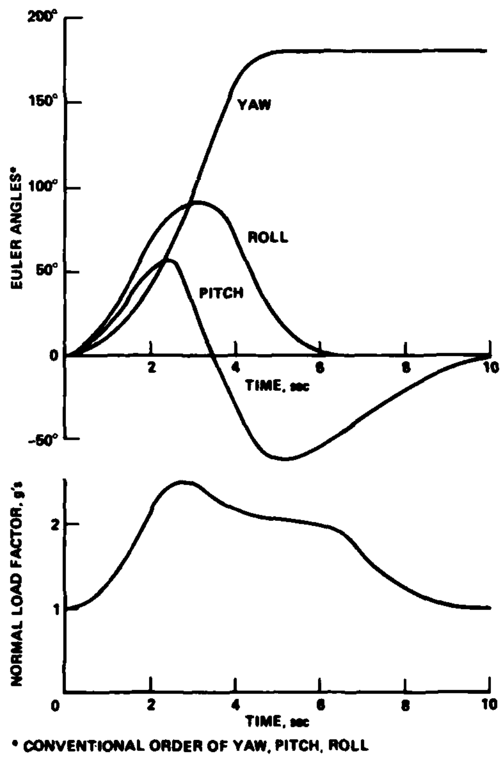


Fig. 5. Time history of an abrupt direction reversal.

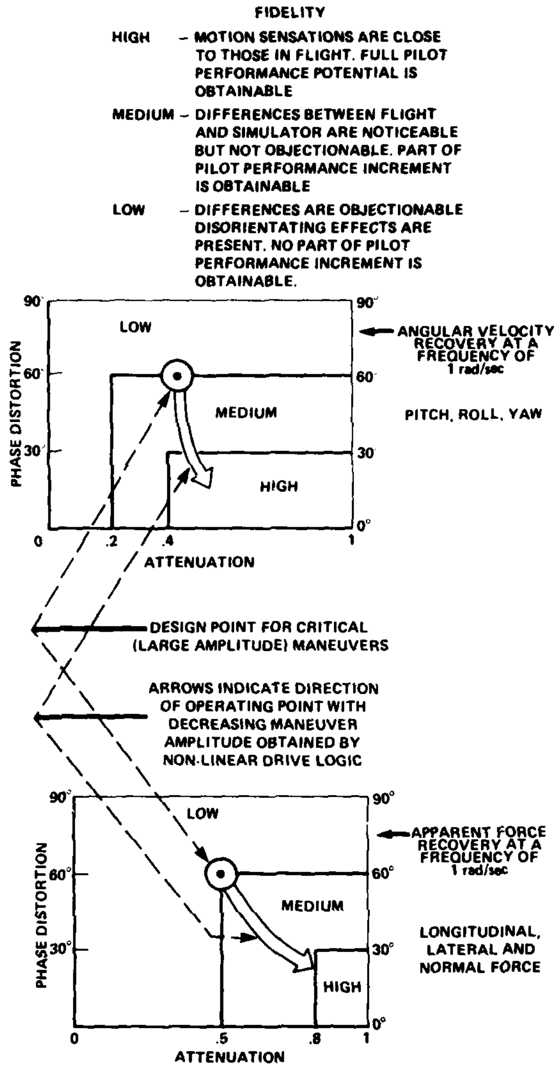


Fig. 6. Platform motion fidelity criteria.

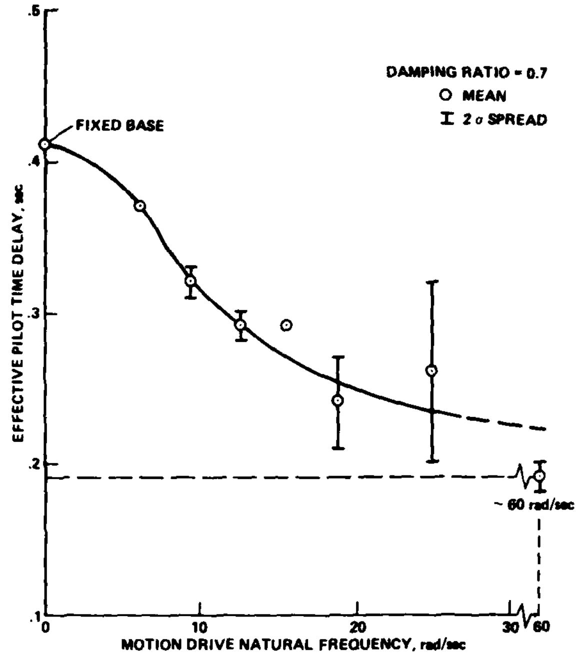


Fig. 7. Effective pilot time delay vs motion drive natural frequency.

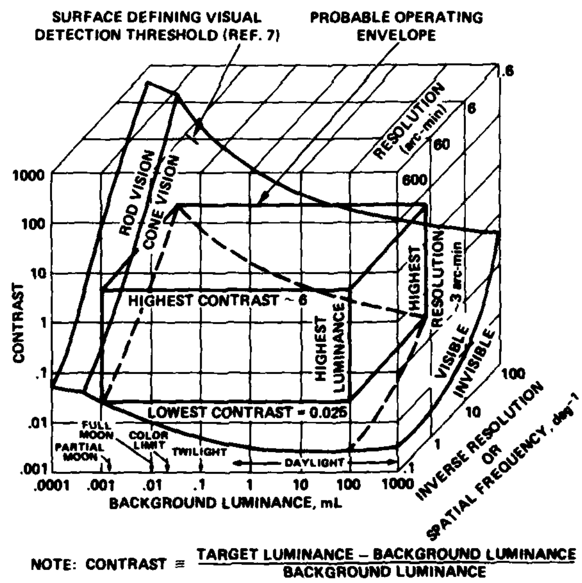


Fig. 8. Visual performance envelope.

Fig. 9. Terrain board detail at 400:1.

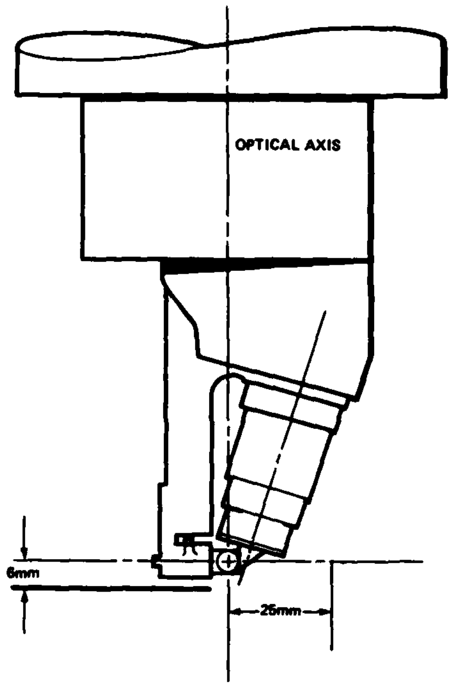


Fig. 10. Outline of 140° probe.

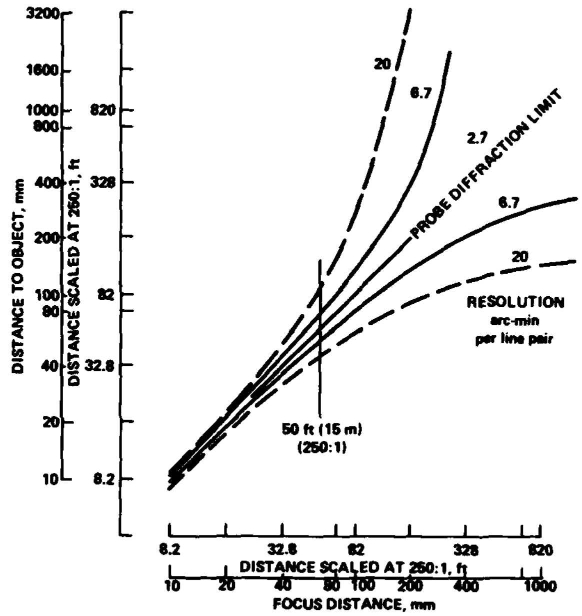


Fig. 12. Probe depth of field vs focus distance.

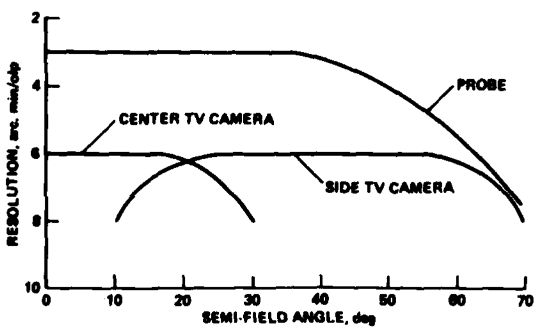


Fig. 11. Limiting resolutions vs field-of-view for probe and TV cameras.

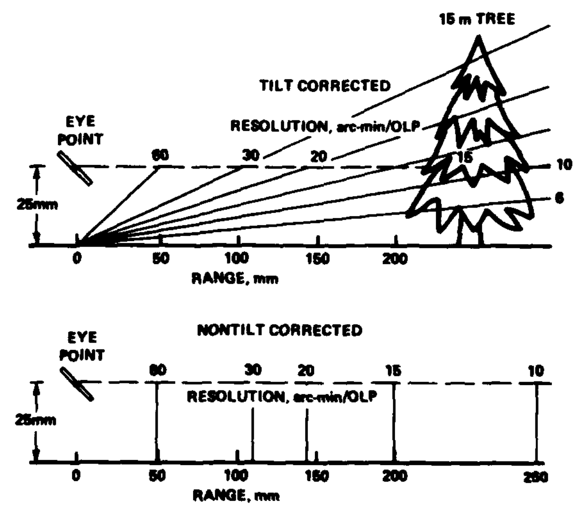


Fig. 13. Effect of tilt correction on resolution vs range and height focus at infinity.

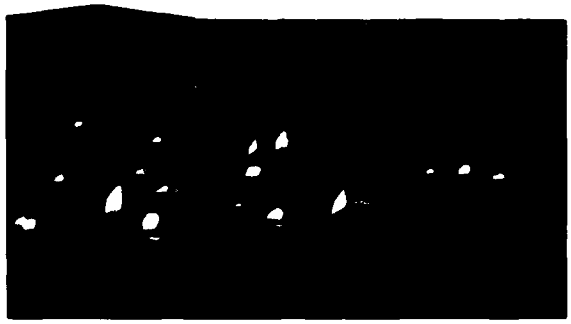


Fig. 14. Detailed CGI scene.

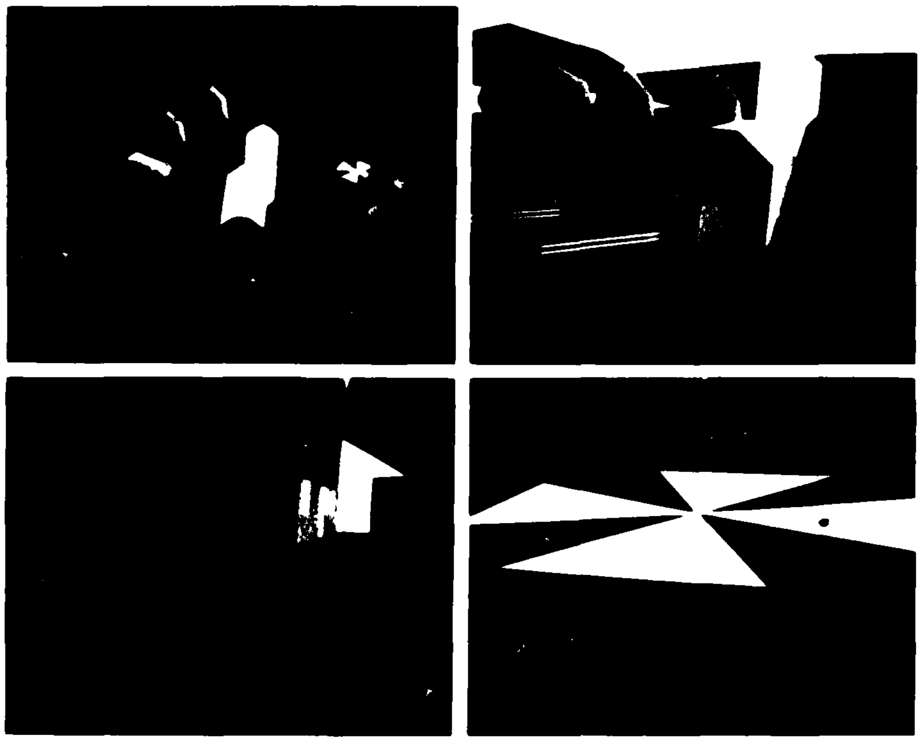


Fig. 15. Reduction in detail as surface is approached.

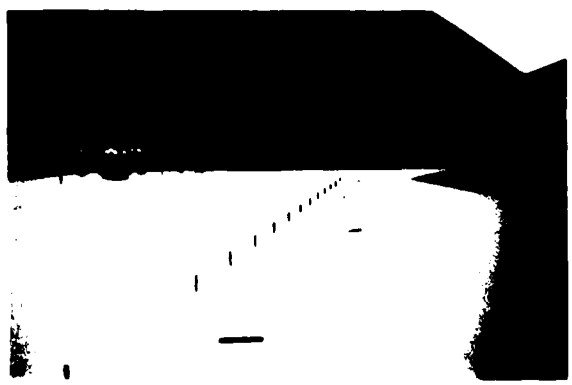


Fig. 16. CGI test terrain.

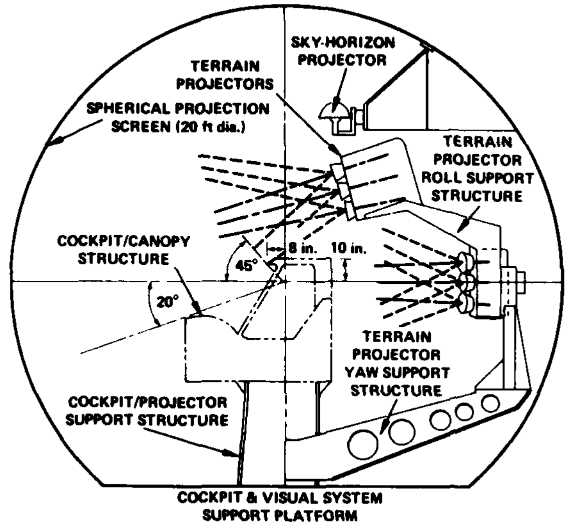


Fig. 17. Display system general arrangement.

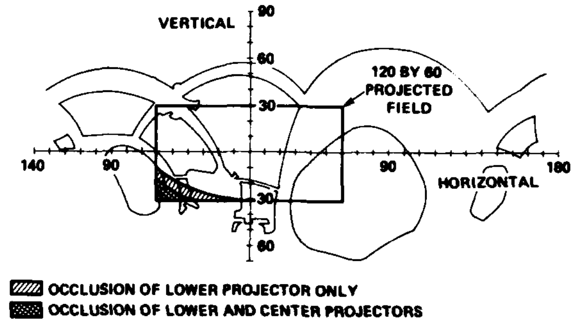


Fig. 18. Occlusion due to cab structure superimposed on field-of-view from OH-6A (right seat).

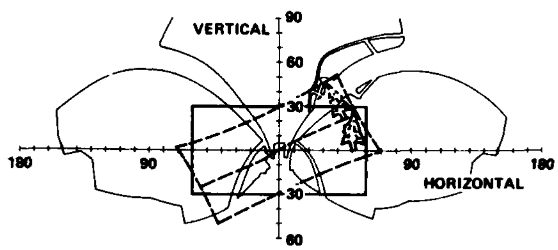


Fig. 19. Effect of display rotation on viewing area (from AH-1G - pilot's position).

ENVIRONMENTAL REQUIREMENTS FOR SIMULATED HELICOPTER/VTOL OPERATIONS FROM SMALL SHIPS AND CARRIERS

BY
LIEUTENANT C. W. WOOMER, USN
ENGINEERING TEST PILOT
ROTARY WING AIRCRAFT TEST DIRECTORATE
NAVAL AIR TEST CENTER
PATUXENT RIVER, MARYLAND 20670, USA
AND
MR. R. L. WILLIAMS
BRANCH MANAGER, MARKETING
SIMULATION SYSTEMS
McDONNELL DOUGLAS ELECTRONICS COMPANY
BOX 426, ST. CHARLES, MISSOURI 63301, USA

SUMMARY

Helicopter/VTOL operations from ships create demanding flying qualities and performance requirements. The environment in which takeoff and landing evolutions must occur has a significant influence on these tasks. Aircraft and simulator designers, each in their own way, must make appropriate provision for environmental factors, such as visual landing aids (VLA), ship motion, turbulence, relative wind, and ground effect.

The unique characteristics of a helicopter combined with the shipboard operations of a naval environment have been successfully simulated in Device 2F106, the SH-2F Weapons System Trainer (WST). It is equipped with a VITAL III computer-generated image (CGI) calligraphic visual system. The development and validation of this device have provided valuable experience on environmental requirements needed to perform takeoff and landing tasks from ships. Technical advances in the state-of-the-art of CGI visual systems now offer capabilities which overcome many previous limitations. This permits additional tasks to be successfully simulated, improving the safety and economics of training.

The paper discusses the specific requirements for the simulated environment to satisfactorily provide training for shipboard takeoff and landing. Test techniques to validate trainer fidelity in flying qualities, performance, and environmental simulation are discussed. The specific subject of calligraphic visual systems is extensively covered, including a report on the current state-of-the-art as related to the at-sea environment. Finally, the utilization of a high-fidelity trainer is explored for research as well as for expanded fleet training.

BACKGROUND

SHIPBOARD TAKEOFF AND LANDING TASKS

The future of the United States Navy (USN) will be radically changed by several programs now in progress concerning the dispersal of aviation units on ships at sea. Presently, one or more of six different types of helicopters are operated to some extent from nearly every major USN ship. Fleet introduction of the SH-60B helicopter, commonly referred to as the Light Airborne Multipurpose System (LAMPS MK III), will greatly increase the number of small-deck operations routinely conducted. Research on and development of Vertical/Short Takeoff and Landing (V/STOL) aircraft are now receiving very high priority within the United States Naval Aviation community. The purpose of the V/STOL Type A effort is to determine whether different models of a minimum number of basic subsonic V/STOL aircraft could replace the various existing fixed and rotary wing aircraft. Dispersal of these aircraft on ships other than large aircraft carriers (CV) is a primary goal of the program.

Shipboard compatibility is an important part of the LAMPS MK III program and is generally considered the overriding design goal of any Navy V/STOL proposal. Static interface in the form of deck structure, rotor and airframe clearance, VLA, navigation aids, etc., is formally inspected and requires certification. This certification of a specific ship is categorized, depending on the facilities provided, into one each of three levels and seven classes for a specific helicopter type. The Naval Air Engineering Center (NAVAIRENGCEN) performs this comprehensive evaluation. Highlights of the aviation facilities ship helicopter certification program are contained in reference 1.

Static interface provides only a portion of the overall ship/aircraft integration. After certification that a ship can accommodate and service an aircraft, a second phase of tests is required. Dynamic Interface (DI) is the determination of the specific launch/recovery capabilities of a particular helicopter and ship combination in the at-sea environment. DI is one type of flight testing carried on by the Naval Air Test Center (NAVAIRTESTCEN). This testing is intended to provide a safe operational flight envelope for fleet usage. The cumulative effect of factors such as ship motion, ship-generated turbulence, obstructions, VLA, field of view (FOV), and wind over deck establish the test environment. Aircraft flying qualities and performance are then evaluated in this environment to establish actual takeoff and landing limitations. Test results are published in reference 2 as Launch/Recovery envelopes in terms of ship motion and relative wind velocity.

Real emphasis in the area of helicopter/ship interface in the USN has developed only within the last 9 years and has roughly paralleled the development of the LAMPS MK I and MK III. The decks are small; clearances are often less than 5 feet. The lighting package of the ship provides the only approach and landing aids. There are no automatic approaches, cockpit instrument glide slope indicators, closure rate indicators, nor any heads-up displays. The approach commences in a landing configuration in cruise flight similar to a fixed wing aircraft. A descending, decelerating, constant glide slope angle type approach is employed. Prior to landing, a transition to hovering flight based on visual reference to a moving platform must be made. This platform on a conventional mono-hulled ship is generally in motion in all 6 degrees of freedom. Figure 1 illustrates the pilot's view of the landing area. Personnel acting as landing signal directors provide advisory information and with experience can predict ship lull periods which provide the best opportunity for landing. Depending on the size and flying qualities of a particular aircraft, it may be held in a hover either just short of the ship or actually over the flight deck. This position is maintained until the quiescent period approaches, at which time the landing is commenced. Vertical landing is required within the confines of a 24-foot circle painted on the deck. Once the decision to land has been made, the maneuver is made expeditiously. Exacting positional control must be maintained from initial positioning in the landing area until on deck. The complexity of the task of landing aboard a small ship is documented by the extent of the test and evaluation (T&E) efforts described above for establishment of operating limits.

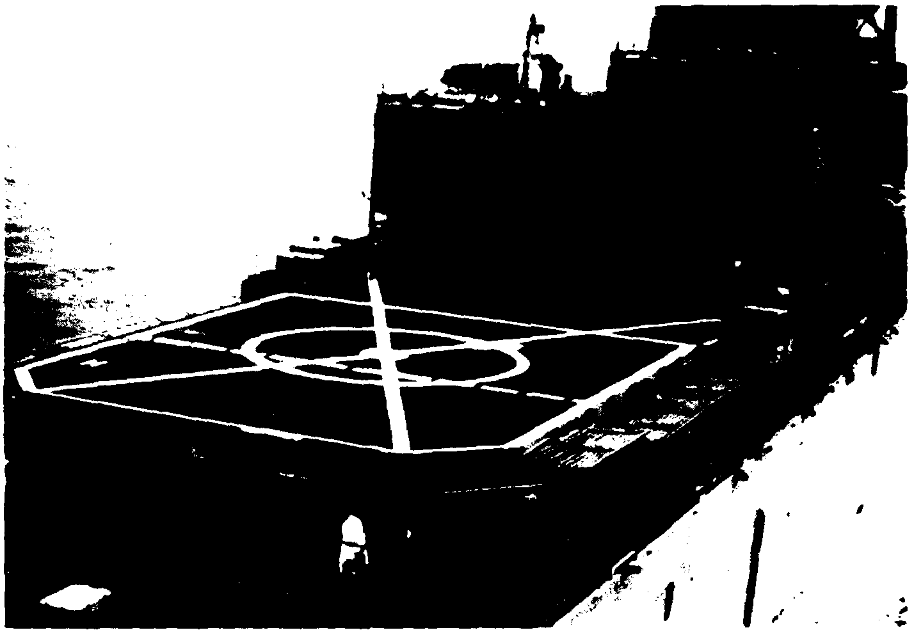


Figure 1
DD-963 from Approach

Research and development of more modern aids to landing aboard small ships are currently being considered as part of the LAMPS MK III and, more especially, the V/STOL Type A programs. Haul-down systems are being considered with designs based on existing Allied operational systems. Improved visual glide slope indicators as well as cockpit-displayed glide slopes are being evaluated. Improved shipboard lighting packages and heads-up displays (including a closure rate presentation) are under consideration. It has even been proposed that a control command system be developed that would permit a completely automatic approach and landing.

The SH-2F aircraft holds the designation as LAMPS MK I. It is presently being employed around the world on USN ships for the antisubmarine warfare mission. As such, it has been the subject of many DI evaluations. Recently, NAVAIRTESTCEN devoted considerable effort to the development and evaluation of a full WST for this aircraft.

Figure 2
2F106 Visual Installation

SH-2F WST EXPERIENCE

The SH-2F WST Device 2F106, presented in figure 2, is the first modern USN helicopter simulator and is intended to provide LAMPS MK I crew training. It was developed for the USN by Reflectone, Incorporated, Stanford, Connecticut. Extensive effort was applied by both the contractor and the Navy on the subject of flying qualities and performance. Technical evaluations of both the aircraft and trainer were conducted by qualified flight test personnel including engineers and test pilots. Flight test instrumentation requirements in the trainer were similar to that of the aircraft. Data were directly compared and used as a basis for establishing flight fidelity.

Subsystems such as motion, sound, and visual add to the simulated environment. The visual system display configuration consists of three units oriented to the pilot with a single forward repeater display for the copilot. The presentation is night-only CGI. In addition to specific Naval Air Stations, scenes include both an aircraft carrier (CV) and a frigate (FF). These shipboard scenes were provided to increase training in tactical operations, including shipboard landing and takeoff. Ships and other tactical targets can be independently maneuvered via instructor control.

The dynamic response of the visual system is of primary concern during target or ground-referenced maneuvers. In a helicopter trainer, the low altitude, low airspeed flight regime is particularly limited by the visual system lag times. These lag times represent the response delay measured between simulator and visual attitude. Simulator computation, data transfer, visual system computation, and display requirements each contribute to lag time. Pilot-induced oscillations and overcontrol are common problems when lag times are a significant part of the dynamic response. This is particularly true in closed-loop maneuvers, such as hover. Lag times in the SH-2F WST are approximately 300 milliseconds and result in reduced training effectiveness in these areas.

The FOV of Device 2F106 is presented in figures 3 and 4. Specific flight testing of this configuration was not accomplished. It was based on a consensus reached between instructor pilots and the contractor, given the apparently obvious factors governing visual system configuration. In particular, the physical mounting area required by the displays was a real limitation on this small cockpit.

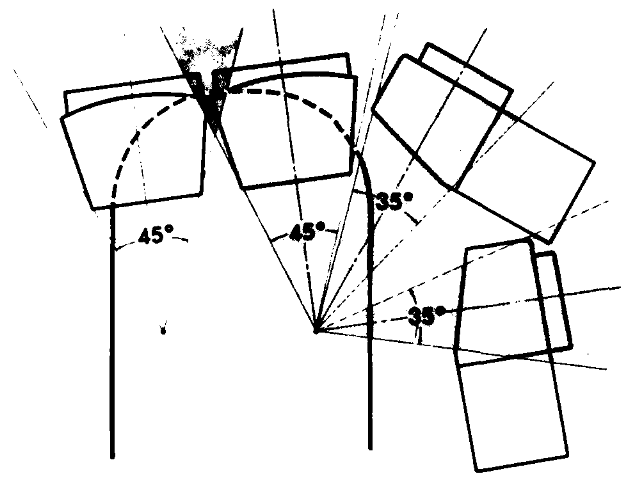


Figure 3
LAMPS SH-2F Display Unit Layout

Scene content was studied and developed in an attempt to construct a reasonable likeness of the aircraft carrier (CV) and frigate (FF). Effective aircraft carrier (CV) presentations had been previously developed for other USN trainers (F-14 and S-3A). The frigate (FF) model was a new development for this program. Significant features of the VLA were provided. The effect on pilot performance (beyond the most obvious requirements) was not necessarily considered in the scene construction. Occultation was not available in this system and, as a result, one surface could not obscure another (i.e., hangar face in front of horizon). Ship motion was programmed; however, no ship-generated turbulence was present. Ground effect was provided, as were engine and rotor sounds and landing gear reactions.

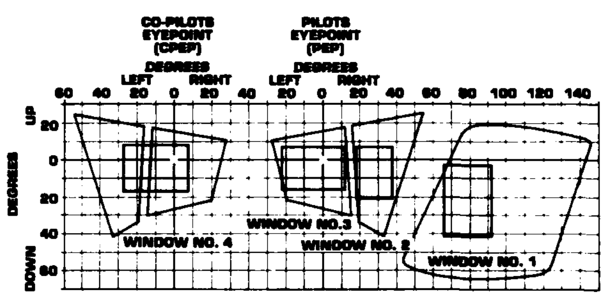


Figure 4
Helicopter Vision Plot/SH-2F
(Cylindrical Projection)

The results of the SH-2F WST development provided significant information on the environmental requirements for meaningful helicopter/shipboard simulation. Up and away flight was enhanced by the visual system. Approach phases of shipboard operations were considered extremely useful for pilot training. Run-on landings to the field and carrier (CV), similar to those accomplished by fixed wing aircraft, were also satisfactory. These run-on landings generally require only forward FOV and are much less dynamic than transition to and landing from a hover. Normal instrument scan, a steady rate of descent and a good lineup accomplished during the approach phase resulted in satisfactory landings. Some overcorrection was required due to an incorrect ground effects model, but this caused only minimal problems. Hover landings ashore or aboard the aircraft carrier (CV) required significantly increased pilot workload. As altitude and airspeed were decreased, greater reliance on visual cues naturally occurred. Although control response fidelity in hover was specifically verified, pilot perception of dynamic response was directly affected by the visual system lag time. The limited FOV was found to be insufficient in look-down angles, both forward and laterally. Lack of lateral reference resulted in increased pilot workload and overcontrol during low speed flight and hover. However, large area targets, such as the flight deck of the aircraft carrier (CV), allowed visual reference to distant features. Excessively strong ground effect, a discrepancy in Device 2F106, added to pilot workload. Successful hover landings could be accomplished, although increased pilot workload and compensation were required.

During frigate (FF) approaches, visual reference was lost as the deck edge was crossed due to trainer FOV limitations. From hover height of 15 feet over the deck, no appreciable amount of the flight deck could be seen. Minimal assistance was provided by the hangar face, due to its lack of texture and detail, and the transparency of the superstructure resulting from the lack of occultation. Positional reference to the simulated ship was not reasonable once the deck edge was crossed. As a result, training in frigate (FF) landings was not recommended for the SH-2F WST. Shipboard landing is a major portion of LAMPS training and is a highly desirable capability for the simulator, yet it had to be removed from the planned training syllabus.

DEVELOPMENT OF CALLIGRAPHIC VISUAL SIMULATION

The use of computers to produce a visual scene for airline pilot training is now starting its seventh year. In that short time, CGI visuals for flight simulators have almost completely supplanted every other type of equipment being ordered by the airlines and by the military. In fact, they are now being purchased as outright replacements for some of the older television model board and film type systems. Relatively low acquisition and operating costs as well as flexibility for expanded training capability are the prime reasons for this acceptance.

The visual equipment responsible for this dramatic change comes from a technology usually identified as "calligraphic" - a convenient extension of the word more commonly associated with penmanship, either in its antiquated or its artistic meaning. In computer graphics, the word calligraphic applies to the equipment which makes line drawings on the face of a cathode ray tube (CRT) and the technique employed to convey digital information in picture-like format.

The pilot of a flight simulator equipped with a calligraphic visual system is the object of a delusion. It is deliberate because the value of the equipment resides in the illusion it creates. The real-world illusion achieved by a calligraphic visual system is, in fact, quite good, producing scenes outside the simulator windshields that are very realistic in appearance and geometrically accurate. Pilots accept the illusion enthusiastically.

When the first VITAL II visual simulation system went into service, a little over 6 years ago, it initiated changes into the then-existing philosophies of simulator training which are just now gaining momentum. Being the first CGI visual to be used for training, it eliminated many of the shortcomings of its predecessor systems. In spite of the night-only characteristic of this system, which displayed lightpoints only, the U.S. Federal Aviation Administration (FAA) officials authorized the use of VITAL II for commercial airline training. This approval included initial, upgrade, and transition training, as well as proficiency checks to the full extent permitted by the regulation (FAA Parts 62 and 121). The reason given was quite simple: VITAL II presented all of the visual cues desirable and necessary for such training, and these cues were presented more accurately and realistically than with the older types of systems.

Other manufacturers soon joined in. The result is that over 50 of the world's airlines and many military services (see Appendix A) have incorporated systems of this general type and are relying on them heavily for present and future pilot training needs.

The earlier calligraphic visuals, while very realistic, were composed completely of lightpoints on a black background and were primarily useful for approaches to landings rather than to landing itself. When greater attention was given to actual touchdown of the aircraft, a second generation of these visuals was developed. Thus, the systems incorporated textured surfaces to complement the lightpoints. With this surface technique, the runway surface itself with associated paint stripes and markings as well as airport structures was simulated as it would appear under aircraft landing light illumination. It was found that this surfacing capability could also be applied to ship simulation in depicting hull, deck, superstructure, and VLA. Figure 5 illustrates the evolution of the aircraft carrier (CV) scene with these developments. This is the technology chosen by the USN for the SH-2F WST, the first unit of which was placed in operation in July 1976 at NAS Norfolk, Virginia; a second system was accepted at NAS North Island, California, in November 1976. This system, called VITAL III, is the first helicopter application of CGI visual technology. Further developments in calligraphic visual simulation will be discussed in the latter part of this paper.

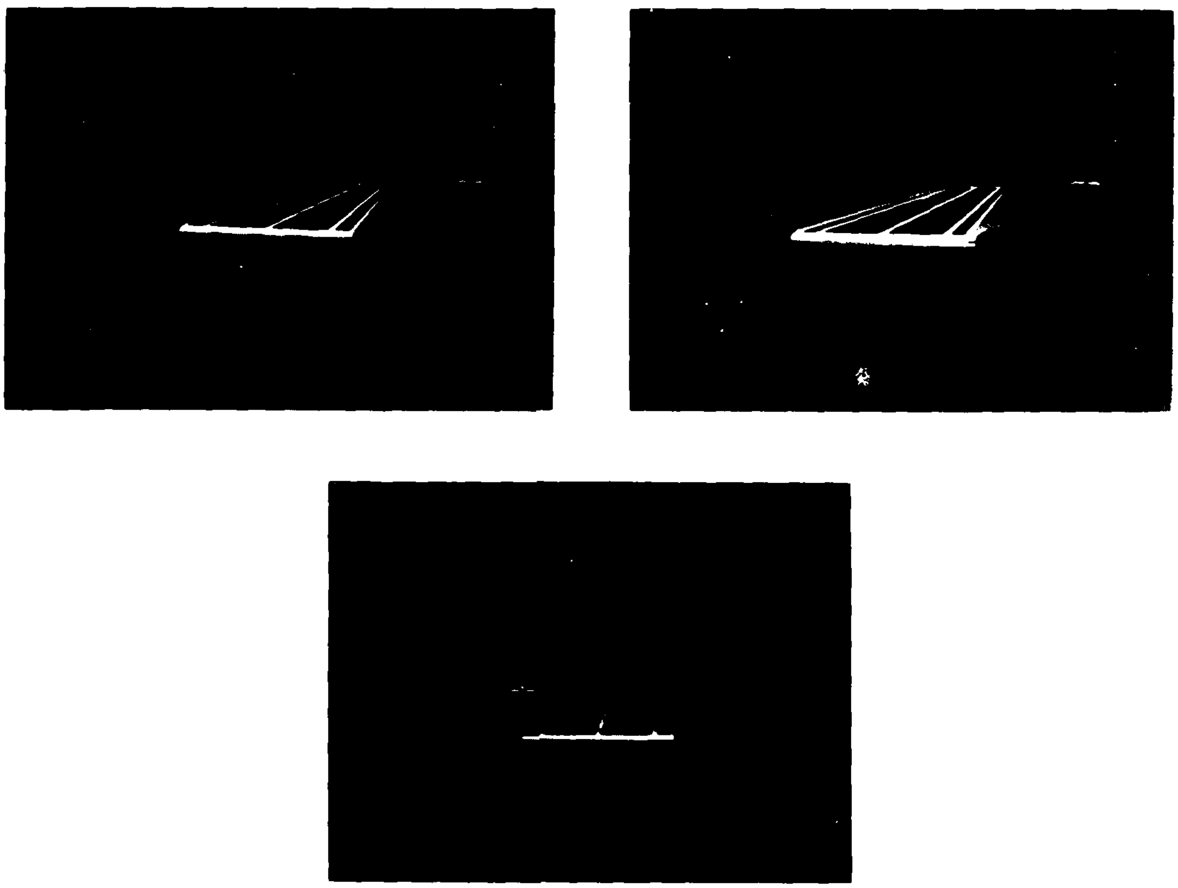


Figure 5
Three Generations of Aircraft Carrier (CV) Scene

REQUIREMENTS

DYNAMIC RESPONSE FIDELITY

Modern trainers are used for extensive tactical maneuvering and high workload closed-loop tasks. If positive training is to result, high fidelity with the actual aircraft is necessary. Reinforcement of learned techniques should be available between the trainer and the aircraft. This is particularly important in high workload tasks where, once learned, responses become nearly automatic. Aircraft limitations based on both flying qualities and performance characteristics are essential pilot cues during maneuvers such as shipboard landings. As such, they are part of the environment confronting the pilot.

VISUAL SYSTEM

The dynamic response of the visual system in an overwhelming factor in its suitability for pilot training. Lags in response, as mentioned earlier, are only tolerable to a maximum of a few hundred milliseconds. Mission relation may dictate sharply reduced maximum tolerable lag times. Prediction routines for attitude changes may be necessary to reduce lag times and have been used successfully. On the other hand, jerky and unstable motion of the scene often result from prediction routines that are forced to excess. This condition may be even more unsatisfactory than the lag time and can be disorienting and even nauseating to the pilot. Visual system dynamic response must also remain in phase and produce full amplitude displacements. Response in all axes must be capable of matching the vehicle being simulated. For example, yaw response in helicopter is much more demanding than that of fixed wing aircraft. Dynamic response is a limiting factor in the suitability of visual system integration for pilot training. However, it is also important to recognize that the visual system will dramatically illustrate basic simulator program weaknesses. Visual systems can be made to accurately track the host program and still not be suitable for training. In this case, modifications to the basic trainer program are required.

The FOV of a visual system is critical to the accomplishment of simulator training tasks. The importance of mission relation to the design cannot be overemphasized. In particular, acceptable fixed wing visual configurations should not necessarily be considered satisfactory for helicopter/VSTOL applications. In general, these trainers should be provided with maximum coverage. For landings on small-deck ships, this is particularly true since the entire deck could be out of view from normal over heights. Selectable, moving, and wide-angle display configurations should each be considered, based on mission requirements. Ultimately, an identical FOV to that of the aircraft is desirable. Until such time as the state-of-the-art can economically provide this capability, a training limitation is being created and optimization of the available FOV is critical.

The term "scene content" encompasses many specific items. A reasonable facsimile of the specific ship is a basic requirement. Detailed representation of the hull, superstructure, and primary obstructions must be provided in proper perspective. The simulation must be an independently moving model within the visual scene. It must be free to move with instructor-commanded changes in course, speed, and sea state. Landing area markings must be provided in exact detail. Floodlighting must be provided in terms of relative intensity and be controllable by the instructor acting as the Helicopter Control Officer (HCO). The entire package of VLA must be presented exactly as installed, including directionality, intensity, position, flashing, strobing, and color. A summary of the existing VLA used by the USN is presented in figure 6. Control of the individual elements of this package needs to be provided for training in degraded mode operation. Relative sizes and locations are critical, since at present the only closure rate cue is the relative "spread" of specific elements of the VLA as the helicopter approaches the ship. Relative sizes are also important to establish proper perspective of the scene. Figure 7 illustrates the frigate (FF) presently used in the SH-2F WST. Surface discontinuity and texturing should be employed to provide improved perspective. Homogenous surfaces, presented close-in and used as primary references, tend to cause a loss of perspective. This is particularly true of "pure" runways and hangar faces when attempting to hover, land, or takeoff. A display nearly filled by a purely homogenous surface provides no cue to movement until the FOV extends beyond that surface. More intensity in scene content concentrated in areas of intended landing is a specific requirement of VTOL operations. Imaginative presentations could result in significant improvement in pilot performance. Additional visual scene requirements should include tactical elements such as independently moving targets consisting of freighters, trawlers, submarines, smoke markers, and sonobuoys.

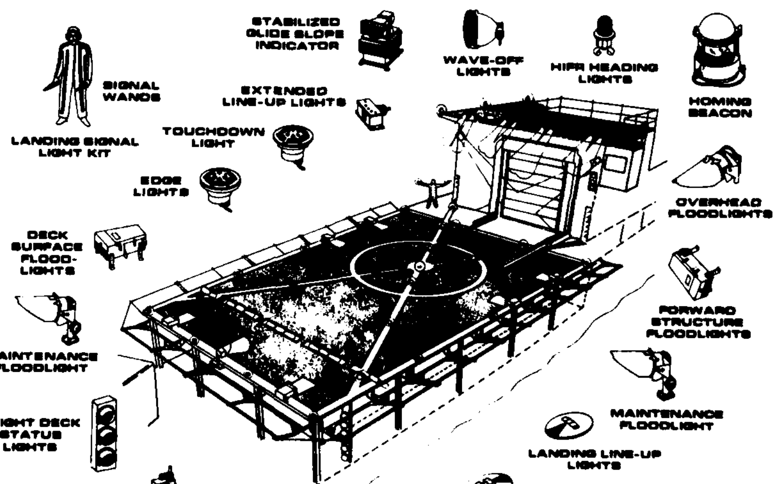


Figure 6
VLA Requirements

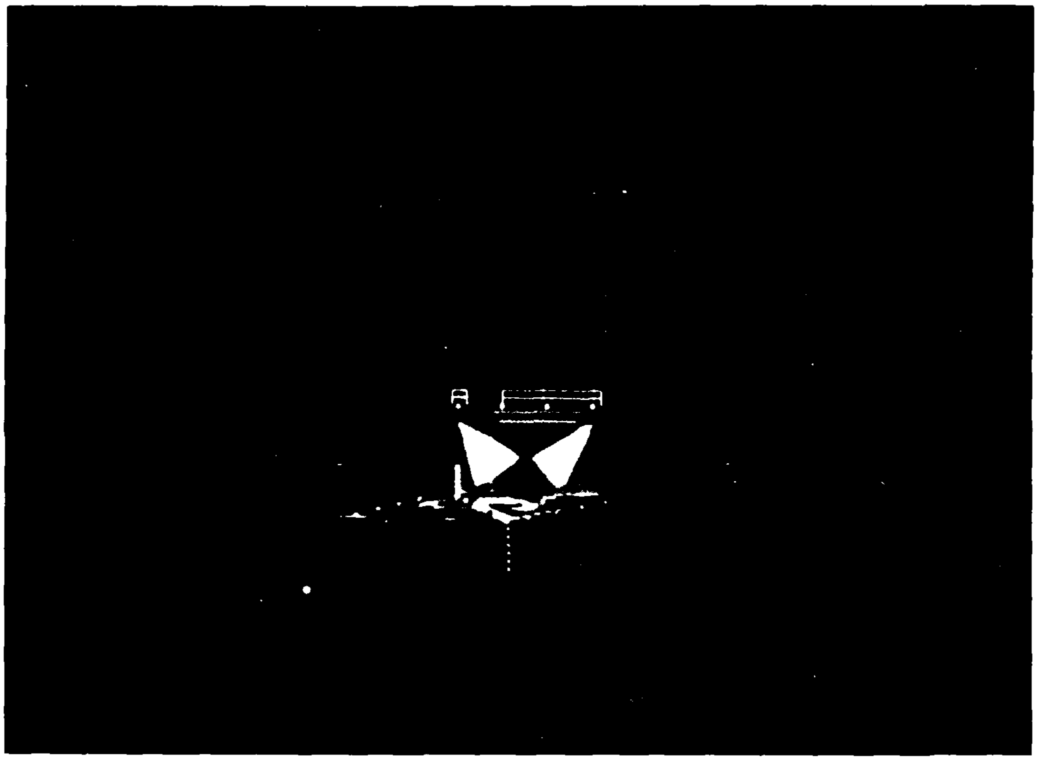


Figure 7
Frigate (FF) Night Scene

Occultation, or the masking of scene content by an intervening surface, could add significantly to the depth and perspective of a scene. In land-based scenes, hangars blocking background cityscapes would add to the sense of motion presently lacking at low altitude and low speed. Aboard ships the requirement for occultation is mandatory. Horizons passing through ships' superstructures are intolerable. The horizon image appears to take precedence over other scene content and relative position to the ship is lost. On systems where occultation is not available, such as that on the 2F106, the impact was considered so great that alternate measures were devised. For work aboard the frigate (FF), a routine was devised in which the hangar face coverage of a specific display unit was monitored. When a specified percentage of the display was filled by hangar surface, the horizon was automatically switched off (in that display only). This artificiality was considered much less distracting than the horizon show-through discussed earlier.

Details of scene content often used in actual flight must be considered objectively in visual design. Ocean surface and ship wakes may be detracting, as presented, and better not included. This is particularly true if no dynamic presentation is proposed. All CGI visual systems, regardless of make, have a limited capability for displaying surfaces and lightpoints. Consideration must be given to actual mission requirements so that this limited amount of scene content is not wasted on so-called "eye wash" or elements that may be nice to have but that do not contribute to training.

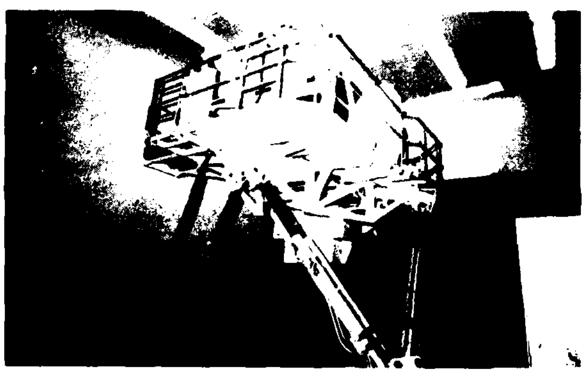


Figure 8
2F106 Motion Base

MOTION SYSTEM

A full 6 degrees of freedom motion system appears to be not only appropriate but a necessity to VTOL trainers. Figure 8 illustrates the type motion base used by the SH-2F WST. Significantly improved pilot performance has been noted with the inclusion of the system. Added cues provided by the motion system seem most helpful in flight at low speed and/or during degraded modes of the automatic flight control system. Emphasis should be placed by the contractor on matching the motion and visual systems response. This is necessary to prevent confusion of the pilot's sensory perception. Particular confusion is apparent when experiencing simulated shipboard motion without the motion system activated and the only cue is that provided by the visual system.

Ship motion models are necessary elements of the at-sea environment. Ship motion is a function of wind, sea state and direction, and relative heading of the ship. During approaches, the effects of ship motion on the VLA presentations are essential for positive training. Expanded experience with the dynamic "sight picture" of the VLA under various conditions is extremely valuable to fleet readiness and could have a direct impact on safety. Final phases of the approach followed by hover and landing are based directly on a visual presentation of ship motion. With the aircraft on deck, ship motion simulation (using visual and motion systems) provides realistic exposure to the environment and allows the introduction to techniques of judging the period and lull of the ship. Proper simulation of landing gear reactions not only are necessary for landings but also for ship motion inputs while on deck. Coordination of the visual presentation is essential to the effective use of a ship motion model. Caution must be exercised not to exceed pilot limitations by attempting approaches and landings in the trainer well beyond those considered safe in actual operations. The modelled enviornment alone creates increased pilot workload. Lesser sea states than operational limits would be expected to require sufficient pilot workload for training purposes.

TURBULENCE

Turbulence models provide a disturbance in the "perfect atmosphere" of simulation. Motion-based trainers have a tremendous capability to introduce disturbances such as atmospheric turbulence and aircraft vibrations. Turbulence should be introduced through the motion system as well as the aerodynamic program to ensure that flight characteristics are not transparent to turbulence. Pilot workload should be increased as a function of turbulence. Visual systems must be capable of withstanding both the actual motion of the platform as well as the accelerations in the aerodynamic program without degradation in tracking performance during aircraft displacement. Another area to be considered is the subject of ship-generated turbulence. This environmental element is one of the primary limiting factors for operational envelopes and is evaluated in DI testing. A turbulence model for a frigate (FF) class ship has been developed. To be complete, it should include sources such as turbine exhausts, sinks such as large air intakes, downflow (commonly referred to as a "sinkhole") in the landing area immediately aft of a large hangar, downwind extension, and variation due to both wind and the dynamics of ship motion. Evaluation of this model is expected to be accomplished on the SH-2F WST following scheduled improvements to the visual system.

RELATIVE WIND

The computation and results of relative wind should be included in any shipboard simulation effort. Opertional envelopes produced from DI testing are presented in terms of relative wind. A detailed description of this phenomena is available in reference 3. Ship maneuvering with respect to the true wind must produce a shift in relative wind. This shift should be observed in the cockpit according to the peculiarities of the specific pitot-static system. If accurately modelled, the flying qualities and performance involved with takeoff and landing should vary with respect to the relative wind vector. Also, aircraft attitude required to track the approach path should vary as a function of the wind vector. Again, trainer launch/recovery conditions should not necessarily be selected at the extremes of the real envelope since equivalent workload will undoubtedly be achieved at lesser values.

GROUND EFFECT

Ground effects on flying qualities and performance are very significant in helicopter and V/STOL aircraft. The interrelationship of flying qualities and performance is inseparable in the low altitude, low speed flight regime. Fidelity in the ground effect model is essential if takeoffs and landings are to be accomplished in the trainer. In helicopters, natural reduction in rate of descent is provided by ground effect. For instance, if the ground effect is significantly stronger than it should be, ballooning may occur when close to the surface. Pilot reaction would be overcontrol with collective. A secondary result of this excessive vertical motion and collective movement could be coupled reactions in other axes. During shipboard operations, ground effect may be entered abruptly as the aircraft crosses the deck edge. In other types of VTOL aircraft, various ground effect phenomena may occur, including an increased rate of descent. Whatever the effect, the specific characteristics of this phenomena are essential elements of the environment.

SOUND SYSTEM

Sounds in present helicopters are primary cues of the status of engines and dynamic components. Commanded and uncommanded variations of the power train are normally detected initially by sound cues. For that reason, sound simulation is a basic element of the simulated environment. Pilot performance has been observed to improve with the addition of sounds driven by engines and rotor. Other sound elements which contribute to the environment are realistic sidetones for Intercommunication System and radios, background transmissions on recognized frequencies, such as approach control, and standardized controller transmissions.

TEST TECHNIQUES

FLYING QUALITIES AND PERFORMANCE

Aircraft flight test data must be used for references to establish the fidelity of a trainer. This type of data has become known as criteria data, which is in addition to the design data required by the contractor at the earliest stages of system layout. In a manner very similar to actual aircraft testing, the trainer should be evaluated by qualified flight test personnel. Additional aircraft testing may be required specifically for the development of criteria data. Standard flight tests and techniques apply in most cases. Some unique test methods may need to be developed to compensate for the lack of a visual reference as an example. This effort should precede any attempt at visual system integration. A result of validation of basic program fidelity is the simplification of the task of visual system integration. Later, after visual system validation, specific improvements to the basic program can be accomplished using the visual system as an evaluation tool. A typical data comparison is presented in figure 9. A paper on the subject of technical evaluation of helicopter trainers was published as reference 4.

MOTION SYSTEM

Motion systems are tested by the contractor with proof loads and accelerometers during assembly. This is a substantiation of the algorithms inherent to the design and the physical response capabilities of the hydraulic actuator system. Research is presently being conducted at Naval Training Equipment Center on the optimization of these algorithms which vary with each contractor. It is possible that several optimum programs are required, depending on the type of aircraft: conventional fixed wing, single main rotor helicopter, tandem rotor helicopter, V/STOL, etc. Further T&E should be conducted on the motion system. Specifically, the motion response should be compared with both control inputs from the cockpit and simulator aerodynamic response. Linear accelerations at this pilot's station as well as angular accelerations are required data for both aircraft and trainer. Particular attention should be paid to lag times and any differences between simulator program dynamics and motion response.

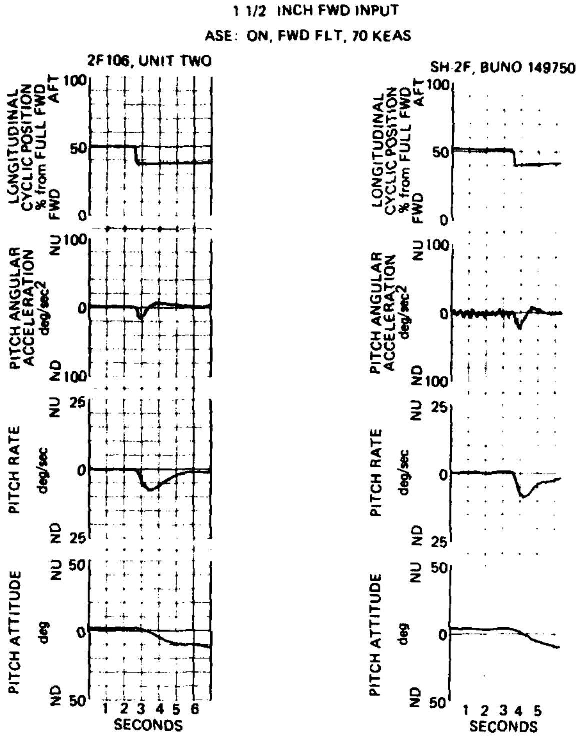


Figure 9
2F106 Flying Qualities Data Comparison

A third discussion while on the subject of motion systems should be that of vibrations. Models of both free air and ship-created turbulence should be based on specific research in those areas. Testing, in addition to the qualitative evaluations, should include analysis of attitudes, rates, and accelerations in each axis while being subjected to these disturbances. Vibrations inherent to the airframe are generally documented and available. Vibration test data should be used as specific criteria data for evaluation and tuning of the trainer. This type of tuning may need to be withheld until the trainer is actually in place and hard-mounted at its permanent facility.

SOUND SYSTEM

The sound system of a trainer is generally qualitatively evaluated. Data from the actual aircraft are provided in the form of recordings. These recordings are analyzed by the contractor to determine the specific character of individual sounds to be generated. Dynamic sounds are cued by other program modules such as the engine and rotor. Radio sidetones are established in the same manner.

VISUAL SYSTEM

The first step in the area of FOV is to determine the exact aircraft FOV available. A unique device, the Field of View Evaluation Apparatus (FOVEA), has been developed by NAVAIRTESTCEN for this purpose. Figure 10 is a picture of this equipment in use. Next, a discussion among the concerned parties, including engineers and pilots, is held to establish several options for display configurations to meet the training requirements. Plots from the FOVEA evaluation, figure 11, are used at this meeting as the background on which proportionally correct display overlays are arranged. The next phase requires the use of an aircraft. Ground tests are conducted by reproducing the proposed display configuration in the cockpit. Amber cellophane is cut to match the configuration and placed on the windows. Blue lens goggles are used by the pilot to cause a restricted FOV identical to that which would be available in the trainer. This setup is established for each potential configuration and evaluated. The purpose of this phase is to reduce the number of potential configurations to be flight tested. Finally, actual flight testing of each remaining configuration is accomplished. Specific mission-related tasks such as approach and landing on a mocked-up flight deck are performed. The result of this T&E effort is a specific design location for each display. In this manner, the capabilities and limitations of the visual system FOV to be installed are well understood. A detailed description of this FOV evaluation is available in reference 5.

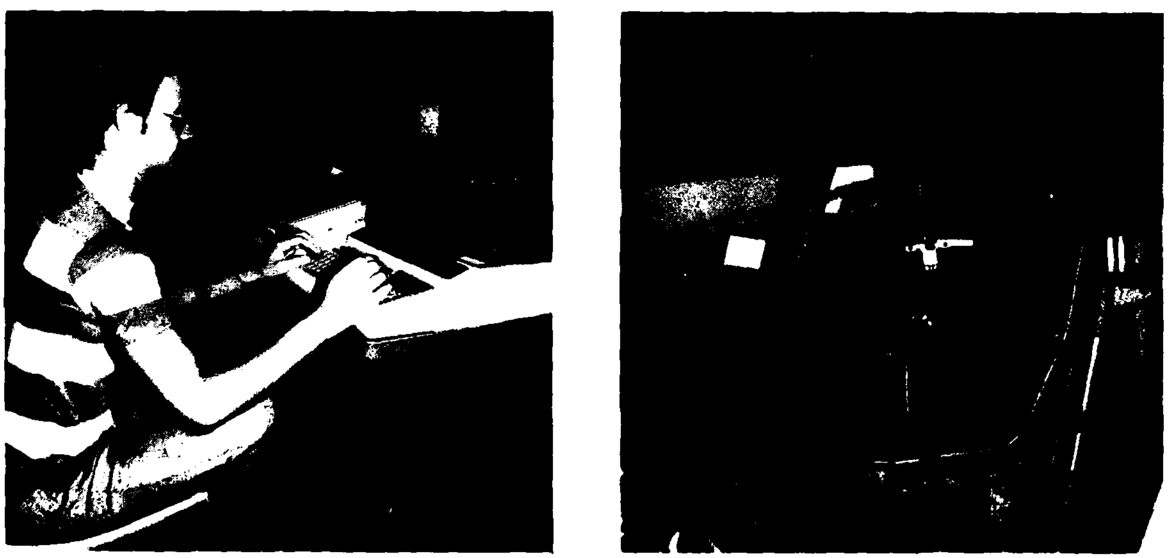


Figure 10
FOVEA Equipment

Once the visual system is in place, the FOVEA can be used to document the actual installed locations. Alignment of the presentation across the several displays must be verified. Again, the FOVEA could be employed. A single straight edge such as the horizon or runway marker should be positioned in the FOV for a reference.

Registration or synchronization of adjacent displays is qualitatively evaluated. Flight through various scenes while performing normal aircraft maneuvers quickly uncovers any problems with registration. The observance of apparent uneven shifting or tracking of adjacent displays is an indication of this problem. A subject for qualitative evaluation is shading of the displays. This is particularly a problem when units are mounted at various relative elevations or rotated 90 degrees from one another. Fixed gradients or computational schemes may have to be altered to present an even presentation across the several displays in the cockpit. This problem is very noticeable when in close proximity to a single homogenous surface such as the hangar face.

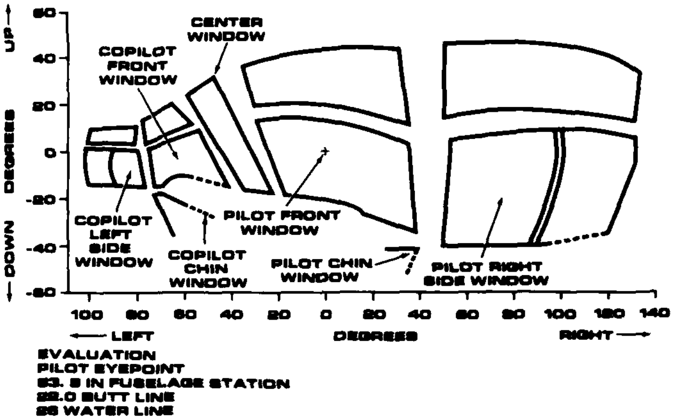


Figure 11
FOVEA Data Plot
CH-46E

The basic qualitative evaluation performed in the past has been extensive flight throughout each scene. The purpose of this type of test is the identification of problems such as misplaced landmarks or the offset of major scene elements such as runways from simulated navigational aids. Various mission-related tasks should be performed to evaluate the effect of FOV and other visual system elements on pilot performance. The effect of scene content can be evaluated during development by interchanging visual programs of various scene intensity and repeating an individual maneuver. The element to be monitored is pilot workload required to accomplish the task. It may be desirable to perform this sort of an evaluation to determine tradeoff considerations, if required, between high scene density in landing areas and the continuation of scene over a larger area.

Quantitative testing of the visual system dynamic response should be accomplished early in the evaluation. Display unit data output is required for this test and must be provided by the contractor for use on-site. It is essential that these data correspond as closely as physically possible to the amplitude and timing of the scene as observed from the cockpit as illustrated in figure 12. Data in the form of time histories of control input, simulator attitude, and visual system attitude should be presented and compared. An example of this data is presented in figure 13. Lag times and amplitudes should be closely evaluated. Predictor routines can be evaluated with this test setup. Response due to control step inputs, reversals, pulses, and mission-related tasks should be analyzed. The procedure should be repeated in each axis. A detailed description of this procedure and its results are presented in reference 6.

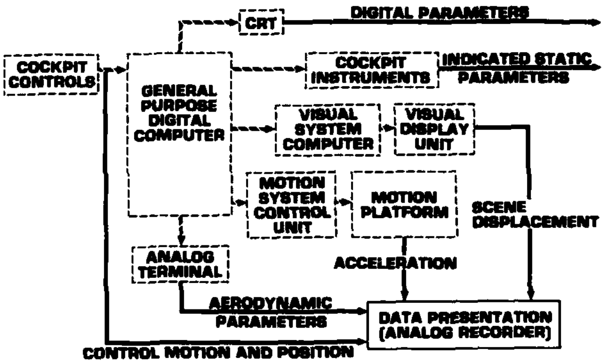


Figure 12
Block Diagram of Test Setup

A geometric perspective test is performed to ensure proper computed perspective of the scene. Calculation should be made to determine where the simulated aircraft should be positioned so that a known scene feature (edge of landing line, etc.) is exactly even with the edge of a display. This evaluation should be repeated for each display while only aircraft position is altered. The performance of this quick check ensures the proper computation of the scene's geometric perspective in each of the variously positioned display units.

STATE OF THE ART IN CALLIGRAPHIC VISUAL SYSTEMS

The next logical generation of this visual technology is now available. The calligraphic technology extends beyond what most observers had at first thought possible. With it, night scenes of greater complexity than previously produced plus twilight and day scenes are displayed. However, display brightness is limited by the beam penetration tubes utilized, to levels significantly lower than normal day simulation.

Efficient generation of surfaces has been the subject of considerable research. The surfacing device or picture controller is pipelined between a computer and a high-speed, color-graphics display

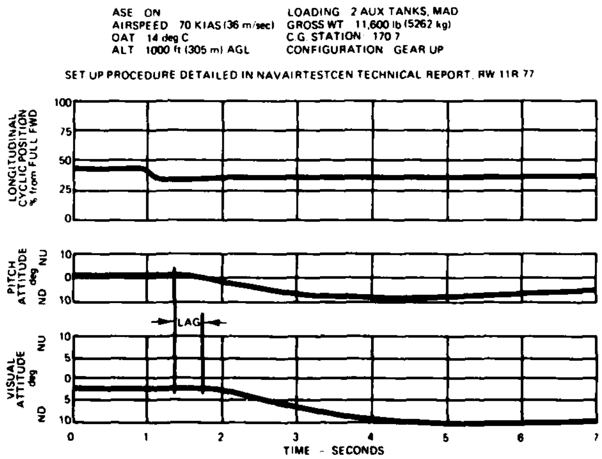


Figure 13
2F106 Visual System Data

unit. The device is designed to generate precision surfaces and lightpoints with minimal computer intervention. The latest generation of calligraphic CGI systems display multicolored day and twilight scenes while retaining the high-resolution characteristics of the earlier night scenes. What results is an imaging device which combines high resolution (unique to the calligraphic system) and high detail.

This new generation of calligraphic visuals promises to offer many additional training possibilities. Its predecessor with display of 2,000 lightpoints and 40 multicolored surfaces is superseded by the increased capability of over 8,000 lightpoints or over 300 multicolored surfaces. Special circuitry has been added to incorporate occultation so that three-dimensional objects appear solid (e.g., nontransparent ships, buildings, and mountains). Occultation is a new capability in the calligraphic system. Because it is new, its ultimate effect on scene quality is not yet fully understood. It will likely receive considerable attention and be part of the basis for future training applications.

This significant increase in quantities of surfaces and lightpoints will directly benefit programs involving the simulation of the ship/sea environment. It is anticipated, in fact, that an increased capability to 6,000 lightpoints (VITAL III 6000) will be incorporated into the SH-2F visual system. While only a portion of the frigate (FF) is presently modelled, the whole ship - in much greater detail - may be depicted. More complex detailing of the deck and hangar door will assist the pilot in positioning the aircraft on the landing area. Existing tactical targets presently portrayed by lightpoints may be simulated to the extent that the vessels may be identified as to class or type and by structure identification. The addition of a sea surface and pseudo wake effects offer potential for training in twilight environments. Recent developments can be applied to simulation of more subtle aspects of the environment. Visible fog can be portrayed during restricted visibility conditions. Realism can be added by simulating the reflections of landing lights, anticollision beacons, and aircraft sequencer strobes while transitioning through fog or cloud layers. Visible cloud bottoms and cloud tops can be portrayed while flying below or above the clouds. An example of the latest carrier (CV) scene is presented in figure 14.

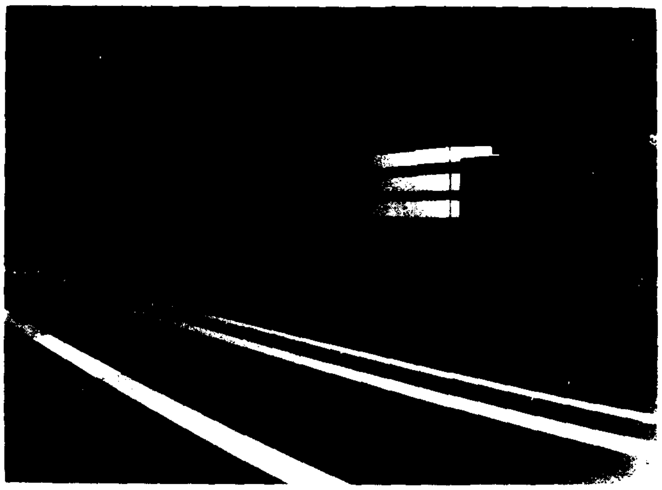


Figure 14
Carrier (CV) Scene

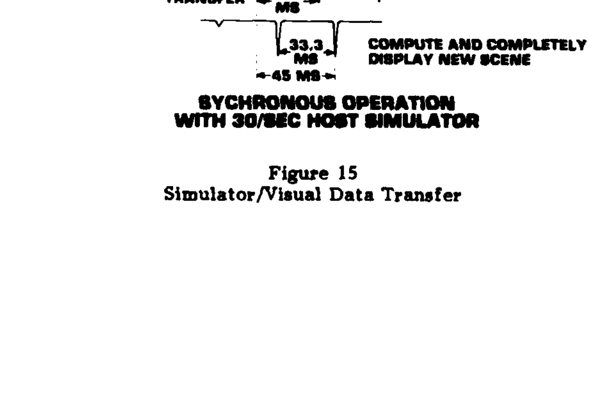


Figure 15
Simulator/Visual Data Transfer

Another of the more important characteristics of newer calligraphic visual system is the capability to dynamically de-focus and focus scene elements under software program control. In unrestricted visibility conditions, this allows perspective growth of lightpoints as they approach the pilot's eye. Along with the accompanying intensity variance, this feature serves to reinforce the pilot's ability to judge distance to scene objects. This de-focus capability also serves to enhance the illusion when visibility is restricted. Runway lights or deck lights obscured properly appear de-focused with a halo effect as they disappear into the fog.

Another result of the improved technology has been a significant reduction in the visual system lagging the host simulator. As discussed previously in this paper, visual lags induce heavy workloads and control problems for the pilot. From the receipt of aircraft positional inputs from the host simulator computer, computation and display of new images are completed in less than 50 milliseconds. It has been found that simulated aircraft with high dynamics such as helicopters and fighter aircraft demand small visual lags in order to fly properly. The first application of the VITAL III update using VITAL IV image generation technology (designated VITAL III 6000) has been proven after incorporation into the U.S. Marines F-4J WST in Yuma, Arizona. The total transport lag, as represented in figure 15, has been demonstrated to be less than 50 milliseconds. Prediction compensation has not been required or utilized.

In the past, gaming areas or environmental data bases have been restricted to finite areas. Airport scenes consisted of one data base, and other airports or ships were located on separate data bases. Flying from one airport to a ship, for instance, consisted of a takeoff and flying away from the modelled area and selecting the new data base, whereupon the display went blank for a period of time while the new data were loaded. New data base manipulation now permits display of contiguous areas of modelled scenes to automatically be loaded in real time from magnetic disc storage. It is now possible to fly uninterruptedly from shore to ship and return to alternate bases if desired.

Easier semi-automated methods of environment data base construction have been developed to complement the increase in surface and lightpoint capability. Reduction of map data to computer data base format can be accomplished by direct map digitizing. The map is affixed to a map digitizer tablet and with the use of a cursor device, the coordinates of map objects are directly transferred to the computer and compiled. Manual reduction of coordinates or extensive use of a keyboard/printer to construct an environment data base is no longer required. Alternative methods have also been developed where an environment can be modified from a CRT in a background mode while normal training continues in a fully interactive conversational mode. These devices should encourage user personnel to exercise the capabilities of the system to a greater extent.

FOV extension is the subject of much development work in visual systems today. The standard VITAL visual display, figure 16, used in the SH-2F LAMPS system has a total FOV of 45 degrees horizontal by 35 degrees vertical. Other display configurations are available to extend the FOV. Modules are available which edge register with only a 1 degree gap. Another configuration consists of two CRT electronics assemblies viewed through one optics unit, figure 17, resulting in an uninterrupted 89 degree by 35 degree FOV. Yet, another display developed for the Royal Swedish Air Force JA-37 consists of three displays arranged in a narrow gap configuration around the pilot with three continuous channels of imagery. Each display channel is 45 degrees horizontal by 60 degrees vertical.

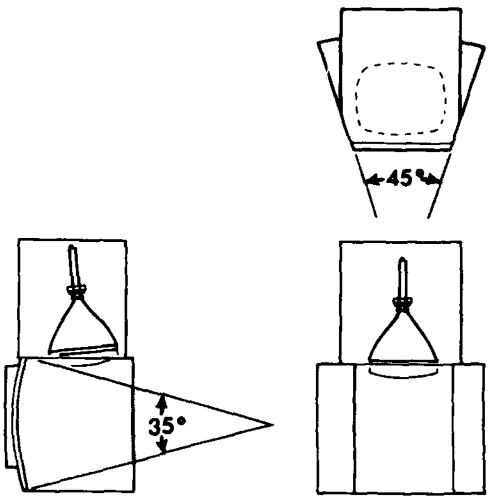


Figure 16
Basic Display Unit

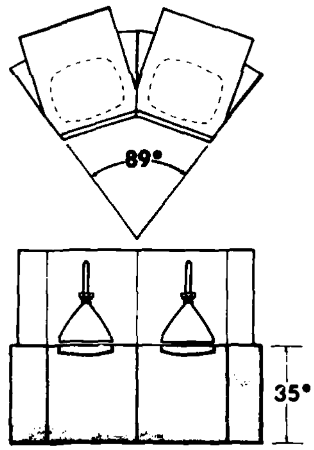


Figure 17
Optional Display Configurations

UTILIZATION OF HIGH FIDELITY TRAINER

TAKEOFF AND LANDING TRAINING

The most often repeated justification for flight simulators is reduced cost of operation. Costs of aircraft and fuel have escalated to the point that actual flight time is being reduced even with the realization of reduced readiness. For simulators to provide this replacement training, high fidelity trainers are required. As part of predeployment training, the simulator should be used heavily for tactical training. A second area for concentrated training and exposure is that of shipboard approaches, landings, and takeoffs. Practical training should include various failure modes of the VLA and could be expanded to include judgment training for winds, ship motion, aircraft failures, and diversion criteria. The provision for this type of training prior to deployment would greatly increase the experience and capabilities of the pilots at sea. Safety would be expected to improve as a function of the added experience. High training transfer is a must in this critical area. Caution must be exercised not to permit any form of negative training that might lead to undesirable procedures or habits.

Of course, the principal usage of the trainer is for initial training in the specific type of aircraft. In this situation, the trainer receives a less critical review but the requirement for high fidelity is no less important. The quality of training can significantly improve and the time required to achieve a desired level may be shortened.

RESEARCH AND DEVELOPMENT

Because the simulator is validated and manned (rather than a computer model), the training device becomes a valuable research and development tool. In some investigations a fleet trainer such as the SH-2F WST may be of more value than a dedicated research device because of its documented fidelity. Also, a direct comparison with existing fleet performance is provided. Evaluation of modified VLA for example may be more economically and efficiently performed on the simulator. Reduced cost, less logistical support, more controlled tests, more timely results, and better test conclusions are a few of the potential gains made possible by use of the validated flight trainer. It is not suggested that simulator usage replace actual aircraft outfit and trials - but preliminary investigations performed in the trainer should be used to reduce the scope of and more efficiently prepare for actual flight evaluation. Improved safety in T&E efforts is to be gained by prior buildup in validated flight trainers. This concept is presently in use at NAVAIRTESTCEN wherever possible.

CONCLUSIONS

The future of the USN, as presently envisioned, holds a significant expansion of small aviation units dispersed among numerous small deck ships. Present helicopter operations, particularly in the LAMPS community, have established the groundwork from which this future will be developed. Training levels required to operate in this demanding environment are high. Safety must remain a key element in these operations if combat effectiveness of our crews and aircraft are to be maintained. Flight simulators have become widely accepted for maintaining pilot proficiency and providing tactical training. Those trainers that have been properly validated and show a high level of fidelity with their design basis aircraft have been most successful at establishing a high level of training transfer. Now high fidelity trainers equipped with sophisticated motion and visual systems are technically capable of even greater effectiveness. Helicopter/VSTOL operations from small deck ships are possible. However, the depth of simulation must include numerous environmental factors such as turbulence, ship motion, and VLA. Of particular importance is the fidelity of the visual system. It must be extremely high in areas such as dynamic response, FOV, and scene content. These continuing improvements will generate increased fidelity, higher quality training, and eventually the ultimate goal - increased effectiveness and safety in the operational environment.

REFERENCES

1. Naval Air Engineering Center, Certification Program, May 1976, NAEC-AWS-656.

2. Office of the Chief of Naval Operations, Shipboard Helicopter Operating Procedures, December 1977, NWP 42(C).

3. Kolwey, H., Pinegar, F., LT, USN, Naval Air Test Center, HH-3F Helicopter/ USCGC HAMILTON (WHEC-715) Dynamic Interface Evaluation, Appendix D, Relative Wind Capability Study, May 1976, RW-26R-76.

4. Woomer, C., LT, USN, Carico, D., Naval Air Test Center, A Program for Increased Flight Fidelity in Helicopter Simulation, April 1977, TM 77-1 RW.

5. Yeend, R., MAJ, USMC, Carico, D., Naval Air Test Center, A Program for Determining Helicopter Flight Simulator Field of View Requirements, 1978, TM 78-1 RW.

6. Woomer, C., LT, USN, Carico, D., Naval Air Test Center, Flight Fidelity Evaluation of the SH-2F Weapons System Trainer, Final Report, March 1978, RW-11R-77.

7. Handberg, G., McDonnell Douglas Electronics Company, Advanced CGI Visual Technology Reshapes Pilot Training Possibilities, ICAO Bulletin, April 1977.

RELATED DOCUMENTS/REFERENCES

Naval Air Systems Command, Helicopter Facilities Bulletin No. 1C, 31 March 1976, NAEC 91122.

Lineback, H., LCDR, USN, Parkinson, R., LT, USN, Naval Air Test Center, American Helicopter Society, Helicopter/Ship Interface Testing, May 1972, Preprint No. 650.

Kolwey, H., Coumatos, M., LT, USN, State-of-the-Art in Non-aviation Ship Helicopter Operations, Naval Engineers Journal, April 1975.

Fortenbaugh, R. L., Naval Air Development Center, NAVTOLAND Simulation Coordination: Assessment of and Plan for Utilizing and Improving Existing Simulation Capabilities, 1977, NADC-76404-30 (Prelim).

Vorst, C. J., McDonnell Douglas Electronics Company, "A New Visual Simulation Technique for Pilot Training," Proceedings of the Ninth NTEC/Industry Conference, of November 1976.

Ricard, G. L., Norman, D. A., and Collyer, S. C., "Compensating for Flight Simulator CGI System Delays," Proceedings of the Ninth NTEC/Industry Conference, of November 1976.

Kraft, C., Elworth, C., and Anderson, C., Boeing Aerospace Company and Allsopp, W., Boeing Commercial Airplane Company, "Pilot Acceptance and Performance Evaluation of Visual Simulation," Proceedings of the Ninth NTEC/Industry Conference, of November 1976.

Gum, D. R., Albery, W. B., Air Force Human Resources Laboratory, Wright-Patterson Air Force Base, "Time-Delay Problems Encountered in Integrating the Advanced Simulator for Undergraduate Pilot Training," Journal of Aircraft, Vol. 14, No. 4.

AGARD, Approach and Landing Simulation, October 1975, AGARD R-632.

Tuttle, R. M., Kaman Aerospace Corporation, American Helicopter Society, A Study in Helicopter Behavior on Small Ships, May 1975, Preprint No. 983.

MILITARY USERS OF CALLIGRAPHIC COMPUTER GENERATED VISUAL SYSTEMS

U.S. Navy	U.S. Air Force
F-14A	A-7D
F-4J	A-10
A-6E	C-5A
EA-6B	C-141
SH-2F	F-4E
S-3A	F-16
E-2C	C-135B
P-3C	T-37
	T-38

Royal Swedish Air Force

JA-37

Royal Saudia Air Force

C-130

Canadian National Forces

CP-140

PROPOSED ADVANCEMENTS IN SIMULATION OF ATMOSPHERIC PHENOMENA FOR IMPROVED TRAINING

William J. Allsopp
Senior Engineering Test Pilot &
Senior Instructor Pilot
The Boeing Company
P.O. Box 3707
Seattle, Washington 98124

When we in the U.S. were preparing to produce a supersonic transport, the crew training was conceptually a "Zero Flight Time" program, emulating the astronaut training but initially requiring a single check ride in the airplane. This program became the model for crew training for the 747 and subsequent wide-body jets.

Obviously, flight simulators became the major training vehicle and the desire to reduce in-airplane training became the driving force to obtain better flight simulator visual systems. As the result of both commercial and military applications, major advancements were made in simulator visual systems, resulting in commercial use of the various electronically generated visual systems.

To break the "Zero Flight Time" barrier further advancement in visual simulation is necessary to provide realistic cues for approach, landing, rollout and taxi with demonstrable positive transfer of training to the airplane. Improvements appear to be required in many areas, such as field of view, resolution, brightness, scene content, lights, visual/motion integration, simulated airplane short-period response, and atmospheric environment. The latter is the subject of this paper.

Designers of closed-circuit television, movie projection and electronically generated systems have addressed themselves to simulating weather phenomena with reasonable success, but are lagging behind the requirements imposed by the steady technological advances of the airplane manufacturers who have airplanes flying with systems which provide a fully automated landing to a full stop with a rollout guidance system in weather conditions giving only a runway visual range (RVR) of 150 feet (46 meters). New training requirements imposed by FAA also will be forcing further visual system environmental development.

In the past, clouds and fog have been presented as a blockage of the pilot forward view much like using a hood in an airplane. Breakout at the cloud base has been sharp edged with unlimited visibility below clouds. Fog was presented with no degrading of visibility out to the assigned limit and was best described as "curtain fog." Electronically generated clouds and fog do provide more realistic cloud effects with a density gradient that gradually occludes the terrain features. Under CAT-II or CAT-III minimums the effect can be surprisingly real.

Inherent in most day/night visual systems is the inability to provide realistic light effects in extremely limited visibility. In the real situation on final approach, strobe lights reflecting on water droplets cause "blooming" in clouds or fog; while the nearest approach, runway or touchdown lights can be seen through the fog. These desirable low-visibility cues are non-existent in most systems. If the luminous intensity of the clouds is reduced, permitting the lights to be seen, other bright objects can cause ghost images, particularly in dusk or night scenes. During development of the Boeing Day/Night Computer Generated Image Visual System (CGI), pilots were seen to make approaches using a ghost image of a fairly bright concrete runway as an alignment cue. Careful programming was required to prevent object luminance intensity from exceeding that of the clouds. This did not permit a density gradient to give the desirable realistic light effects.

In order to receive FAA approval for complete CAT-II training with the Boeing CGI System, a special daytime data base with CAT-II marking and lights was programmed with high contrast between the runway and touchdown lights. The size of these lights was also increased for the first 3000 feet (914 meters) of runway.

The display for the Boeing visual system uses a CRT, beam splitter and infinity mirror. In day scenes the luminous intensity of the fog and scene are reduced by a factor of four by the beam splitter, resulting in a luminous level of six-foot lamberts, a new minimum for a true day scene. Reducing the luminous intensity of the fog to allow the desired light or object to exceed brightness of the fog and become visible moves the overall intensity toward that of dawn and dusk and away from daytime luminances. These limitations make CGI/beam splitter display systems just barely acceptable for daytime CAT-II minimums of 100-foot altitude (30 meters) ceiling and 1200-foot (366 meters) RVR. Lower weather minimums are less acceptable for training as lack of bleed-through of lights can become even more unrealistic.

These problems emphasize the need for careful programming of the cloud, light and object luminous intensities in present systems. They also demonstrate the desirability for developing a visual system with greater display brightness.

Some existing visual systems have only one visibility control and others also have a Runway Visual Range (RVR) control. The Boeing system has both. The selected visibility is always originated at the altitude of the cloud base (which is variable), while the RVR is always at ground level. The resultant visibility then varies linearly from the cloud base to ground level RVR. For a constant visibility at all altitudes, the same value must be assigned both visibility and RVR. This feature permits generation of smog. By assigning the same altitude to the cloud tops and cloud bases, there will be no clouds but the assigned visibility will still occur at the altitude of the cloud base setting with unlimited visibility above this altitude. With a low or zero RVR at ground level, the visibility will now decrease linearly to minimums or below minimums prior to landing, forcing an unprompted pilot decision. This feature also allows a takeoff with good visibility degrading as altitude increases.

Some visual systems permit the instructor to select a visibility from zero to infinity. Many instructor pilots have been observed using unlimited visibility during training. On a night scene this is not too objectionable, but on a day color scene this results in a garish cartoon effect. Electronic generation of the day scene can and does provide realistic atmospheric muting of brightness and color differences, varying with distance in the absence of fog or significant haze. Proper limits should be placed on the instructor's controls to prevent inadvertent selection of inputs which can destroy the realism for the student.

Clouds historically have been generated as a homogenous grey-white scene with unrealistic sharp transitions at their tops and bases, with a single luminous intensity for day and another for night. Rarely does this simulate what the pilot actually encounters. There must be more realistic simulation of other cloud effects vital to pilot decision making.

Use of a texture generator could provide an apparent uneven cloud top sufficient to produce a yawing cue. Uneven cloud bases would add realism. Development of a system to generate individual clouds would fill both of these needs.

Individual clouds with variable density could be produced electronically with some sort of arc generator used to draw curves, which would be combined to form a cloud of variable density. The center of each arc would be located about the centroid of the cloud. Another possibility would be to build one or two clouds from polygons and with use of shading give them a rounded appearance. By multipliers the size and orientation could be changed as well as the location to give different-sized clouds randomly located. Together these would form an uneven cloud top or base. By stacking several clouds, thunderheads could be portrayed. Individual clouds may need to be handled in the visual system generation as objects with edge (or polygon) and light priorities.

Scud or broken fog are not in general use. Existing methods of scud portrayal just occlude the display at random intervals for random durations. When used with a low ceiling and limited RVR, the appearance is fairly realistic. Even the instructor does not know whether the transitioning pilot can land or must go around, forcing an unprompted student decision. Of course this simulation of scud is unreal since there are no visible scud clouds; but with the capability to generate individual clouds, scud clouds could be portrayed.

Presentation of rain and snow is desirable. Flight in precipitation can be very disconcerting, sometimes causing disorientation and vertigo. The onrush of snow toward the windscreen along the flight path angle can eliminate all visual roll cues and give only minimal pitch and yaw cues. A special rain and snow generator could be designed to present dark or white particles originating fairly close to the airplane and approaching along the flight path angle at the airplane's true airspeed. It may be possible to use lights, black or grey, as a substitute for precipitation particles.

The need for the above proposed advancements in visual simulation of atmospheric phenomena has been highlighted by the FAA requirement that low level windshear training be added to pilot training and included as part of their flight simulator program. Some training groups are programming downburst and other variable wind conditions into their simulators. The Boeing Flight Crew Training will use windshear models designed by our 727 Flight Technology group and developed on a 727 engineering simulator with a terrain model board, back projected on a flat screen positioned in the forward view of only the pilot. From many wind models tested, Boeing pilots selected six models as having excellent training value, two for takeoff and four for approach and landing. These wind models may be modified as training experience dictates. The data for these windshear models were derived by a Boeing meteorologist from such sources as Craig 1975, Fujita 1976 and Caracena 1975.

These windshear models contain horizontal (headwind/tailwind), vertical (updraft/downdraft) and crosswind components as a function of altitude and ground distance with all winds oriented with respect to the airport ground level.

At a given altitude and ground distance from the runway, the wind components are constant regardless of the simulated lateral location with respect to the runway centerline. All wind components are zero at the model boundaries to allow a smooth transition when flying into the models. All models are 50,000 feet (15,240 meters) long with an altitude limit of 2000 feet (610 meters) above ground.

The two takeoff windshear models are representative of thunderstorm activity located in the airport vicinity and were developed from flight recorder data and surface anemometer measurements recorded during thunderstorm activity. These takeoff models presently originate at the brake release point. Because the liftoff point and climb profile vary greatly with airplane model, weight, flap setting and engine model, the origin (brake release point) may need to be a variable. Otherwise, the performance of some airplanes may result in a takeoff profile that would not encounter the programmed windshear. This location of the origin of the model will be assigned as the windshear models are integrated with each model simulator.

The Single Cell Thunderstorm Takeoff windshear model, Figures 1 and 2, and the Double Cell Thunderstorm Takeoff windshear model, Figure 3, were developed from the same data with a second thunderstorm downdraft region added to simulate flying through two cells on climbout. The first cell is located over the liftoff end of the runway, causing an abrupt change from a headwind to a tailwind with a downdraft. The double cell model introduces a second cell further out on the flight path with a lower tailwind but a larger downdraft.

The four landing wind models were constructed about a normal three-degree approach path originating 40,000 feet (12,192 meters) prior to approach path intercept with the runway and extending 10,000 feet (3048 meters) beyond the touchdown point. The main windshear region occurs at an altitude of approximately 400 feet (122 meters).

The Night Time Stable Layer Landing windshear model, Figure 4, is derived from data recorded near Dallas, Texas. There is no vertical wind component normally associated with these meteorological conditions so wind components are only varied with altitude.

The Cold Front Landing windshear model, Figure 5, is based on typical cold front characteristics. Initially on approach there is a light headwind changing to a tailwind which again changes to a headwind at low altitude. The headwind then decreases with a rather normal gradient to touchdown. There is a fairly strong crosswind which decreases to touchdown.

The Thunderstorm Landing windshear model, Figure 6, is derived from anemometer measurements taken at several heights on a television tower 1500 feet (457 meters) high in Oklahoma as a thunderstorm passed. Initially there is a tailwind which reduces to about zero just past the halfway point on approach; this abruptly changes to a strong tailwind at 400 feet (122 meters) which decays rapidly to become a headwind at touchdown. Simultaneously a strong downdraft occurs following the pattern of the tailwind. A light crosswind is also introduced at low altitude.

The Downburst Thunderstorm Landing model, Figure 7, presents wind component data derived from a streamline flow diagram developed from flight recorder traces, satellite and other meteorological data recorded in and around a severe downburst phenomenon. The downburst is located over the runway threshold, introducing headwind components which abruptly reverse between 400 and 300 feet (122 to 92 meters) to a light tailwind component. At the same time, a downdraft is abruptly introduced following a similar pattern as the headwind component and is zero at touchdown. The crosswind component is from the right and decreases to touchdown.

It is of interest to review the weather conditions listed for these windshear models in light of today's state of the art of electronically generated visual systems. All systems can produce some form of restricted visibility; some can produce smog, none can produce rain or snow, some can locally reduce visibility with scud but not as if passing through local precipitation showers, none in use can portray thunderstorm clouds or even broken clouds, and although some can produce irregular cloud tops and bottoms, they do not have varying ceiling heights.

Downburst weather phenomena have been contributory to several accidents in the recent past with windshear and minimum visibility in precipitation combined with gusts and crosswinds. On a typical approach the pilot flying performs both the instrument approach and the visual landing. He pilots by reference to his instruments until identifiable runway approach features are in view. Then he switches to a visual/instrument scan pattern with a split to approximately 60% inside (instruments) to 40% outside (visual). This ratio gradually changes to almost 100% outside over the runway. In a minimum weather approach he encounters downburst weather, causing several changes in wind vector which may drop the airplane below the normal flight profile with lateral misalignment and loss of airspeed. In attempting to keep the runway in sight, especially in precipitation, the pilot could easily continue to drop too low. Eventually he must visually release the runway and make a go-around on instruments to prevent impacting the ground.

In an effort to improve approach, go-around and landing techniques to lower weather minimums under severe weather conditions, several airlines have gone to a crew coordinated system such that on approach one pilot flies the airplane solely by reference to instruments, remaining on instruments and performs the go-around if required. When the runway is assured, the other pilot takes over and lands.

In order to qualify for CAT-IIIA, Automatic Approach and Landings with an RVR of 700 Feet (210 Meters), the FAA, in Advisory Circular 120-28B, dated 1 December 1977, requires training in the airplane in performing approaches to touchdown and to a go-around. In some airplanes, the airplane may touch the ground during the go-around. I firmly believe this type of qualification is best performed in a simulator.

Training in windshear conditions and to the minimum weather conditions discussed requires more realistic simulation of atmospheric phenomena. Some problems can be solved with careful software data base management, others by computer hardware design and still others by improved display systems.

METEOROLOGICAL CONDITIONS FOR WINDSHEAR MODELS

TAKEOFF THUNDERSTORMS - SINGLE AND DOUBLE CELL

Rain showers in vicinity

Ceiling ragged at 500 feet (152 meters) above ground

Visibility VFR, except ½ mile (0.8 kilometers) in rain

Moderate to severe turbulence

NIGHTTIME STABLE AIR

No precipitation

Ceiling unlimited

Visibility VFR, reducing to 2 miles (3.2 kilometers) in smoke and haze at ground level

No turbulence on vertical wind component

COLD FRONT

Rain or snow showers at or behind front zone with possible thunderstorms

Ceiling - 2000 feet (600 meters) behind front, higher ahead; except less than 1000 feet (300 meters) and ragged in showers and thunderstorms and less than 100 feet (30 meters) in show showers

Visibility - VFR except ½ mile (0.8 meters) or less in rain showers and zero in heavy snow showers

Light to severe turbulence in frontal zone, light to moderate turbulence behind front. Thunderstorm turbulence is possible behind the front.

THUNDERSTORMS SINGLE AND DOUBLE CELL

Rain showers ceiling ragged - 300 to 400 feet (90 - 120 meters)/ visibility - ½ mile (0.8 meters) or less in rain, otherwise over 8 miles

Light to severe turbulence

REFERENCES

1. Air Carrier Operations Bulletin 75-8, dated December 30, 1975, "Low Level Windshear."

2. "Thunderstorm-Outflow Kinematics and Dynamics," by R. Craig Goff, December, 1975 - NOAA Technical Memo ERL-NSSL-75, National Severe Storms Laboratory.

3. "Spearhead Echo and Downburst Near the Approach End of a John F. Kennedy Airport Runway, New York City," by T. Theodore Fujita, Satellite and Mesometeorology Research Project Paper 137, March, 1976.

4. "Surface Winds in the Vicinity of Stapleton Airport at the Time of the Crash of Continental Flight 426," by Fernando Caracena for National Transportation Safety Board, Docket No. DCA-76A-Z002, Exhibit 5E-1, December 19, 1975.

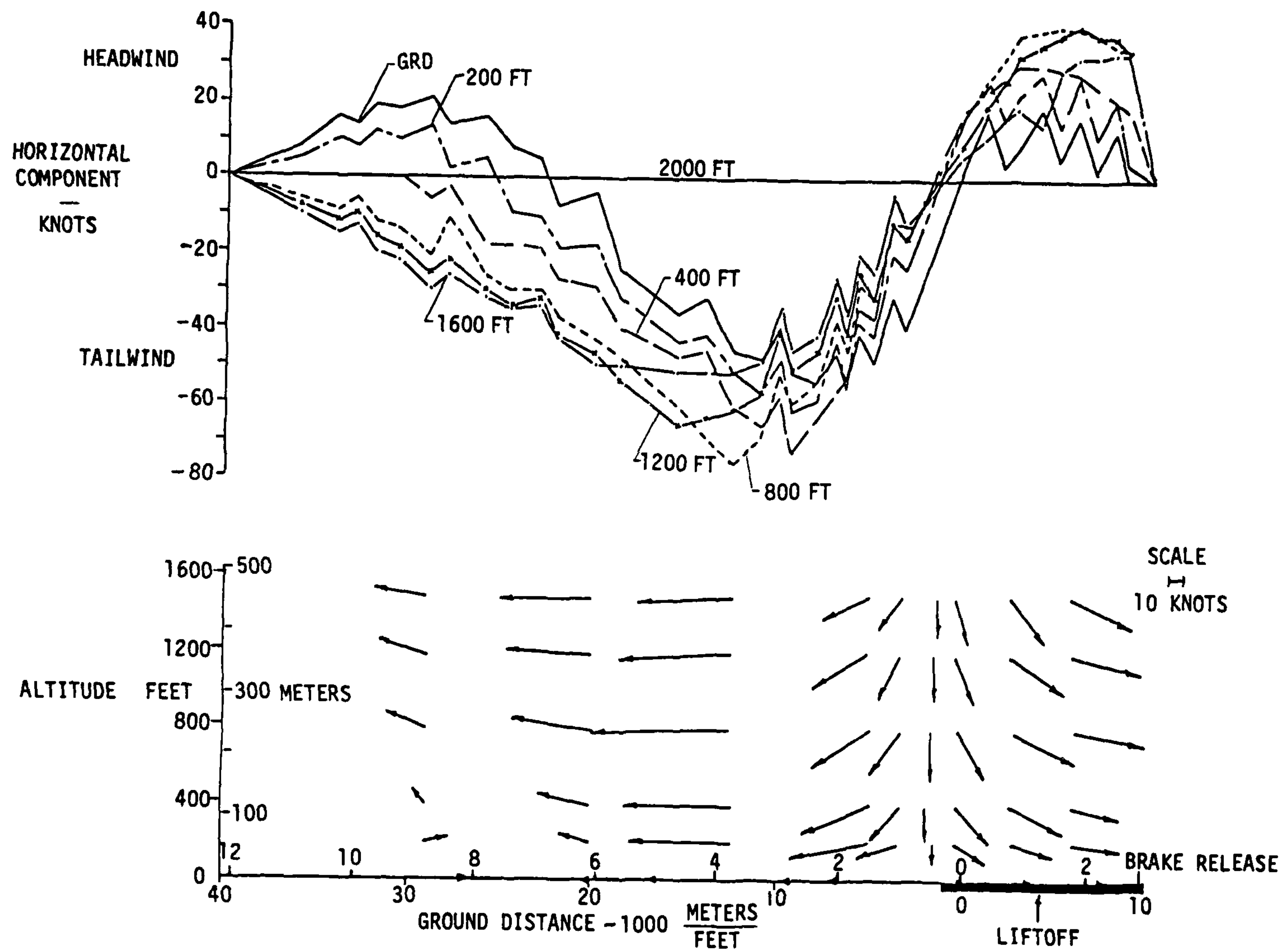


Fig.1 Takeoff – single cell thunderstorm

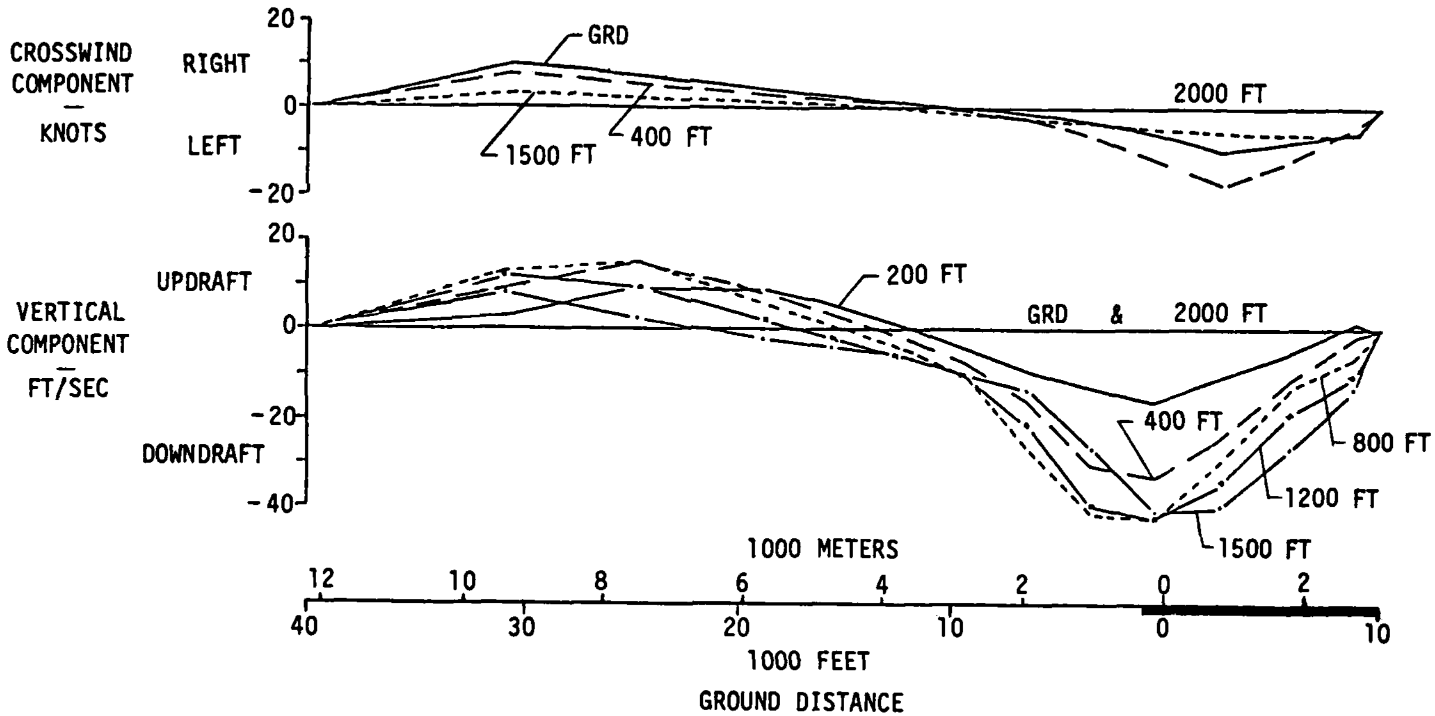


Fig.2 Takeoff – single cell thunderstorm

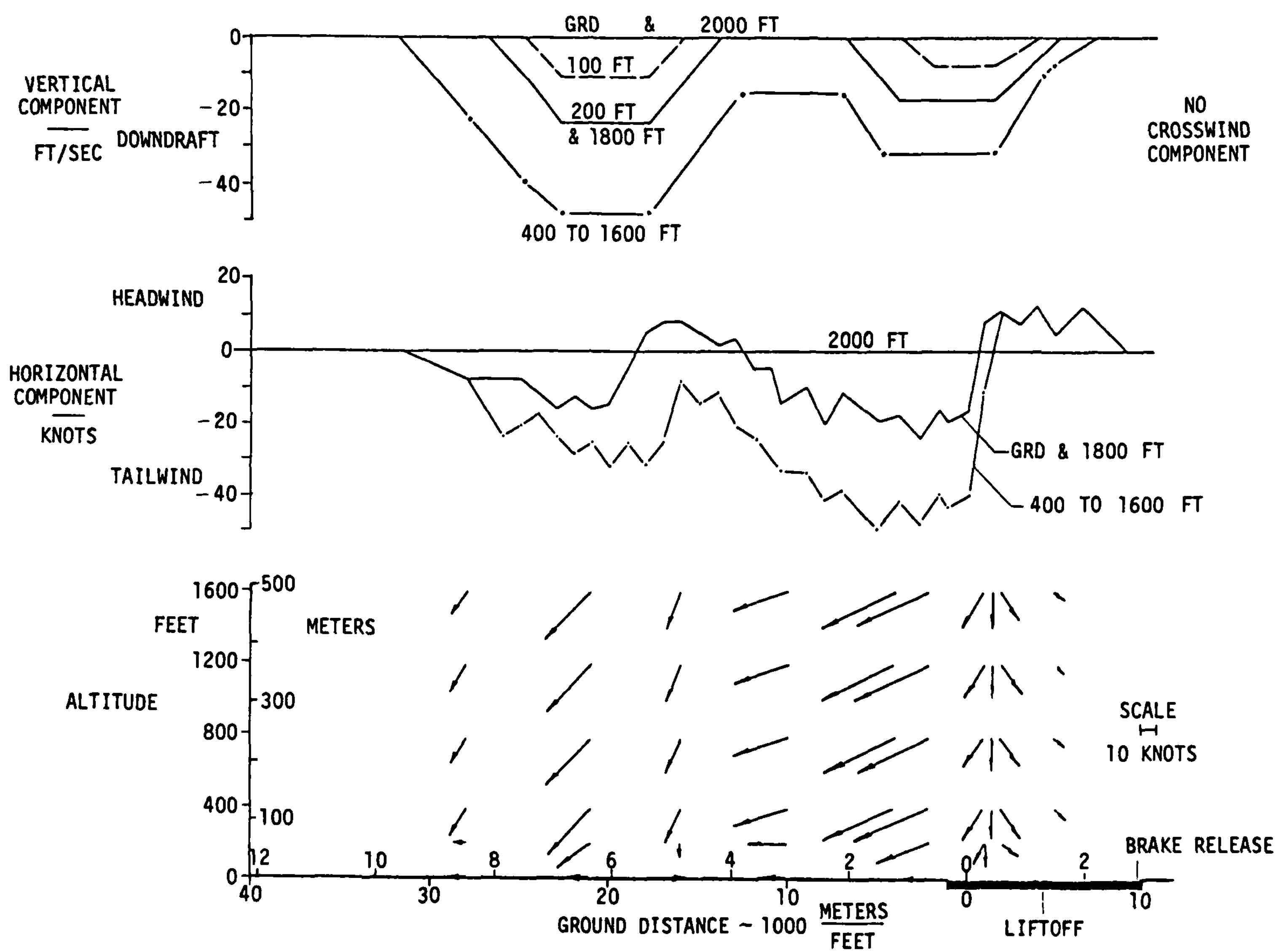


Fig.3 Takeoff – double cell thunderstorm

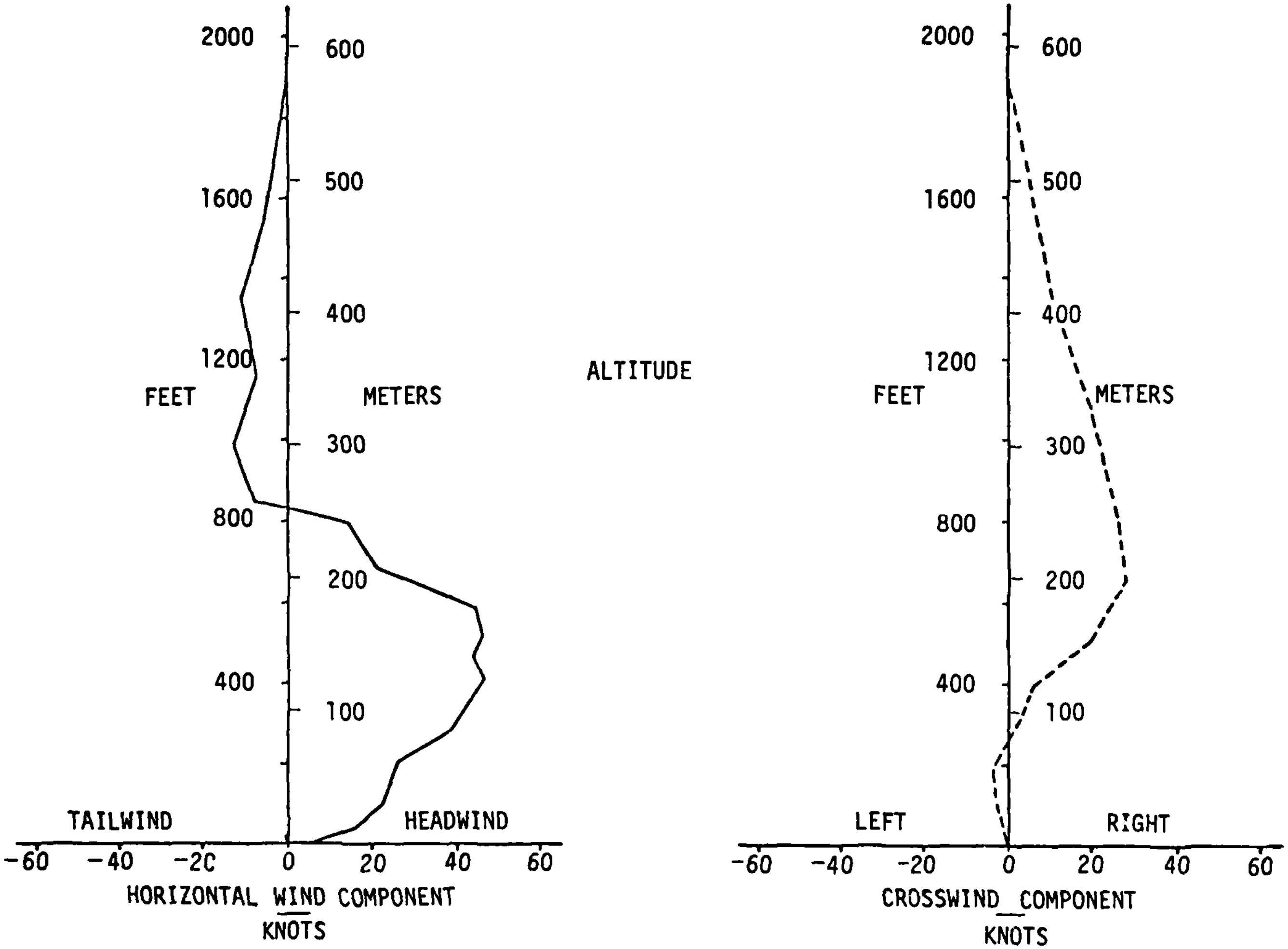


Fig.4 Night time stable layer landing

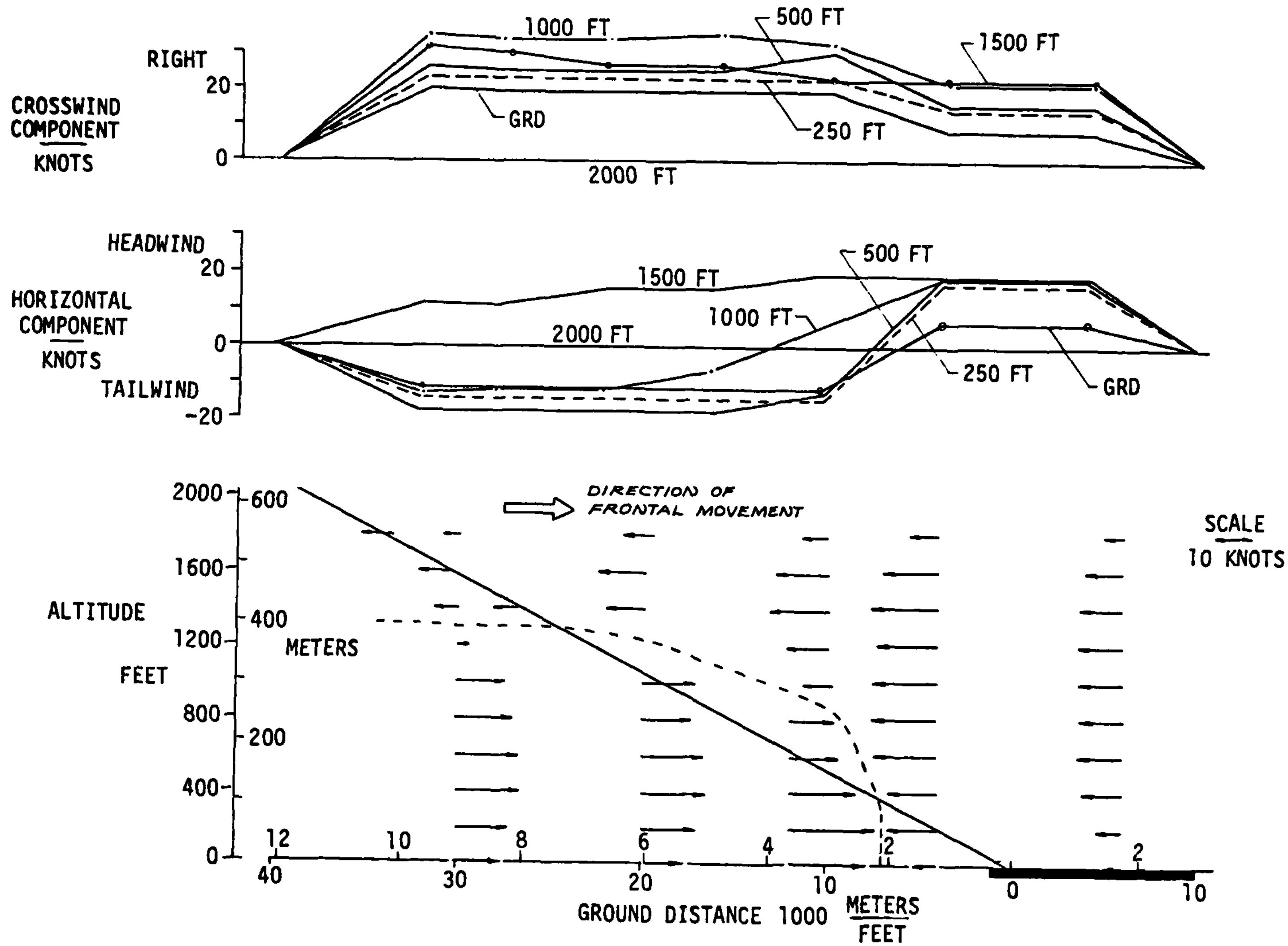


Fig.5 Cold front landing

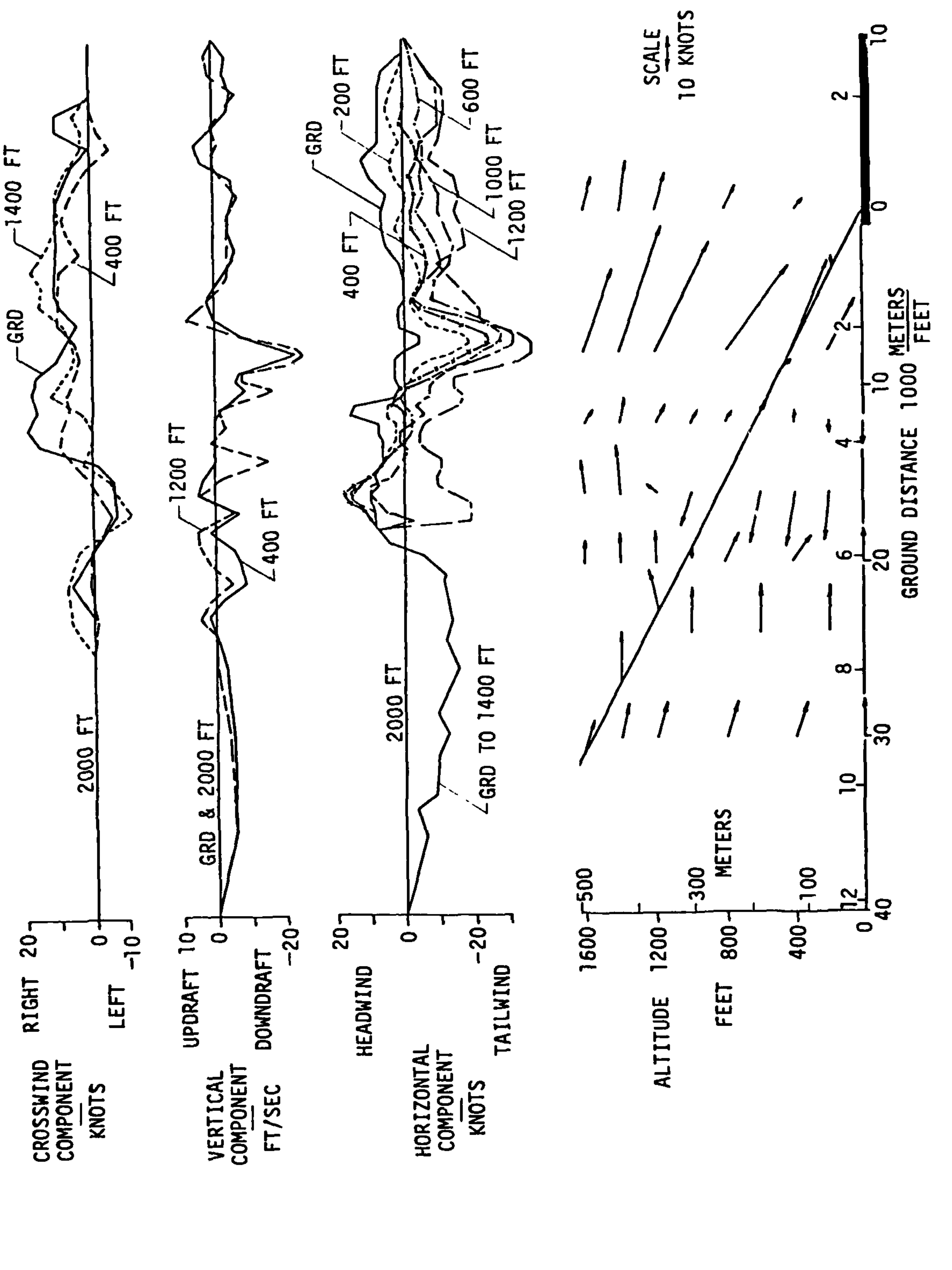


Fig.6 Thunderstorm landing

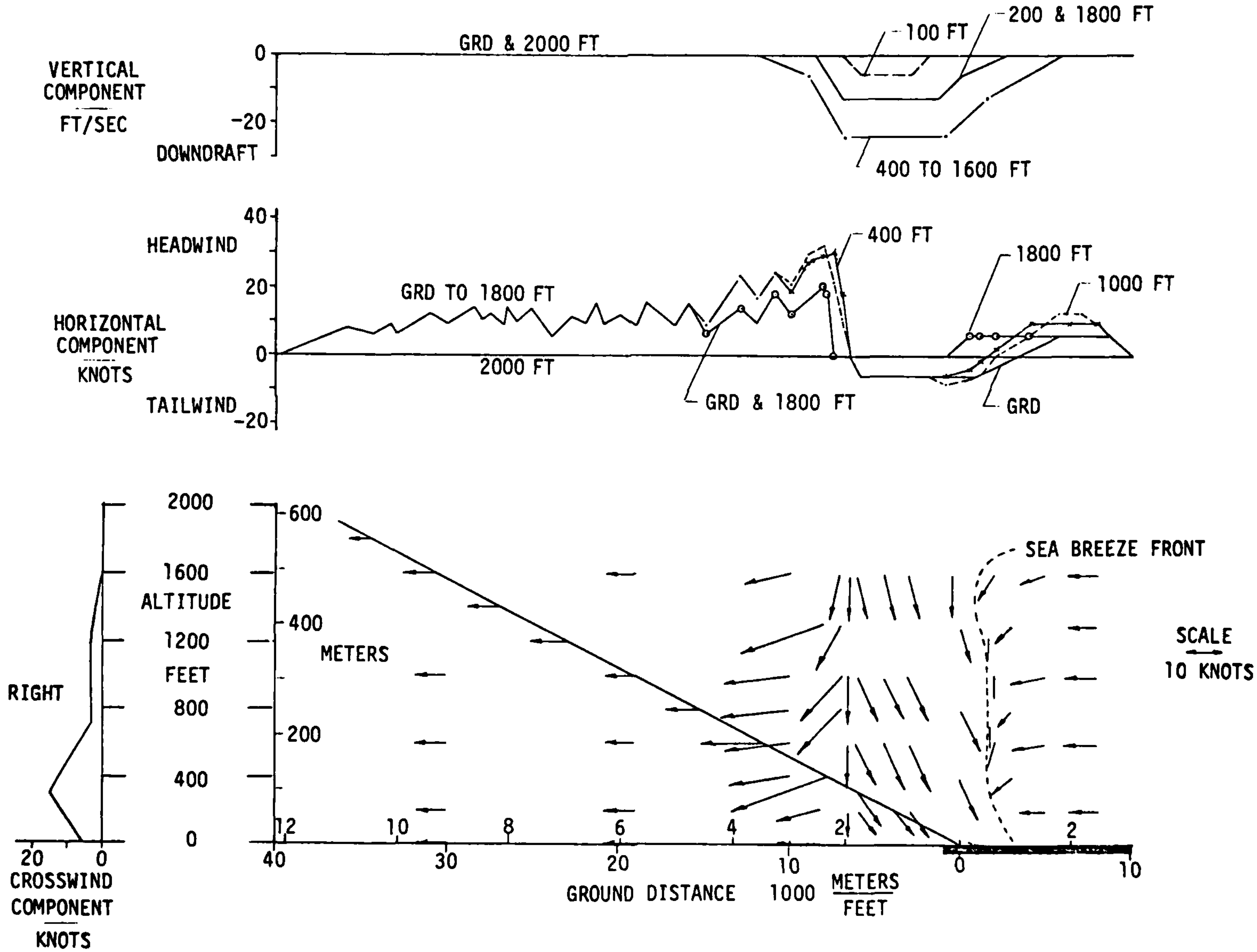


Fig.7 Downburst thunderstorm landing

NON-GAUSSIAN STRUCTURE OF THE SIMULATED TURBULENT ENVIRONMENT IN PILOTED FLIGHT SIMULATION

by

G.A.J. van de Moesdijk
Department of Aerospace Engineering
Delft University of Technology
Delft, The Netherlands

SUMMARY

After a description of the general non-gaussian characteristics of actual atmospheric turbulence as observed in the atmosphere, a non-gaussian turbulence simulation model has been described. The non-gaussian characteristics have been classified as patchiness and intermittency, both dependent on higher order statistics. These non-gaussian characteristics have been mathematically elaborated and described.
The effects of patchiness on pilot's behaviour,using physiological parameters have been evaluated in a small simulator experiment.

1. INTRODUCTION

Ground-based flight simulation has become more and more accepted as a valuable tool for systematic evaluation of complex control system performance as well as for evaluation of human pilot behaviour in the critical phases of flight.
Dependent on the sophistication of the simulation experiment at hand, actual properties of real atmospheric turbulence have to be simulated more accurately. In this context the significance of non-gaussian atmospheric turbulence characteristics is increasingly appreciated, as deficiences in the simulation are detected when comparing simulated flight to actual flight. As a consequence the technique of atmospheric turbulence simulation evolved from simple filtering of gaussian white noise, to cope with the measured power spectra of atmospheric turbulence, into a variety of non-gaussian simulation techniques.

The most important non-gaussian characteristics of atmospheric turbulence have been indicated in many publications, see e.g. Refs. 1, 2, 7 and 11. They have been defined as "patchiness" and "intermittency". Both terms refer to a certain structure in turbulence as revealed when analysing the results of recent measurement programs. Both characteristics can be described in mathematical terms and their mutual dependence will be discussed in this paper.

Attention has further been given in this paper to the problem of correctly modelling turbulence induced aircraft motions.
The effects of the non-gaussian turbulence properties on pilot behaviour in level flight were the subject of an experiment described in this paper.
In an attempt to objectively measure pilot reactions to the simulated non-gaussian turbulence characteristics, several physiological effects have been obtained.

2. GENERAL NON-GAUSSIAN CHARACTERISTICS OF ATMOSPHERIC TURBULENCE

From a practical point of view atmospheric turbulence has a random nature and therefore only statistical methods apply to provide information about its characteristics. In some theoretical publications the stochastic nature of atmospheric turbulence has been questioned, as the Navier-Stokes equations governing turbulent motion are formally deterministic.
Addressing to a more theoretical point of view, the fact that turbulent motion does indeed obey the laws given by the Navier-Stokes equations has important consequences.
Satisfying these equations, turbulence velocity fields cannot develop into a purely gaussian process. It is well-known that the central limit theorem underlying the mathematical description of a gaussian process demands independency of "random events" to produce a gaussian process. This independence is violated due to the existence of the Navier-Stokes equations governing the process by coupling "events" in space and time, see Ref. 1.

As a consequence the simplicity inherent in the mathematical description of a gaussian process, where mean value and covariance provide an essentially complete statistical description of the process, vanishes.
As the Navier-Stokes equations appear to be practically insoluble, non-gaussian properties can only be deduced statistically by analysing observations.

In contrast with a gaussian process, higher order statistics have to be studied in non-gaussian processes, if more detailed knowledge concerning their characteristics is required.

In this paper attention is focussed on two non-gaussian characteristics of atmospheric turbulence, i.e. patchiness and intermittency. Both are determined by higher order statistics of the stochastic process. Patchiness can roughly be described as follows. In actual non-gaussian atmospheric turbulence low activity regions are found to alternate randomly with high activity regions in contrast to the more or less homogeneously distributed energy in a gaussian process. This feature is reflected in the measured probability density distribution function, sometimes called the distribution function, see Fig. 1. Compared to the well-known bell-shaped gaussian distribution, atmospheric turbulence velocities show distinct deviations from the gaussian curve. This shape can easily be understood from the above described properties. A higher probability of occurrence of high turbulence velocities exists because of the high activity regions. Also a higher probability of low turbulence velocities is caused by the low activity regions. In between a lower probability of occurrence of turbulence velocities for the intermediate velocity values will balance the higher probability area's.

A specification of the shape of an arbitrary probability density distribution can be found by its moments M_n defined by:

$$M_n = E\{x^n\} = \int_{-\infty}^{+\infty} x^n\, p(x)\, dx \qquad n = 1, 2, 3, \dots \qquad (2.1.)$$

where E is the expected value and p(x) is the probability density distribution function

A gaussian random variable has the special property that all its higher order moments are completely defined by the first order moment, M_1 or mean value and the second order moment M_2.
If this second order moment is taken relative to the mean value - the so-called central moment - it is known as the variance σ^2. The central moments of the order n of a gaussian process are given by:

$$m_{2n+1} = 0$$

$$m_{2n} = 1.\ 3.\ 5.\ \dots,.(2n-1)\ \sigma^{2n} \qquad (2.2.)$$

If an experimentally observed process - such as atmospheric turbulence - cannot be considered as purely gaussian, the higher order central moments can serve as measures to characterize deviations from the gaussian distribution function.
In particular values of the fourth order central moment are of interest. In a gaussian process m_4 takes the value - $m_4 = 3\sigma^4$ - according to eq. (2.2.). In a non-gaussian process the value of m_4, in excess of $3\sigma^4$, is used as a measure of the patchiness of the process. More often the term Kurtosis, K, is used. It is defined as:

$$K = \frac{m_4}{(m_2)^2} \qquad (2.3.)$$

Eq. (2.3.) produces a measure of patchiness independent of the variance. Analysis of actual turbulence measurements shows that values of K up to about 6 are found in the atmosphere, see e.g. Ref. 1.

In Ref. 4 it is shown that patchiness is only partially reflected by the value of the fourth order central moment or Kurtosis value. Different forms of patchiness may exist having the same Kurtosis value and even identical probability density distribution functions, see Ref. 4 and Section 3. Before proceeding with this issue, it is necessary to introduce the second non-gaussian characteristic to be discussed in this paper.

This second characteristic of non-gaussian behaviour is usually referred to as "intermittency". This term is generally associated with the probability density distribution of the velocity differences at two instants in time, an interval Δt apart:

$$\Delta w(t, \Delta t) = w(t) - w(t - \Delta t) \qquad (2.4.)$$

where w(t) is the longitudinal, vertical or lateral turbulence velocity.

The probability density of Δw provides another type of information of the non-gaussian structure of the turbulence velocities. If Δt is taken relatively small, for instance $\Delta t = 0.1$ sec., the small scale structure of non-gaussian properties is visualized. If w(t) were a gaussian process, the probability density distribution function of the velocity differences or increments $p_{\Delta w}(x)$ would also be gaussian. Therefore the probability density functions of the increments of the turbulence velocities - or rather the deviations from the gaussian curve - may indicate statistically significant non-uniformity of the spatial and/or temporal distribution of the velocity gradients.
In contrast to a gaussian process the velocity gradients tend to concentrate in space or time as the aircraft flies through the turbulence velocity field. Measurements in actual atmospheric turbulence of these increment distribution functions at a given short time-lag Δt, e.g. $\Delta t = 0.1$ sec. show a pronounced non-gaussian behaviour. In general the measured fourth order central moment or Kurtosis value of the increments of the turbulence velocities appears to have a higher value at a time-lag of $\Delta t = 0.1$ sec. than the - non-gaussian - Kurtosis value of the turbulence velocities tnemselves, calculated from the same record, see Fig. 2 and Ref. 1. This phenomenon appears to be important in view of the mutual dependence of patchiness and intermittency, as will mathematically be explained in the next Section.
Although patchiness is always accompanied by intermittency, such high central fourth order moment values as experimentally obtained cannot be explained from the patchy structure alone. If for instance atmospheric turbulence were gaussian within the patches, non-gaussian behaviour of the increments can only be caused by the relatively low occurrence of sudden velocity changes in the transient periods, when going from patch to patch.
Within a patch the velocity increments would be gaussian too and would not contribute to the deviations in the overall distribution function of the increments from the gaussian curve.
Therefore, besides patchiness other structural properties of non-gaussian processes must be held responsible for the production of highly intermittent behaviour. This is expressed by the use of the term intermittency along with that of patchiness.

It is of importance to note that both patchiness and intermittency are not necessarily expressed by the power spectral densities of atmospheric turbulence, i.e. the spectral forms due to Dryden or von-Karman, see Ref. 4. Assuming a certain power spectral density function in simulated atmospheric turbulence, both patchiness and intermittency can be generated artificially, separately and independently from the power spectral density of the turbulence velocities. In Ref. 7 results have been reported of the generation of simulated turbulence having a highly intermittent behaviour.

3. BASIC CONCEPTS OF NON-GAUSSIAN TURBULENCE SIMULATION

3.1. Introduction

The observed non-gaussian structure of atmospheric turbulence described in the preceding Section sets the requirements to be satisfied by a correct model of atmospheric turbulence.
Most important in constructing such a model is a firm mathematical description. Without such a description results of a model will show at best phenomenological agreement with actual turbulence data as far as can be deduced from statistical analysis. In particular, when estimating higher order statistics from actual or simulated turbulence data, excessively long records have to be analysed, if adequate estimation accuracy is to be achieved, see for instance Ref. 10. Addressing also to other fields in aeronautics, e.g. structure response and fatigue, interpretation of resulting responses to simulated non-gaussian turbulence inputs will remain obscure.
Calculation of characteristics of aircraft responses to non-gaussian turbulence may offer formidable mathematical difficulties. At least in principle a solution seems to be not quite impossible. Therefore most ideal non-gaussian time-histories produced by some simulation technique should be accompanied by mathematically well-defined model expressions of all those properties, observed in reality.
Such mathematical description of non-gaussian properties is available in the non-gaussian turbulence simulation, initiated originally by Reeves, see Ref. 2. Based upon his idea the observed patchiness property has been further developed and described in mathematical terms in Refs. 4, 5 and 6.
For reasons of clarity the basic concepts will be repeated here.

3.2. The non-gaussian turbulence model

Non-gaussian turbulence time-histories of simulated turbulence can be obtained by utilizing the concept of amplitude-modulation of two independent gaussian random processes. Consider the blockdiagram of Fig. 3. By means of multiplication, a gaussian random process is amplitude-modulated by an independent gaussian process of different scale. A third independent gaussian process is added to the process just mentioned, to obtain probability density distributions of the output turbulence velocities comparable to those measured in actual atmospheric turbulence.
Starting from independent gaussian processes as forcing inputs to the system as indicated in Fig. 3, enables to calculate all necessary statistical properties of the output turbulence velocities.
From a mathematical derivation given in Ref. 4 the following statistical properties have been established.
The probability density of the simulated turbulence velocities is given by, see Ref. 4:

$$p_w(x) = \frac{(1+Q^2)^{\frac{1}{2}}}{\pi\sigma_w} \int_0^{\infty} \left[\frac{2}{1+2\xi^2 Q^2}\right]^{\frac{1}{2}} \exp\left\{-\xi^2 - \tfrac{1}{2}\left(\frac{x}{\sigma_w}\right)^2 \frac{1+Q^2}{1+2\xi^2Q^2}\right\} d\xi \qquad (3.2.1.)$$

Through the parameter Q a complete class of probability density distributions has been defined by eq. (3.2.1.). Any particular value of Q - which ranges from zero to infinity - determines a corresponding choice of the probability density function. The limiting cases are $Q = 0$ and $Q = \infty$, corresponding to the gaussian distribution and the so-called "Bessel distribution", respectively. The class of non-gaussian distribution functions is presented as a function of Q in Fig. 4. The Kurtosis value used earlier in this paper as a measure to express non-gaussian properties from observed turbulence data has a fixed relationship with the parameter Q expressed by:

$$K_w = \frac{9Q^4 + 6Q^2 + 3}{(1+Q^2)^2} \qquad (3.2.2.)$$

In fact all higher order moments can be expressed as a function of the parameter Q, see Ref. 4.

In addition to probability density distribution functions, atmospheric turbulence can further be characterized using spectral analysis. In the mathematical model the shapes of the power spectral density functions of actual as well as simulated turbulence are described by the expressions due to Von-Karman and Dryden, see Ref. 4. Both power spectral shapes can also be obtained in the non-gaussian model of Fig. 3, although the slope of the high frequency asymptote of -5/3 in the Von-Karman spectral functions requires an approximation, see Ref. 20.
The basic equation of the power spectral density function in the model depicted in Fig. 3 is, according to Ref. 4:

$$\Phi_{ww}(\omega) = \tfrac{1}{2}\int_{-\infty}^{+\infty} \Phi_{aa}(\omega-\lambda)\,\Phi_{bb}(\lambda)\,d\lambda + \Phi_{cc}(\omega) \qquad (3.2.3.)$$

where $\Phi_{aa}(\omega)$ is output power spectral density of filter A
$\Phi_{bb}(\omega)$ is output power spectral density of filter B
$\Phi_{cc}(\omega)$ is output power spectral density of filter C
(see blockdiagram of Fig. 3).

In the time-domain the autocovariance functions corresponding to the above auto-power spectral densities take the form of a product relation:

$$C_{ww}(\tau) = C_{aa}(\tau)\,C_{bb}(\tau) + C_{cc}(\tau) \qquad (3.2.4.)$$

3.3. Patchy characteristics

Specification of either the auto-power spectral density $\Phi_{ww}(\omega)$ or the autocovariance function $C_{ww}(\tau)$ does not uniquely specify the two composing spectral shapes $\Phi_{aa}(\omega)$ and $\Phi_{bb}(\omega)$ or their equivalent autocovariance functions $C_{aa}(\tau)$ and $C_{bb}(\tau)$.
The ratio R between the cut-off frequencies of filter A and filter B in Fig. 3 can still be chosen freely, affecting neither the power spectral density $\Phi_{ww}(\omega)$ nor the probability density function $p_w(x)$ of the output turbulence velocities. Varying this ratio R does however, affect the characteristics of the output simulated turbulence. In fact the value of R appears to determine the scale length of patchiness relative to the integral scale length of turbulence L_g appearing in the spectral density functions of both Von-Karman and Dryden. As the ratio R decreases from R = 1 to R ≈ 0 the "average patch length" increases, as can be detected in Fig. 5. Higher order statistics have to be calculated to express these non-gaussian characteristics in mathematical terms. In Ref. 4 the power spectral densities of the square of the turbulence velocities and their associated autocovariance functions have been studied. They appeared both to explain and to establish mathematically the properties of patchiness. The spectral shapes of the squared turbulence velocities are presented in Fig. 6 and Fig. 7. An important property of any power spectral density function is its relation to the variance:

$$\sigma_w^2 = \int_0^\infty \Phi_{ww}(\omega)\, d\omega \tag{3.3.1.}$$

Thus the value of the integrand $\Phi_{ww}(\omega_1)\, d\omega$ at ω_1 indicates how much is contributed to the variance σ_w^2 by harmonic functions, having frequencies in the interval $(\omega_1, \omega_1 + d\omega)$. Applying eq. (3.3.1.) to the power spectral density of the squared turbulence velocities reveals an interesting aspect of patchiness.

$$\sigma^2_{w^2} = \int_0^\infty \Phi_{w^2w^2}(\omega)\, d\omega \tag{3.3.2.}$$

It can be shown mathematically, see Ref. 4 that the following relation exists:

$$(K_w - 1)\,\sigma_w^4 = \int_0^\infty \Phi_{w^2w^2}(\omega)\, d\omega \tag{3.3.3.}$$

And thus combining eq. (3.3.2.) and eq. (3.3.3.), the term $(K_w - 1)\,\sigma_w^4$, which is the value of the Kurtosis or fourth order central moment of the turbulence velocities minus σ_w^4, equals the variance of the stochastic process $w^2(t)$. The term σ_w^4 is the square of the mean value of $w^2(t)$, which is of course not equal to zero.
It can therefore be concluded that the integrand $\Phi_{w^2w^2}(\omega_1)\, d\omega$ in eq. (3.3.3.) at constant value of σ_w^2 represents the contributions to the Kurtosis value, obtained from harmonic functions having frequencies in the interval $(\omega_1, \omega_1 + d\omega)$. Furthermore if the ratio R decreases from 1 to lower values the main contributions to the fourth order central moment or Kurtosis value, K_w, appear to shift to the lower frequency range, as can be seen from Figs. 6 and 7. This is equivalent to the occurance of longer turbulence patches, see Fig. 5.
The above discussion can be summarized by saying that the values of Q or the Kurtosis values are indicative of the "mean intensity" of turbulence patches relative to the overall variance of the turbulence velocities, whereas the value of R affects the "average scale length" of turbulence patches.

The notion, however, of a patchiness scale length is rather vaque. Such a distance is even more difficult to measure than the integral scale length L_g of the turbulence velocities. A more convenient manner to extract a measure of the patchiness from the power spectral density of the squared turbulence velocities has been developed in Ref. 4. This measure of patchiness can briefly be described as follows. A low-pass first order filter with variable time-constant τ has been used as a means to detect how patchiness is arranged in the frequency domain, see Fig. 8. Let the output of this low-pass filter be called z(t). Then the value of the variance σ_z^2 of this filter output expresses the contribution to the fourth order central moment of the turbulence velocities in a frequency band determined by the cut-off frequency of the filter, $\omega = \frac{1}{\tau}$. As such $\sigma_z^2(\tau)$ can be considered a descriptive function of patchiness. The function $\sigma_z^2(\tau)$ in the case of gaussian turbulence, when the patchiness is minimal is taken as a reference line. In this way a patchiness parameter P as a function of the time-constant τ of the low-pass first order filter has been defined in Ref. 4:

$$P_\tau = \frac{\sigma_z^2(\tau)_{\text{non-gaussian}}}{\sigma_z^2(\tau)_{\text{gaussian}}} \tag{3.3.4.}$$

The procedure is illustrated in Fig. 8. In Ref. 4 closed analytical expressions have been derived for the patchiness parameter P_τ, in non-gaussian turbulence assuming a Dryden spectral density function for the turbulence velocities. The behaviour of P_τ as a function of the non-gaussian turbulence model parameters Q and R, governing the patchy characteristics, is presented in Fig. 9 and Fig. 10. If the time-constant τ is taken to infinity the final measure of patchiness $P_{\tau=\infty}$ appears to have a linear relation to the Kurtosis value, K_w, dependent on the value of R, see Ref. 4. This linear relation is presented in Fig. 11 for the vertical turbulence velocities.

The above description of the parameter P_τ, offers a very simple analytic tool to determine also the degree of patchiness in actual atmospheric turbulence data. The recorded turbulence velocity has to be squared yielding $w^2(t)$. This squared velocity record serves as the input signal to the first order linear filter with time-constant τ, having an output z(t). The variance of z(t) calculated at various values of the time-constant τ provides the descriptive function $\sigma_z^2(\tau)_{\text{non-gaussian}}$ of patchiness. The variance

$\sigma_z^2(\tau)_{gaussian}$, additionally needed to obtain P_T, according to eq. (3.3.4.) can be expressed analytically as, see Ref. 5:

$$\sigma_z^2(\tau)_{gaussian} = \int_0^{\infty}\int_{-\infty}^{+\infty} \Phi_{ww}(\lambda)\ \Phi_{ww}(\omega - \lambda)\,|H(j\omega,\ \tau)|^2\ d\lambda\ d\omega \tag{3.3.5.}$$

where $\Phi_{ww}(\omega)$ is the auto-power spectral density function derived from the measured turbulence velocities. Finally applying eq. (3.3.4.) yields the patchiness parameter P_T. An example of such calculations is shown in Fig. 12, as well as fitting of the parameters Q and R by least squares.

3.4. Aspects of intermittency

In Section 2 the term intermittency of atmospheric turbulence has been attached to the spatial and/or temperal distributions of the gradients of the turbulence velocities. These gradients possess a statistically significant non-uniformity. As mentioned earlier the probability density distribution of the velocity increments:

$$\Delta w(t,\ \Delta t) = w(t) - w(t - \Delta t) \tag{3.4.1.}$$

at a given short time-lag of e.g. $\Delta t = 0.1$ sec., in actual atmospheric turbulence shows a pronounced non-gaussian behaviour.

To see whether the non-gaussian turbulence model, indicated in Fig. 3 is capable of producing comparable results, it is interesting to derive model expressions for the probability density functions of the velocity increments. To simplify the mathematical difficulties arising when attempts are made to derive such analytical expressions, use is made of the concept of characteristic functions. These functions are defined, e.g. in Ref. 8, as the Fourier transform of the probability density distribution function.

$$C_w(\omega) = \int_{-\infty}^{+\infty} p_w(x)\ e^{j\omega x}\ dx \tag{3.4.1.}$$

The characteristic function provides a convenient way to calculate the moments of the distribution function, using the following expression, see Ref. 8:

$$\frac{d^n\ C(o)}{d\omega^n} = j^n\ M_n \qquad n = 1,\ 2,\ 3,\ \ldots.. \tag{3.4.2.}$$

where M_n is moment or order n
j^n is imaginary unit: $j = \sqrt{-1}$

Because of this property the characteristic function is frequently called the moment generating function, Ref. 8.
Thus according to eq. (3.4.2.) the fourth order moment of the velocity increments can be calculated by taking the fourth order derivative of the characteristic function $C_{\Delta w}(\omega)$ at $\omega = 0$.
In order to arrive at the characteristic function of the velocity increments the two-dimensional characteristic function of $w_1(t) = w(t)$ and $w_2(t) = w(t - \Delta t)$ has to be calculated, defined as the two-dimensional Fouriertransform of the joint probability distribution function.

$$C_{w_1w_2}(\omega_1,\omega_2) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} p_{w_1w_2}(x_1,x_2)\ e^{j(\omega_1x_1+\omega_2x_2)}\ dx_1\ dx_2 \tag{3.4.3.}$$

An expression for the joint distribution function $p_{w_1w_2}(x_1,x_2)$ follows from the functional relations of the gaussian component processes, a(t), b(t) and c(t) in Fig. 3 and from the independence of these processes. Using the properties of the Fouriertransform the following result is obtained for the two-dimensional characteristic function of the turbulence velocities w(t) and w(t - Δt).

$$C_{w_1w_2}(\omega_1,\omega_2) = \frac{\exp\left[-\tfrac{1}{2}\sigma_c^2\left\{\omega_1^2 + 2\rho_c(\tau)\ \omega_1\omega_2 + \omega_2^2\right\}\right]}{\left[\sigma_a^4\sigma_b^4\left(1-\rho_a^2(\tau)\right)\left(1-\rho_b^2(\tau)\right)\omega_1^2\omega_2^2 + \sigma_a^2\sigma_b^2\omega_1^2 + 2\rho_a(\tau)\ \rho_b(\tau)\ \sigma_a^2\sigma_b^2\omega_1\omega_2 + \sigma_a^2\sigma_b^2\omega_2^2 + 1\right]^{\frac{1}{2}}} \tag{3.4.4.}$$

where σ_i is variance of output of a(t), b(t) or c(t), the index indicating the process concerned (see block-diagram, Fig. 3).
$\rho_i(\tau)$ is normalized covariance function defined as $\rho_i(\tau) = \frac{1}{\sigma_i^2}\,C_{ii}(\tau)$, the index indicating the process concerned.

This result has also been given previously in Ref. 9. According to Ref. 8 the characteristic function of the velocity increments follows from the transformation relation:

$$C_{w_1-w_2}(\omega) = C_{w_1,w_2}(\omega,\ -\omega) \tag{3.4.5.}$$

Applying eq. (3.4.5.) to eq. (3.3.4.) yields the following result for the characteristic function of the velocity increments, expressed in the model parameters Q and R, see Ref. 12.

$$C_{\Delta w}(\omega)_{\Delta t=\tau} = \frac{\exp\left[-\frac{1}{1+Q^2}\sigma_w^2\left(1-\rho_w(\tau)\right)\omega^2\right]}{\left[\frac{Q^4}{(1+Q^2)^2}\sigma_w^4\left(1+\rho_w^2(\tau)-\rho_w^{\frac{2}{R+1}}(\tau)-\rho_w^{\frac{2R}{R+1}}(\tau)\right)\omega^4+\frac{2Q^2}{1+Q^2}\sigma_w^2\left(1-\rho_w(\tau)\right)\omega^2+1\right]^{\frac{1}{2}}} \qquad (3.4.6.)$$

where $\rho_w(\tau)$ is the value of the normalized covariance-function of atmospheric turbulence, dependent on the time-lag Δt used, at the velocity-increments considered.

An expression for the fourth order central moment of the velocity-increments can now be obtained by combining eqs. (3.4.2.) and (3.4.6.). The result is:

$$m_{4\,\text{vel.incr.}} = 12\sigma_w^4(1-\rho_w(\tau))^2\left[\frac{3Q^4+2Q^2+1}{(1+Q^2)^2}\right] - \frac{12Q^4}{(1+Q^2)^2}\sigma_w^4\left(1+\rho_w^2(\tau)-\rho_w^{\frac{2}{R+1}}(\tau)-\rho_w^{\frac{2R}{R+1}}(\tau)\right) \qquad (3.4.7.)$$

Similarly the variance or second order moment of $\Delta w(t, \Delta t)$ can be calculated by using eqs. (3.4.2.) and (3.4.6.). The result is:

$$\sigma_{\Delta w}^2(\Delta t = \tau) = 2\sigma_w^2(1-\rho_w(\tau)) \qquad (3.4.8.)$$

Combining eqs. (3.4.8.) and (3.4.7.) according to eq. (2.3.) yields an expression for the Kurtosis value, $K_{\Delta w}$, of the velocity-increments as a function of the model parameters Q and R:

$$K_{\Delta w} = 3\left[\frac{3Q^4+2Q^2+1}{(1+Q^2)^2}\right] - \frac{3Q^4}{(1+Q^2)^2}\,\frac{1+\rho_w^2-\rho_w^{\frac{2}{R+1}}-\rho_w^{\frac{2R}{R+1}}}{(1-\rho_w)^2} \qquad (3.4.9.)$$

where ρ_w is the value of $\rho_w(\tau)$ at $\tau = \Delta t$

In Fig. 12 the value of the Kurtosis of the velocity-increments at $\Delta t = 0.1$ sec. has been compared to the associated value of the Kurtosis of the turbulence velocities at various values of Q and R.
This figure presents an interesting result. For a given velocity component, i.e. u_g, v_g or w_g, patchiness increases the intermittent character of the turbulence record produced. The Kurtosis value of the velocity-increments, $K_{\Delta w}$, however, will always be lower than the Kurtosis value, K_w, of the turbulence velocities themselves.
The limit value of $K_{\Delta w}$, theoretically attainable at R = 0 equals the value of K_w, the Kurtosis of the turbulence velocities themselves. In actual atmospheric turbulence, measurements of velocity-increment characteristics show in general a higher value of $K_{\Delta w}$ than the Kurtosis value, K_w, of the turbulence velocities, measured from the same record. One has to conclude therefore that the non-gaussian model in the form presented in Fig. 3 is not quite capable to produce an equally large number of concentrated gradients as observed in the actual atmosphere.

To solve this problem, advantage has been taken of a possible structure of the phase angles of the composing harmonic signals in modelling the simulated turbulence. A definite structure of the phase angles in the Fourier space must have an effect on intermittency, because it can be shown that statistical moments or order ≥ 3 are both amplitude and phase dependent, see Ref. 11.
An illustration of the effect of modelling phase angles is given in Fig. 14. In this Figure the mutual phase angles of four harmonics have been chosen such, that they will be in-phase at a quarter of the fundamental wavelength. Such in-phase behaviour produces an effect, which can be viewed as an "intermittent" peak.
The amplitudes of each harmonic were chosen according to the -5/3 law inherent to the spectral density functions due to Von-Karman.
As can be seen from this Figure, a 90-degrees phase-shift at t = 0, of each frequency relative to the lower harmonic has been applied to produce the result. Spectral analysis will not reveal this structure of in-phase behaviour, since the power spectrum provides only amplitude information and ignores the phase relationships.

The approach taken in modelling the phase angles in the non-gaussian simulation model to obtain the possibility of high intermittency is based on the above described phenomenon. The non-gaussian characteristics of the simulated turbulence result from multiplication of gaussian signals, as shown in Fig. 3.

A 90-degree phase-shift at all frequencies has been enforced between the two composing gaussian processes serving as inputs to filter A and filter B, respectively, see again block-diagram of Fig. 3. This 90-degree phase shift has been realized by the application of a Hilbert transformation to the gaussian white noise input to filter A to obtain the input to filter B.

The Hilbert transform of a process $\tilde{x}(t)$ is by definition a process x(t) given by the stochastic integral:

$$\tilde{x}(t) = \frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{x(\tau)}{t-\tau}\,d\tau \qquad (3.4.10.)$$

In an abbreviated notation, eq. (3.4.10.) expresses the convolution in the time-domain:

$$\tilde{x}(t) = x(t) * \frac{1}{\pi t} \tag{3.4.11.}$$

In the frequency domain this filter - known as a quadrature filter - see Ref. 8 has the following properties:
a. it has a constant amplitude ratio:

$$|H(j\omega)| = 1 \tag{3.4.12.}$$

b. its phase angle equals $-\pi/2$ at all frequencies, $\omega > 0$.
If for instance the input is cos $\omega_0 t$, than the output will be sin $\omega_0 t$ at any value of ω_0. The properties of the Hilbert transform as regards the covariance-functions and power spectral densities of the output, expressed in terms of the covariance functions and power spectral densities of the input are described in Ref. 8.

The non-gaussian turbulence model in its modified form is shown in the block-diagram of Fig. 15. At several settings of the parameters Q and R of the original model, probability density distributions of the velocity-increments have been measured as well as the corresponding probability density distributions of the turbulence velocities themselves from the same data. Some typical results are presented in Fig. 16. From this Figure it may be clear that the modified non-gaussian turbulence model does indeed produce the high intermittency comparable to the intermittent behaviour found in actual atmospheric turbulence data.
As will be seen in Fig. 16 a higher Kurtosis value, $K_{\Delta w}$, of the velocity increments has been consistently found, compared to the Kurtosis value K_w of the turbulence velocities of the same data. Similar analysis of turbulence velocities without the Hilbert transform applied, showed lower values of $K_{\Delta w}$, in agreement with the theoretically derived expression given in eq. (3.4.9.), see also Fig. 16.
A comprehensive mathematical description of the complete modified non-gaussian turbulence simulation model, including patchiness and intermittency has not yet been completed.
The expansion of the non-gaussian model with the Hilbert transformation will, however, affect not only the intermittency but also the mathematical description of patchiness, since patchiness and intermittency are not completely independent, see eq. (3.4.9.). To avoid unnecessary complications, the concept of the Hilbert transform to produce high intermittency has not been used in the simulator experiment to be described in the next Section.

4. THE SIMULATOR EXPERIMENT

4.1. Introduction

The principal object of the flight simulator experiment to be described in this Section was to classify the importance of non-gaussian characteristics in piloted flight simulation. It is a well-known fact that actual non-gaussian atmospheric disturbances are critical in the sense that they limit the overall level of precision in a specific flight task and increase pilot workload. Whereas gaussian turbulence simulation has proved to be inadequate in producing a representative pilot workload, it is important to obtain some index of the sensitivity of the non-gaussian characteristics in view of subsequent simulator experiments. It was therefore decided to measure pilot's performance in a rather simple flight task, i.e. maintain level flight as accurately as possible, under various non-gaussian turbulence conditions. From the model of patchiness 10 representative values of patchy conditions have been chosen as test cases. These cases are given in Fig. 17. Variance and integral scale length of the turbulence velocities have been taken constant at 1 m^2/sec^2 and 160 m respectively. During the runs physiological activity has been measured as in indication of pilot workload. These physiological measurements have been used especially to investigate a possible measuring technique to identify peaks and troughs in workload patterns, which could be expected considering the nature of patchiness.

4.2. Linear equations to simulate aircraft motions due to turbulence

Simulation of aircraft motions has been accomplished by solving the well-known perturbation equations in stability axes on a real-time basis. As only level-flight in turbulence has been considered in the simulator experiment, this simplified mathematical model is found adequate. The aircraft simulated is the DHC-2 "Beaver" aircraft as owned and operated by the Department of Aerospace Engineering of Delft University of Technology. This aircraft has a low wing loading and a relatively low cruising speed. As a result the aircraft is quite sensitive to atmospheric turbulence, especially with respect to asymmetric motions. The aircraft data have been summarized in Table I.
The differential equations to be solved can symbolically be written as:

$$\underline{\dot{x}}(t) = A\,\underline{x}(t) + B\,\underline{u}(t) \tag{4.2.1.}$$

Actually eq. (4.2.1.) defines two sets of four simultaneous first order differential equations, explicitly defined in Refs. 13 and 14. These sets of first order differential equations have been solved digitally using Heun's method of numerical integration at a sampling rate of 20 times per second. The input vector $\underline{u}(t)$ contains the control surface deflection angles $\delta_e(t)$, $\delta_a(t)$ and $\delta_r(t)$ as well as five turbulence input signals. Due to limited computer capacity, these five turbulence inputs were computed off-line stored on disk, for a given turbulence situation.
During simulation runs the turbulence signals were entered from disk into the mathematical aircraft model using a direct memory access channel. The turbulence situations simulated, differed only in the model parameters Q and R.

Within the scope of this paper a complete description of the aircraft simulation model is considered not quite possible. Details of the mathematical model have been presented in Refs. 13 and 14. Nevertheless

a short survey of the methods used to account for effects of the spatial distributions of the turbulence velocities over the aircraft will be given here.
With respect to the symmetric motions due to turbulence, the spatial distribution of turbulence velocities between the wing and tail has been accounted for by using separate inputs to the wing and tail. The turbulence velocities at the tail were obtained by using a pure time-delay:

$$w_{g_{tail}}(t) = w_{g_{wing}}\left(t - \frac{\ell_h}{V}\right) \qquad (4.2.2.)$$

The gust-derivatives, related to the time-derivatives of the longitudinal turbulence u_g and vertical turbulence w_g, i.e. $C_{z_{\dot{u}_g}}$, $C_{z_{\dot{\alpha}_g}}$, $C_{m_{\dot{u}_g}}$, $C_{m_{\dot{\alpha}_g}}$, appearing in the input matrix B of eq. (4.2.2.), see Ref. 13, have been replaced by equivalent expressions valid for a pure time-delay. For instance the pitching moment due to vertical turbulence can be written as:

$$C_{m_g} = C_{m_{\alpha_g}}\alpha_{g_w}(t) + \left\{C_{m_q}\frac{\bar{c}}{\ell_h} - C_{m_{\dot{\alpha}}}\frac{\bar{c}}{\ell_h}\right\}\left\{\alpha_{g_w}\left(t - \frac{\ell_h}{V}\right) - \alpha_{g_w}(t)\right\} \qquad (4.2.3.)$$

The method of calculating aerodynamic gust induced forces and moment using separate inputs to the wing and the tail has been described in Ref. 15.
With respect to the asymmetric motions due to turbulence, spatial distribution effects across the wing-span have been taken into account as well. The turbulence velocity field has been considered here as two-dimensional, i.e. the turbulence velocities vary along the longitudinal axis as well as along the lateral axis. In Ref. 14 two-dimensional autocorrelation functions, which express the average relations between gust velocities in two different points of a two-dimensional turbulence field of flow have been calculated. The autocorrelation functions are transformed into two-dimensional power spectral density functions by applying the Fourier-transform for two variables. From these two-dimensional power-spectral density functions, the power spectral density functions of the rolling and yawing moments due to longitudinal and vertical gusts are derived. The complete description of calculating asymmetric force and moments acting on an aircraft due to atmospheric turbulence has been given in Ref. 14. According to Ref. 14, the gust-induced asymmetric force and moments acting on an aircraft can be written as:

$$C_{Y_g} = C_{Y_\beta}\cdot\beta_g$$

$$C_{\ell_g} = -C_{\ell_{r_w}}\hat{u}_{g_a} + C_{\ell_\beta}\beta_g + C_{\ell_{p_w}}\alpha_{g_a} \qquad (4.2.4.)$$

$$C_{n_g} = -C_{n_{r_w}}\hat{u}_{g_a} + C_{n_\beta}\beta_g + C_{n_{p_w}}\alpha_{g_a}$$

The gust velocities $\hat{u}_{g_a}$, α_{g_a} have effective one-dimensional power spectral densities expressed by, see Ref. 14:

$$I_{\hat{u}_g}(\omega, B) = I_{\hat{u}_g}(o, B)\frac{L_u}{V}\frac{1 + \tau_3^2\omega^2\frac{L_u^2}{V^2}}{\left(1 + \tau_1^2\omega^2\frac{L_u^2}{V^2}\right)\left(1 + \tau_2^2\omega^2\frac{L_u^2}{V^2}\right)}$$

$$(4.2.5.)$$

$$I_{\alpha_g}(\omega, B) = I_{\alpha_g}(o, B)\frac{L_w}{V}\frac{1 + \tau_6^2\omega^2\frac{L_w^2}{V^2}}{\left(1 + \tau_4^2\omega^2\frac{L_w^2}{V^2}\right)\left(1 + \tau_5^2\omega^2\frac{L_w^2}{V^2}\right)}$$

where $B = \frac{b}{2L_u}$, $\frac{b}{2L_w}$ respectively (b = wingspan)
$I_{\hat{u}_g}(o, B)$, τ_1, τ_2, τ_3 and $I_{\alpha_g}(o, B)$, τ_4, τ_5, τ_6 are constants depending on aircraft wingspan and turbulence integral scale length, see Ref. 14.

The power spectral density of β_g is, according to Ref. 14:

$$\Phi_{\beta_g}(\omega) = \frac{\sigma_{\beta_g}^2}{\pi}\frac{L_v}{V}\frac{1 + 3\omega^2\frac{L_v^2}{V^2}}{\left(1 + \omega^2\frac{L_v^2}{V^2}\right)^2} \qquad (4.2.6.)$$

where $\beta_g = \frac{v_g}{V}$.

To generate the turbulence inputs $\hat{u}_{g_a}$ and α_{g_a}, giving rise to the asymmetric motions as a function of time with patchy characteristics, filter transfer functions for the filters A, B and C of the block-diagram of Fig. 3 have been designed, according to the method described in Ref. 4. From a mathematical elaboration given in Ref. 12, the filter transfer functions will read:

$$H_a(j\omega) = \frac{1}{K_a}\sqrt{C}\,\frac{1}{1 + j\omega A} \qquad \text{(filter A)} \qquad (4.2.7.)$$

$$H_b(j\omega) = \frac{1}{K_b}\sqrt{F}\,\frac{B + j\omega E}{(1 + j\omega D)\ (1 + j\omega G)} \qquad \text{(filter B)} \qquad (4.2.8.)$$

$$H_c(j\omega) = \frac{1}{K_c}\sqrt{H}\,\frac{1 + j\omega L}{(1 + j\omega M)\ (1 + j\omega N)} \qquad \text{(filter C)} \qquad (4.2.9.)$$

The constants A up to and including N have been specified in Appendix A. K_a, K_b and K_c are constants depending on the gaussian white noise input signals. Using eq. (4.2.4.) the asymmetric moments due to patchy atmospheric turbulence have been calculated as part of the input matrix B of eq. (4.2.1.).

The asymmetric rolling and yawing moments thus calculated, generated simulated aircraft motions which appeared to be surprisingly close to the behaviour of the real aircraft. Due to the patchy nature of the input, an up-gust at one wing-tip and a down-gust at the other one causing a rolling moment was not necessarily following by an opposite one, thus forcing the pilot to be very alert on roll-angle and yaw. This behaviour is typical of aircraft having a low-wing loading. In fact the asymmetric motions appeared to occupy the pilot most in his flight task, a behaviour also observed flying the real aircraft in turbulence.

4.3. Simulator characteristics

The flight simulator of the Department of Aerospace Engineering of Delft University of Technology is provided with a three-degree-of-freedom motion system, visual display and hydraulic control feel system. It has a two-seat civil aircraft type cockpit and the required computations are performed on a hybrid computer. The hydraulically operated motion system provides pitch, roll and heave motion. The hydraulic actuators have a stroke of 66 cm and they are provided with hydrostatic bearings, resulting in very smooth motion characteristics. A picture of the general layout of the flight simulator is given in Fig. 18. A comprehensive description of simulator performance, motion drive laws and control feel systems is given in Refs. 16 and 17.

4.4. Pilots and flight task

Two staff members of the Department of Aerospace Engineering acted as subjects in the experiment. Both are experienced pilots having flight experience in general aviation and in regular airline service amounting to a total of approximately 1100 and 1700 hours respectively. Flight experience on the DHC-2 "Beaver" aircraft is approximately 100 hours for pilot A and 65 hours for pilot B. One pilot took part in the preliminary flight simulator evaluation program. He has much simulator experience, whereas the second pilot has only limited simulator experience.
Training in the flight task was performed in patchy turbulence comparable to those of the test cases, but none of the pilots ever flew in the patchy turbulence realisations of the test cases. The 10 patchy turbulence testcases were flown in random order. The pilots were not informed about the conditions of the turbulence with respect to its patchy nature. Pilot A performed a total of 4 repetitions during 40 runs, each lasting 3½ minutes. Pilot B performed only two repetitions during 20 runs, each lasting also 3½ minutes. The actual patchy conditions of the test-cases have been presented in Fig. 17. The flight task simply was to maintain straight and level flight at an altitude of 500 ft as accurately as possible.

4.5. Physiological effects on the pilot due to non-gaussian turbulence

During the turbulence simulation runs the following physiological activities have been measured:
a. Skin resistance
b. Heart rate variability (sinus arrhythmia).
Variations in skin resistance and heart rate variability may provide indications of changes in levels of nervous activity, see Ref. 18 and have been used to detect changes in arousal. The concept of arousal has been accepted by many as being synonomous with activation, which "appears to affect intensity and coordination of response and therefore the quality of performance", see Ref. 18. An equal level of performance can be obtained in a specific flight task by increasing the effort put out by the pilot, if the environmental conditions become more demanding. It seems, therefore, worthwhile to measure the pilot's physiological activity as an indication of changes in effort and therefore workload. In view of the patchy nature of the turbulence, it can be argued that alternating workload patterns will exist. If the pilot's physiological activity reflects those patterns, the physiological measurements may be helpful in augmenting the subjective measures of pilot workload in terms of pilot ratings in subsequent experiments.

Skin resistance has been measured by passing a small direct current between two electrodes, attached to the innerside of the pilot's left foot. From the resulting signal two components can be distinguished, when properly filtered, viz. a low frequency component related to the overall level of activation and a high frequency component related to "sudden events", which has been used to detect changes in activation, see Ref. 19. At the same time heart rate variability has been measured using a cardiotachometer and results are displayed as a beat-to-beat plot of heart rate against time. In this way a possible suppression of variability of sinus arrhythmia during a short period of time can be detected. According to Ref. 18 such a phenomenon is considered indicative of increase of a short-time workload.
In Figs. 19 to 22 some typical examples of the recorded flight parameters as well as the turbulence input and the physiological effects have been given. A significant increase of activity in the high frequency component of the skin resistance can be seen when going from the gaussian case to a non-gaussian case, see Figs. 20 and 22.
The high activity regions in the high frequency component of the skin resistance seem to correlate well with the patches, but statistical analysis has not yet been finished.
Only a few, tentative remarks on these data can be given here. In Fig. 23 a total of 3 repetitions of the

high frequency component of pilot A to a non-gaussian turbulence case are shown as well as his response to gaussian turbulence and rest condition. For comparison the bottom time-history shows the response of pilot B to the same turbulence. From this Figure it may be seen that the high frequency component of the skin resistance is accurately reproduced, flying the same patchy test case. The last two time-histories shown have been scaled down by a factor 2 to account for different sensor settings of pilot A, whereas pilot B showed in general a larger response during all runs. Although a suppression of sinus arrhythmia may be seen locally during heavy patches, such an effect is not very clear from visual inspection of the experimental data.

Relative performance of the two pilots in terms of r.m.s. values of pitch-angle, roll-angle and yaw-angle as well as δ_e and δ_a are shown in Figs. 24 to 28. Due to the patchy nature of the simulated turbulence and the relative shortness of the runs, i.e. 3½ minutes, significant differences between the long-term r.m.s. settings of turbulence and the r.m.s. values, actually measured over 3½ minutes may occur. To account for this effect, which will affect absolute performance measures, the r.m.s. values of pitch-angle, roll-angle, yaw-angle, elevator deflection angle and aileron-deflection angle have been normalized by correcting for these differences in calculating the r.m.s. values of the rolling and yawing moments caused by the respective disturbances. The resulting, corrected relative performance measures are presented in Figs. 24 to 28, as functions of the final measure of patchiness P_∞, see Section 3.3. It will be seen that the relative performance of the pilots remains at a more or less constant level at all patchiness conditions. It is, however, very interesting to note a tendency to produce more consistent results as patchiness increases. This effect is most clearly seen in the scatter behaviour of the r.m.s. values of the aileron deflection angle, see Fig. 28. According to Ref. 18 this reduced scatter may also be seen as an indication of increased workload with increasing patchiness.

5. CONCLUSIONS

In this paper certain non-gaussian characteristics of atmospheric turbulence have been described. They have been classified as patchiness and intermittency. Both characteristics can be included in an atmospheric turbulence simulation. Based upon the non-gaussian simulation technique, described in this paper the mutual dependence of patchiness and intermittency has been explained and established in mathematical terms. The use of the non-gaussian simulation technique is highly flexible in its ability to match the various non-gaussian statistical properties as observed in the actual atmosphere. With respect to the described simulator experiment, the relative level of performance seemed to be very nearly constant in all patchy conditions. Increased activity in the high frequency component of the skin resistance, as well as reduced scatter in the performance data indicated an increase workload level when patchiness increases, while the intensity of the turbulence and its power spectral density remain constant. A similar effect, however, on sinus arrhytmia has not yet clearly been detected from visual inspection alone.

6. REFERENCES

1. Rosenblatt, M., Van Atta, C. (Editors) — Statistical models and turbulence, Lecture Notes in Physics, Springer-Verlag, Berlin, Heidelberg, New York, 1972.

2. Reeves, P.M. — A non-Gaussian turbulence simulation, AFFDL-TR-69-71, 1969.

3. Reeves, P.M., Campbell, G.S., et al. — Development and application of a non-Gaussian atmospheric turbulence model for use in flight simulators, NASA-CR-2451, 1974.

4. van de Moesdijk, G.A.J. — The description of patchy atmospheric turbulence, based on a non-Gaussian simulation technique, Delft University of Technology, Report VTH-192, 1975.

5. van de Moesdijk, G.A.J. — Simulation of patchy atmospheric turbulence, based on measurements of actual turbulence, AGARD Conference Proceedings no. 198 on "Flight Simulation/Guidance Systems Simulation", 1975, The Hague.

6. Gerlach, O.H., van de Moesdijk, G.A.J., van der Vaart, J.C. — Progress in the mathematical modelling of flight in turbulence. AGARD Conference Proceedings no. 140 on "Flight in Turbulence, 1973, Woburn Abbey.

7. Tomlinson, B.N. — Developments in the simulation of atmospheric turbulence, AGARD Conference Proceedings no. 198 on "Flight Simulation/Guidance Systems Simulation", 1975, The Hague.

8. Papoulis, A. — Probability, random variables and stochastic processes, McGraw-Hill, 1965, New York.

9. Sidwell, K. — A mathematical examination of the Press model for atmospheric turbulence, NASA TN D-8038. 1975.

10. Lumley, J.L., Panofsky, H.A. — The structure of atmospheric turbulence, J. Wiley & Sons, New York, 1964.

11. Spark, E.H., Dutton, J.A. — Phase angle considerations in the modelling of intermittent turbulence, Journal of the Atmospheric Sciences, Volume 29, 1972.

12. van de Moesdijk, G.A.J. — Pilot response to the non-gaussian structure of atmospheric

turbulence, University of Technology, Report LR (to be published).

13. Gerlach, O.H. — Calculation of the response of an aircraft to random atmospheric turbulence, Part I: symmetric motions, Delft University of Technology, Report VTH-138, 1966.

14. Gerlach, O.H.; Baarspul, M. — Calculation of the response of an aircraft to random atmospheric turbulence, Part II: asymmetric motions, Delft University of Technology, Report VTH-139, 1968.

15. van der Vaart, J.C. — Calculation of the r.m.s. value of the normal acceleration of an aircraft due to turbulence, Delft University of Technology, Report VTH-213, 1976.

16. Baarspul, M.; van Dooren, J.P. — The hybrid simulation of aircraft motions in a piloted moving-base flight simulator, Delft University of Technology, Report VTH-178, 1976.

17. den Hollander, J.G.; Baarspul, M. — The three-degree-of-freedom motion system of the Department of Aerospace Engineering of Delft University of Technology, Report VTH-269, 1978.

18. Roscoe, A.H. — Physiological methods, AGARDograph no. 233, "Assessing Pilot workload", 1978.

19. Anon. — Het NLR fysiologisch meetsysteem, NLR Memorandum VV-77-001 U, Amsterdam, 1977 (in Dutch).

20. Anon. — Approach and landing simulation, AGARD Report no. 632, 1975.

APPENDIX A

According to Ref. 14, Section 4.4., the asymmetric moments due to the two-dimensional horizontal and vertical turbulence velocities may be approximated by the following one-dimensional power spectral densities:

Rolling moment due to horizontal turbulence velocities:

$$\Phi_{C_{\ell_g}}(\Omega_x\ Lg,\ B) = C^2_{\ell_{r_w}}\ I_{\hat{u}_g}(\Omega_x\ Lg,\ B)$$

Rolling moment due to vertical turbulence velocities:

$$\Phi_{C_{\ell_g}}(\Omega_x\ Lg,\ B) = C^2_{\ell_{p_w}}\ I_{\alpha_g}(\Omega_x\ Lg,\ B)$$

Yawing moment due to horizontal turbulence velocities:

$$\Phi_{C_{n_g}}(\Omega_x\ Lg,\ B) = C^2_{n_{r_w}}\ I_{\hat{u}_g}(\Omega_x\ Lg,\ B)$$

Yawing moment due to vertical turbulence velocities:

$$C_{n_g}(\Omega_x\ LG,\ B) = C^2_{n_{p_w}}\ I_{\alpha_g}(\Omega_x\ Lg,\ B)$$

where $C_{\ell_{r_w}}$, $C_{\ell_{p_w}}$, $C_{n_{r_w}}$ and $C_{n_{p_w}}$ express the contribution to the stability derivatives C_{ℓ_r}, C_{ℓ_p}, C_{n_r} and C_{n_p} of the wing.
$I_{\hat{u}_g}(\Omega_x\ Lg,\ B)$ and $I_{\alpha_g}(\Omega_x\ Lg,\ B)$ are effective one-dimensional power spectral density functions of, respectively, the stochastic two-dimensional turbulence velocities $\hat{u}_{g_a}$ and α_{g_a} giving rise to asymmetric moments.
To generate stochastic turbulence variables $\hat{u}_{g_a}$ and α_{g_a} as a function of time with patchy characteristics, serving as input signals to the asymmetric aircraft mathematical model, three gaussian white noise sources are used, driving three linear filters A, B and C to produce, each output signal, according to the block diagram of Fig. 3.
The filter transfer functions for the filters A, B and C respectively read:

$$H_a(j\omega) = \frac{1}{K_a}\sqrt{C}\ \frac{1}{1 + j\omega A}$$

$$H_b(j\omega) = \frac{1}{K_b}\sqrt{F}\left[\frac{B + j\omega E}{(1 + j\omega D)\ (1 + j\omega G)}\right]$$

$$H_c(j\omega) = \frac{1}{K_c}\sqrt{H}\left[\frac{1 + j\omega L}{(1 + j\omega M)\ (1 + j\omega N)}\right]$$

The constants A until N in the above expressions read:

Longitudinal turbulence velocities $\hat{u}_{g_a}$:

$$A = \frac{Lu}{V}\,\frac{R+1}{R}\,\tau_2$$

$$B = \left[\tau_2(R+1) - \tau_1 R\right]^{\frac{1}{2}} \cdot \left[1 + \frac{(\tau_2^2 - \tau_3^2)\,R}{\tau_2(\tau_2 + \tau_1)}\right]^{\frac{1}{2}}$$

$$C = \frac{Q}{\sqrt{1+Q^2}}\left[\frac{2}{\pi}\,I_{\hat{u}_g}(o,B)\left\{\frac{\tau_2^2 - \tau_3^2}{\tau_2(\tau_2^2 - \tau_3^2)} + \frac{\tau_1^2 - \tau_3^2}{\tau_1(\tau_1^2 - \tau_2^2)}\right\}\right]^{\frac{1}{2}}\frac{Lu}{V}\,\tau_2\,\frac{R+1}{R}$$

$$D = \frac{Lu}{V}\,(R+1)\,\tau_2$$

$$E = \frac{Lu}{V}\,(R+1)\left[\tau_2\tau_3^2 - \frac{R\tau_2^2(\tau_1^2 - \tau_3^2)}{(\tau_2 + \tau_1)}\right]^{\frac{1}{2}}$$

$$F = \frac{Q}{\sqrt{1+Q^2}}\left[\frac{2}{\pi}\,I_{\hat{u}_g}(o,B)\,\frac{\tau_2\tau_1(\tau_2^2 - \tau_1^2)}{\tau_1\tau_2^2 - \tau_1\tau_3^2 - \tau_2\tau_1^2 + \tau_2\tau_3^2}\right]^{\frac{1}{2}}\frac{\frac{Lu}{V}\,\tau_2(R+1)}{[\tau_2(R+1) - \tau_1 R]^2}$$

$$G = \frac{Lu}{V}\,\frac{\tau_2\tau_1(R+1)}{\tau_2(R+1) - \tau_1 R}$$

$$H = \frac{1}{1+Q^2}\,I_{\hat{u}_g}(o,B)$$

$$L = \frac{Lu}{V}\,\tau_3$$

$$M = \frac{Lu}{V}\,\tau_1$$

$$N = \frac{Lu}{V}\,\tau_2$$

K_a^2, K_b^2 and K_c^2 are constants of input white noise power spectral densities for the filters resulting in the $\hat{u}_{g_a}$ signal.

The same expressions for the filter transfer functions apply to the vertical turbulence velocity α_{g_a}, except that:

τ_1 should be replaced by τ_4
τ_2 should be replaced by τ_5
τ_3 should be replaced by τ_6
$I_{\hat{u}_g}(o,B)$ should be replaced by $I_{\alpha_g}(o,B)$
Lu should be replaced by Lw

The values of $I_{\hat{u}_g}(o,B)$, τ_1, τ_2, τ_3 and $I_{\alpha_g}(o,B)$, τ_4, τ_5, τ_6 are given in Ref. 14, dependent on wing span and integral scale length of atmospheric turbulence.

Table I - Aircraft data -

Weight = 2217 kgf
Wingarea = 23.23 m^2
Speed V = 52 m/sec.

$\bar{c}$ = 1.5875 m	C_L = 0.565
$2\mu_c$ = 97.963	b = 14.63 m
$2\mu_c K_Y^2$ = 125.686	$2\mu_b$ = 10.65
$2\mu_b K_X^2$ = 0.090	$2\mu_b K_Z^2$ = 0.2047
	K_{XZ} = 0

Stability derivatives

C_{X_o} = 0	C_{Z_o} = -0.565	
C_{X_u} = -0.18	C_{Z_u} = -1.27	C_{m_u} = 0.031
C_{X_α} = 0.374	C_{Z_α} = -5.74	C_{m_α} = -1.051
$C_{X_{\dot\alpha}}$ = 0	$C_{Z_{\dot\alpha}}$ = -0.74	$C_{m_{\dot\alpha}}$ = -2.817
C_{X_q} = 0	C_{Z_q} = -4.32	C_{m_q} = -16.3
C_{X_δ} = 0	C_{Z_δ} = -0.407	C_{m_δ} = -2.00
C_{Y_β} = -0.684	C_{ℓ_β} = -0.0805	C_{n_β} = 0.031
C_{Y_p} = 0	C_{ℓ_p} = -0.6319	C_{n_p} = -0.038
C_{Y_r} = -0.145	C_{ℓ_r} = 0.0926	C_{n_r} = -0.057
$C_{Y_{\delta_a}}$ = 0	$C_{\ell_{\delta_a}}$ = -0.18	$C_{n_{\delta_a}}$ = -0.003
$C_{Y_{\delta_r}}$ = 0.0607	$C_{\ell_{\delta_r}}$ = 0.006	$C_{n_{\delta_r}}$ = -0.062
$C_{Y_{\dot\beta}}$ = 0		$C_{n_{\dot\beta}}$ = 0.0

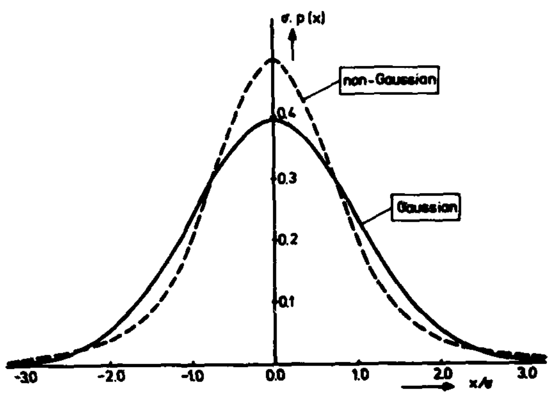


Fig. 1. The Gaussian - and a possible non-Gaussian distribution function.

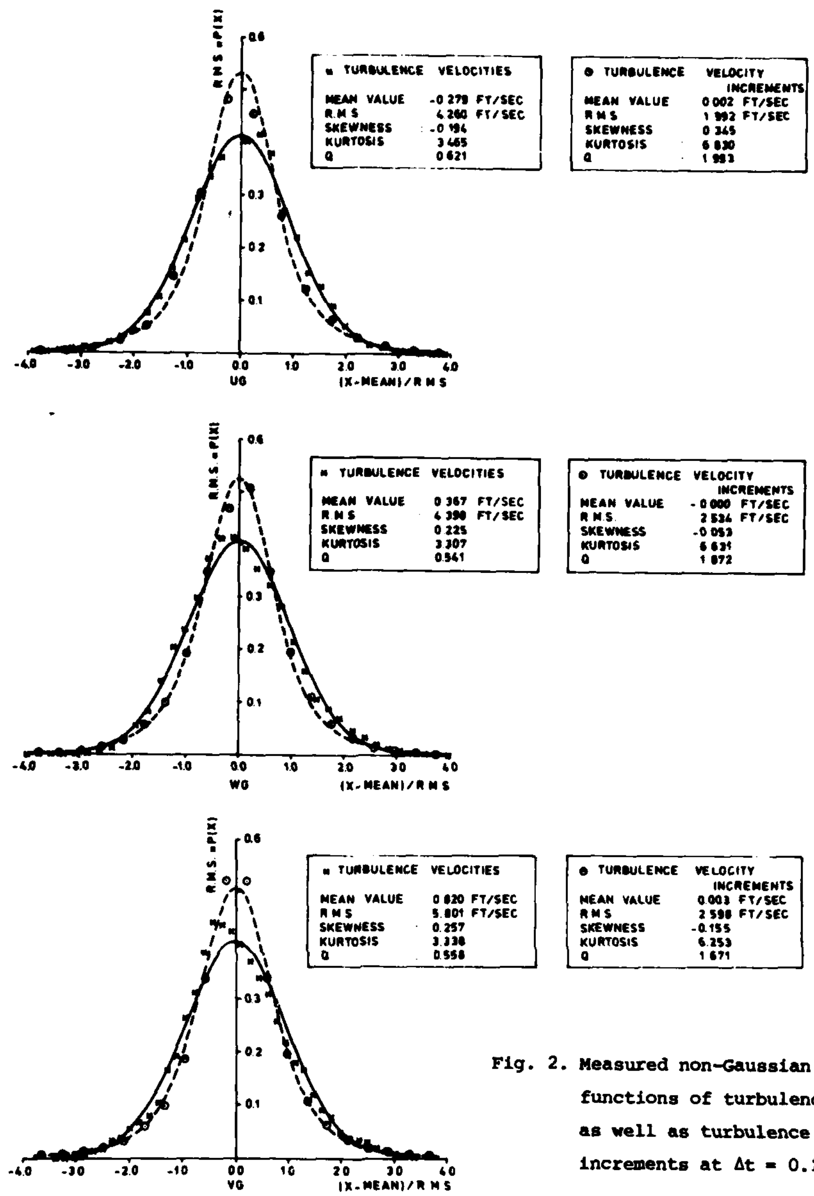


Fig. 2. Measured non-Gaussian distribution functions of turbulence velocities as well as turbulence velocity increments at Δt = 0.1 sec.

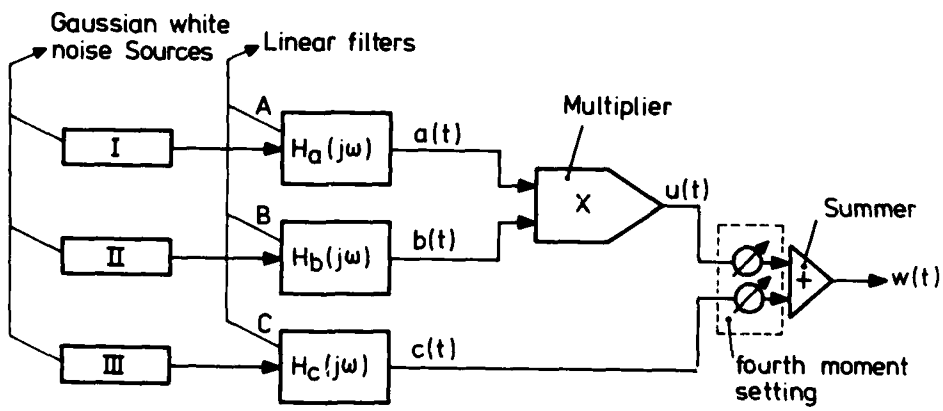


Fig. 3. Block diagram, representing the generation of a non-Gaussian process having an arbitrary fourth order moment: $3\sigma^4 < m_4 < 9\sigma^4$.

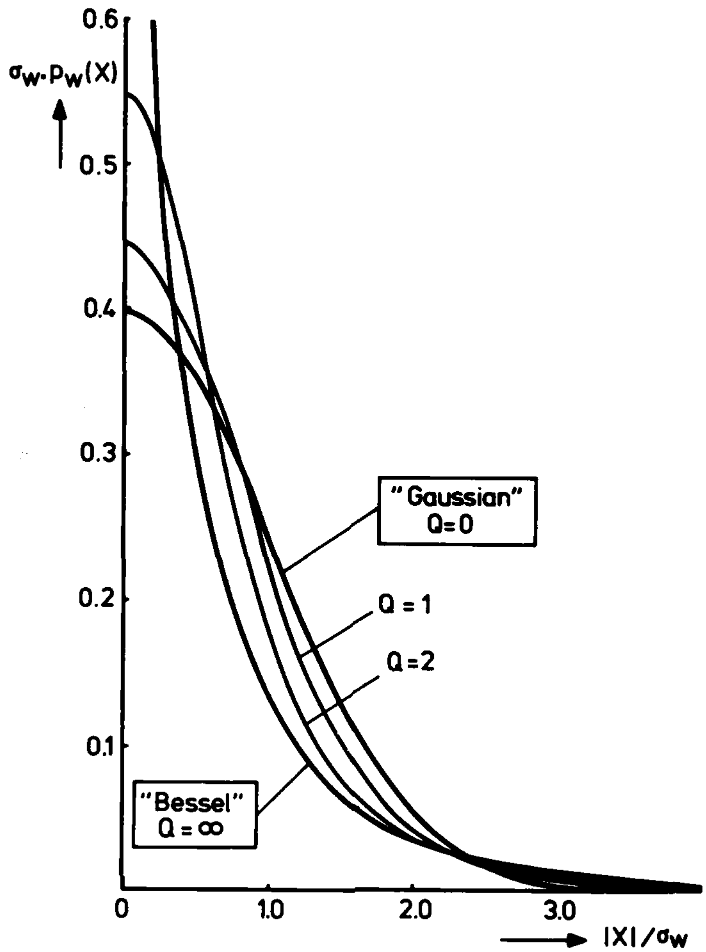


Fig. 4. Normalized probability density functions of w(t) for various values of Q.

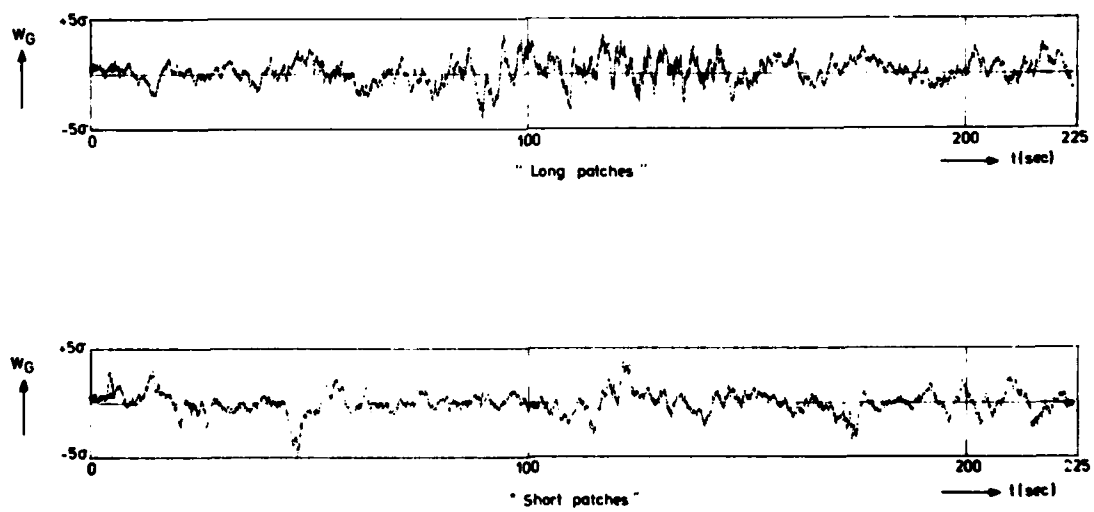


Fig. 5. Two non-gaussian turbulence records with the same fourth order moment setting but different "average patchlength".

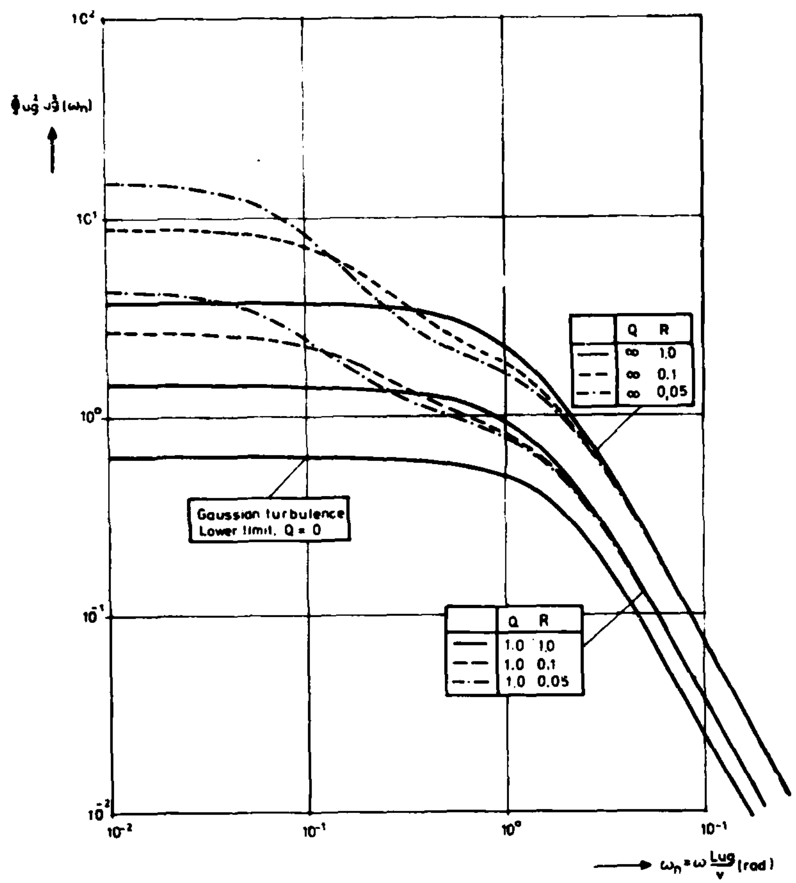


Fig. 6. The power spectral density of the squared longitudinal turbulence velocity.

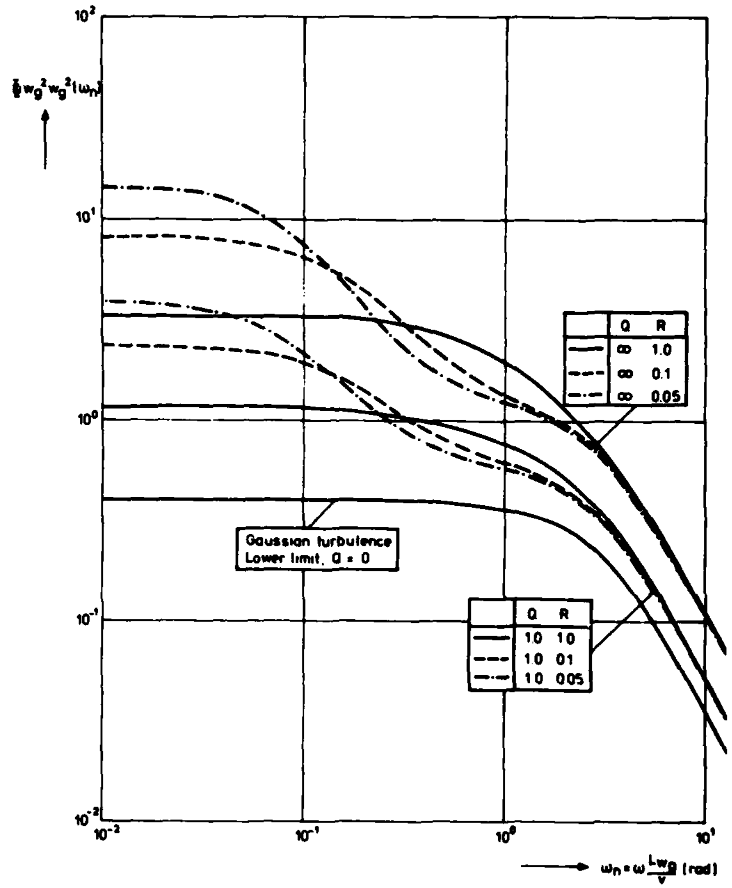


Fig. 7. The power spectral density of the squared vectical or lateral turbulence velocity.

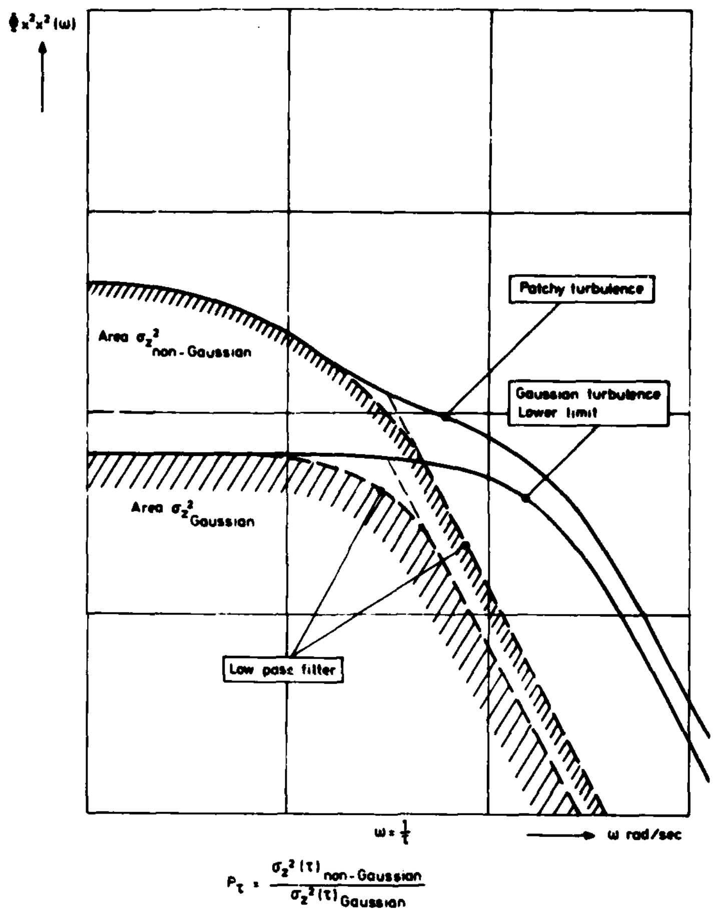


Fig. 8. Construction of the patchiness parameter P_τ.

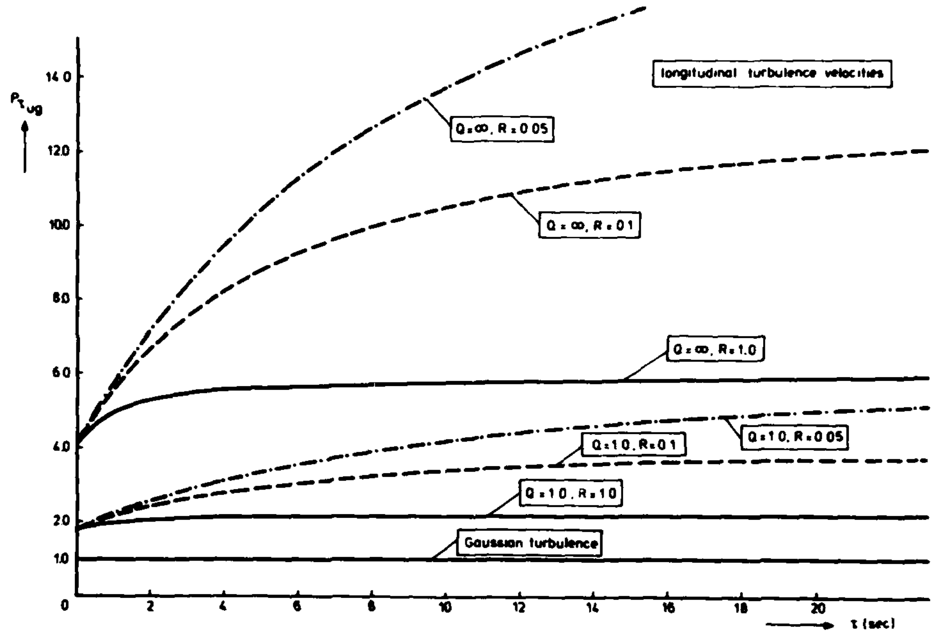


Fig. 9. The patchiness P_τ, as a function of τ, time-constant of the low-pass first order filter.

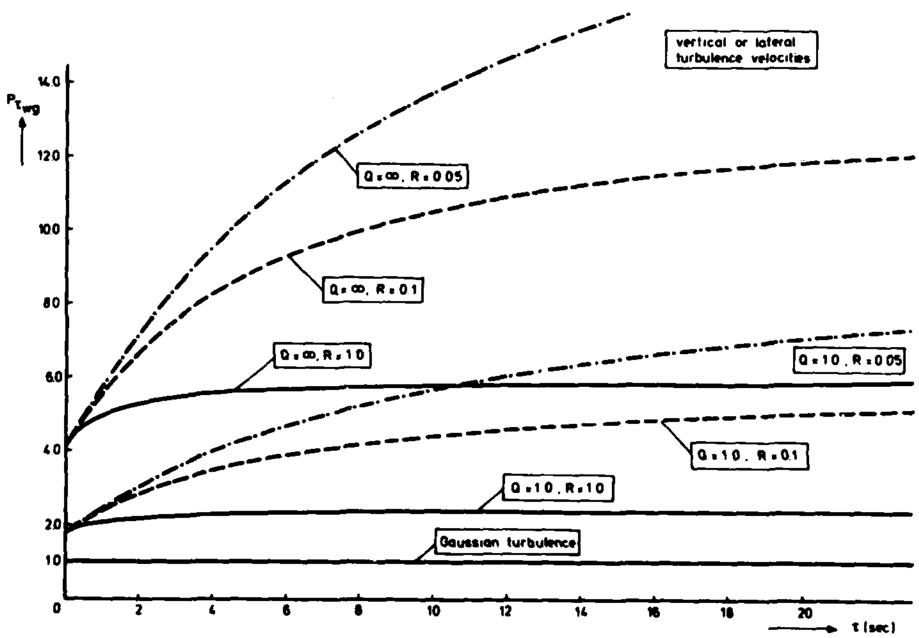


Fig. 10. The patchiness P_τ, as a function of τ, time-constant of the low-pass first order filter.

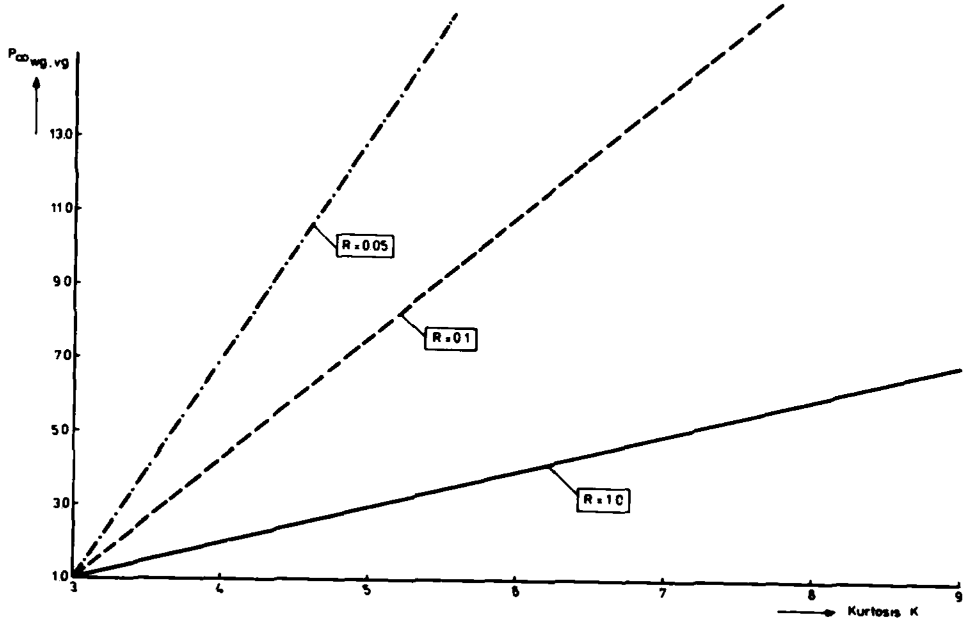


Fig. 11. The patchiness parameter P_∞ as a function of the Kurtosis, vertical or lateral turbulence velocities.

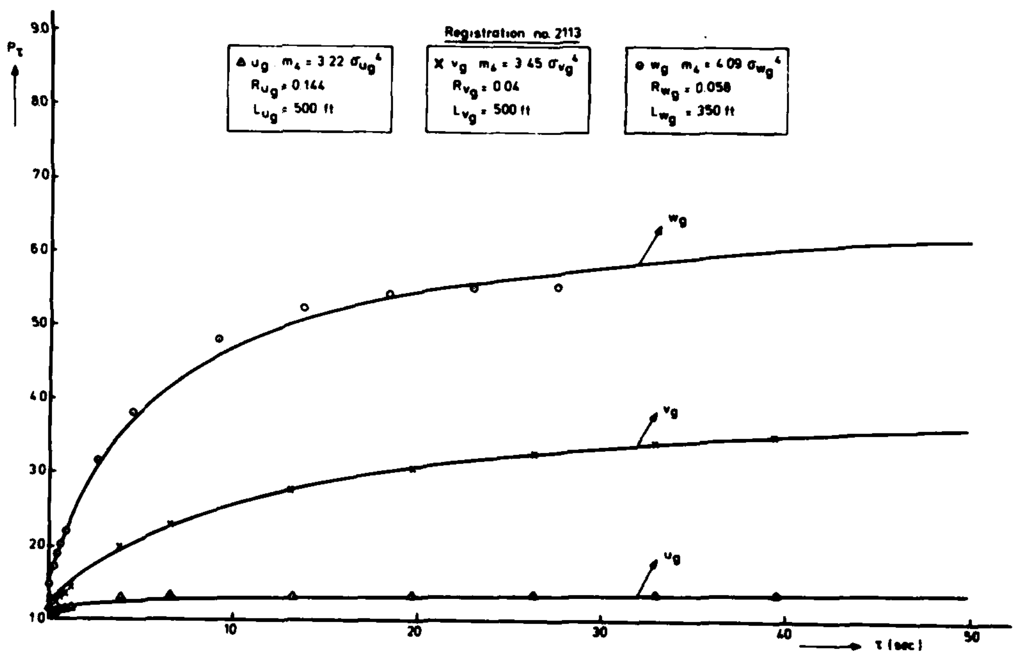


Fig. 12. Measurement of P_τ from actual turbulence data and model results.

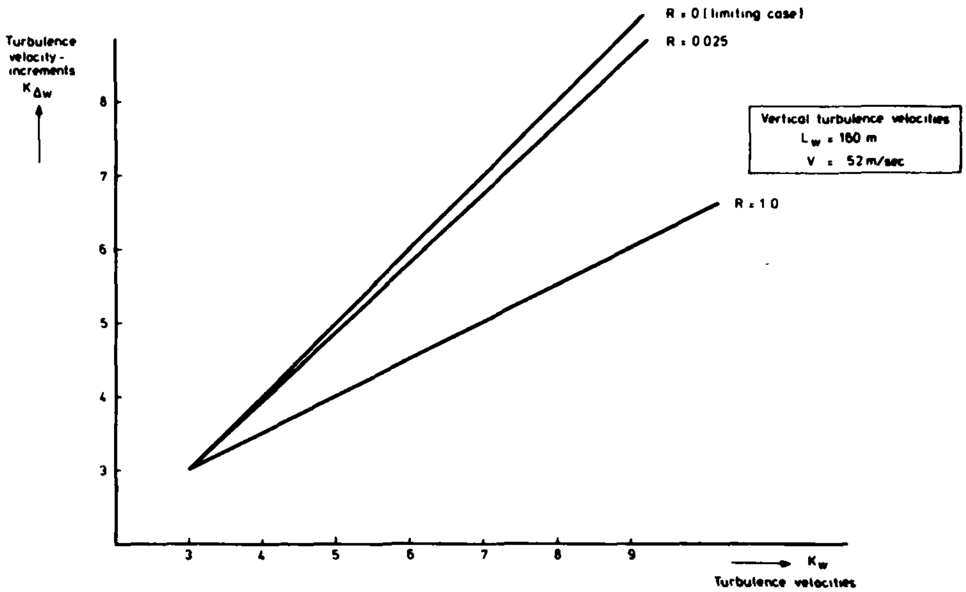


Fig. 13. Model prediction of Kurtosis values of turbulence velocities and turbulence velocity increments at $\Delta t = 0.1$ sec.

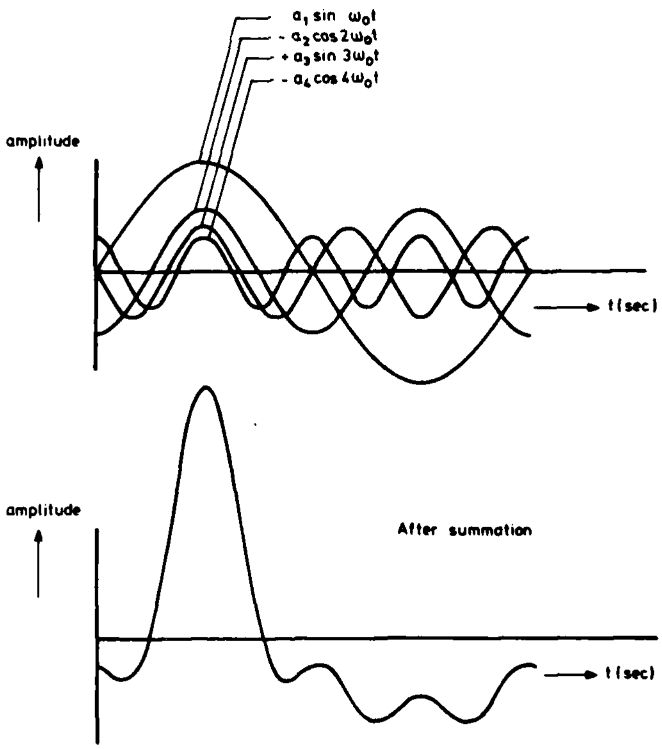


Fig. 14. Illustration of phase angles producing "intermittent" peak.

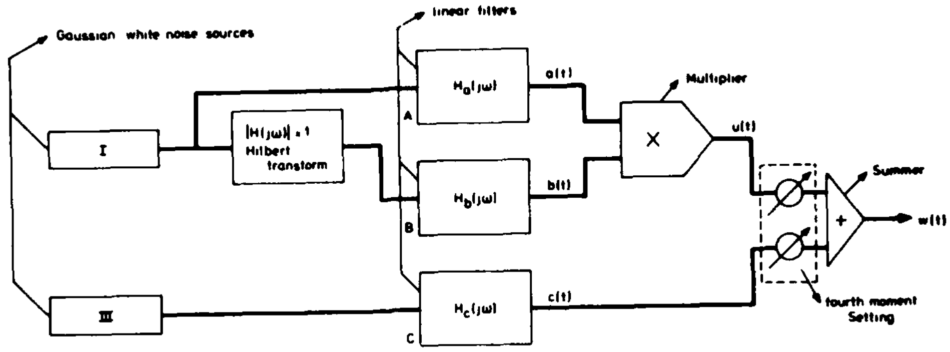


Fig. 15. Block diagram of modified non-gaussian turbulence generation.

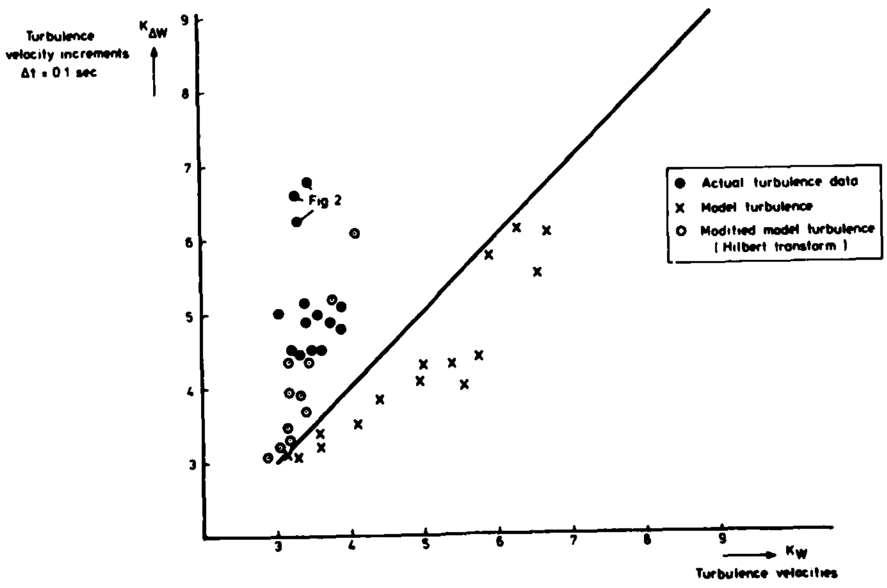


Fig. 16. Kurtosis values of the turbulence velocities and Kurtosis values of velocity increments from the same data.

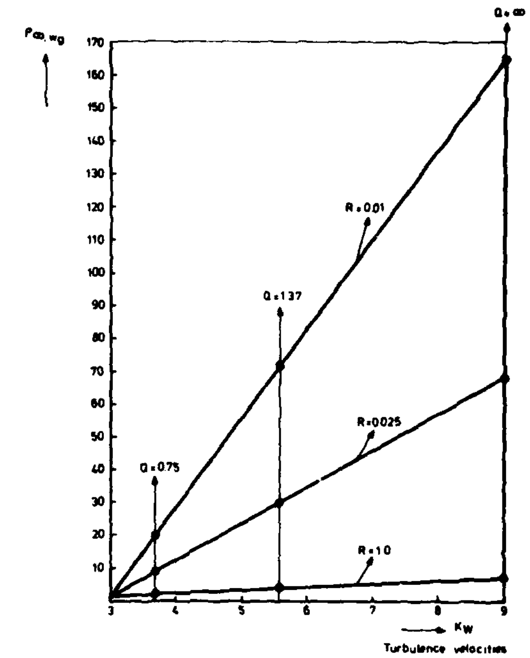


Fig. 17. Testcases of patchiness in the simulator experiment.

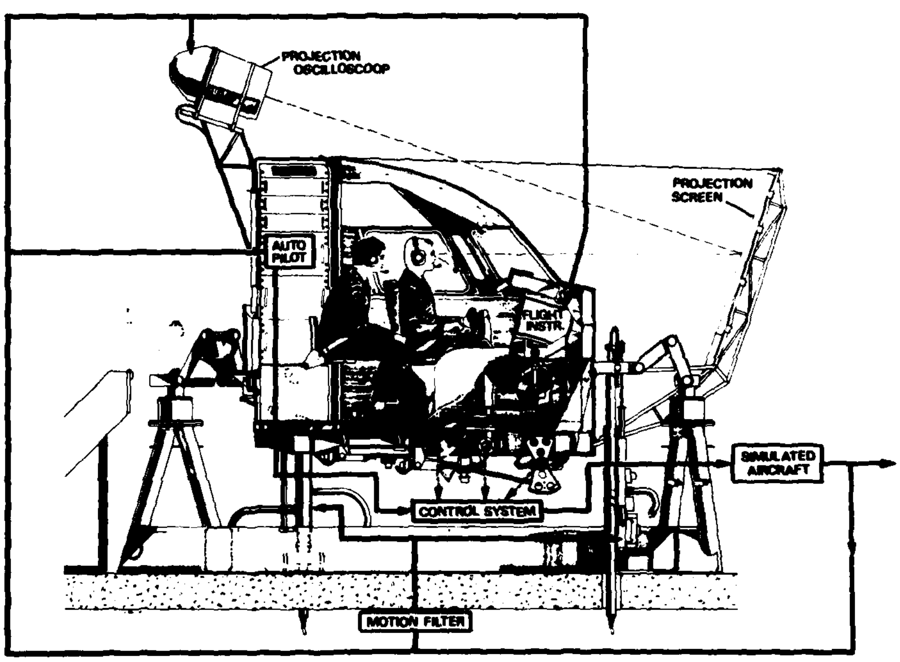


Fig. 18. Layout of the piloted flight simulation.

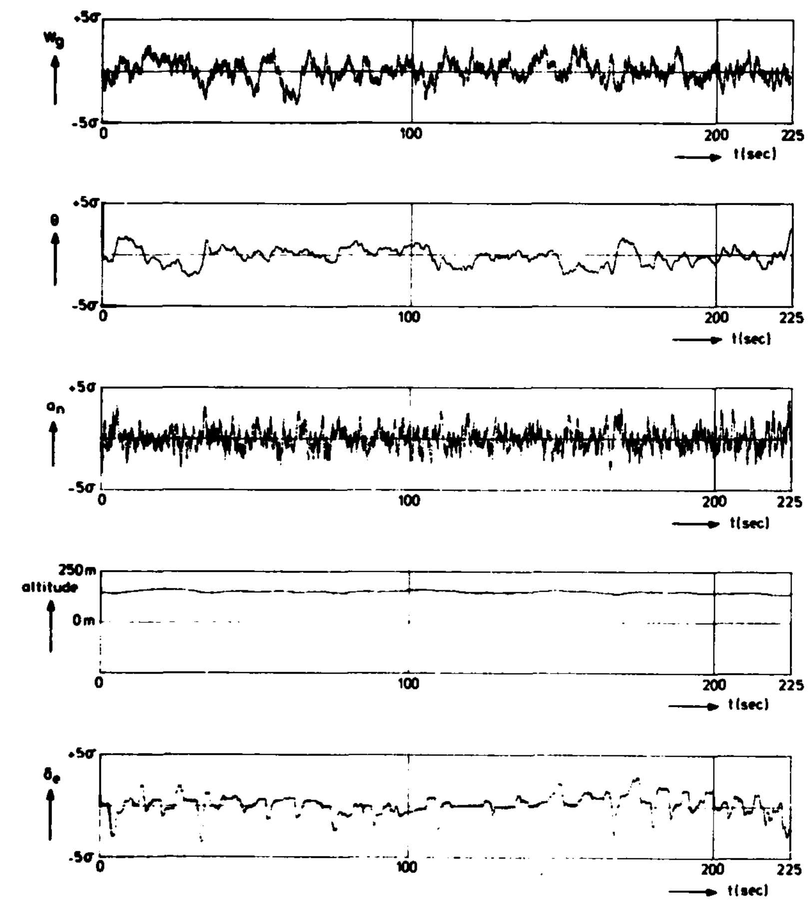


Fig. 19. Flight parameter records in gaussian turbulence (Pilot A).

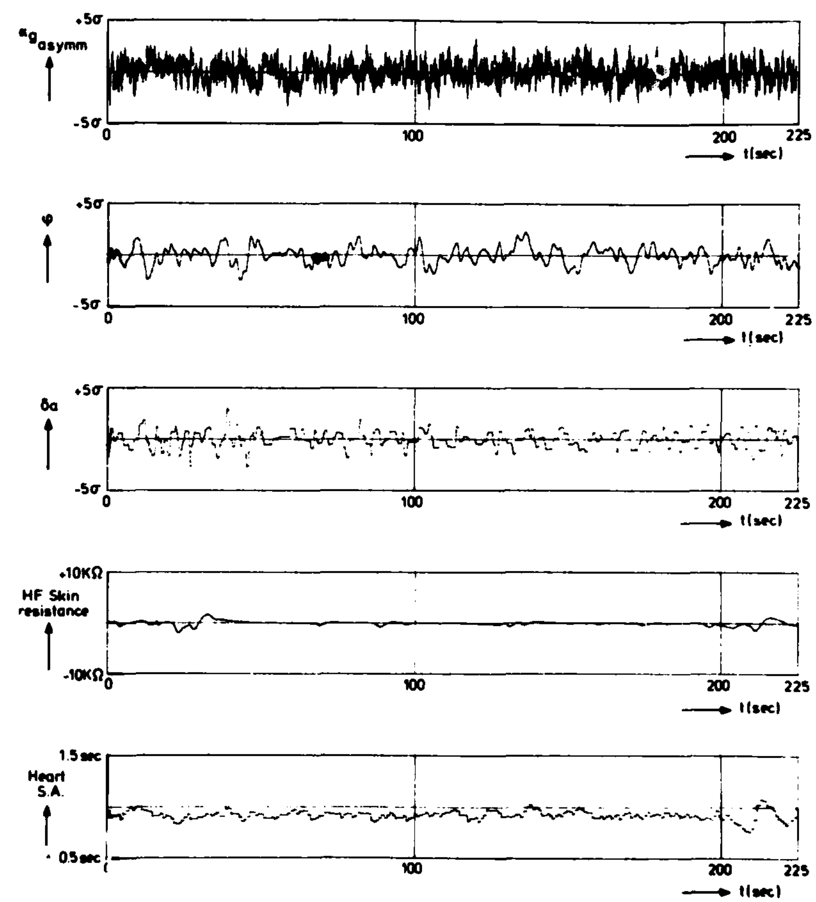


Fig. 20. Flight parameter records and physological effects in gaussian turbulence (Pilot A).

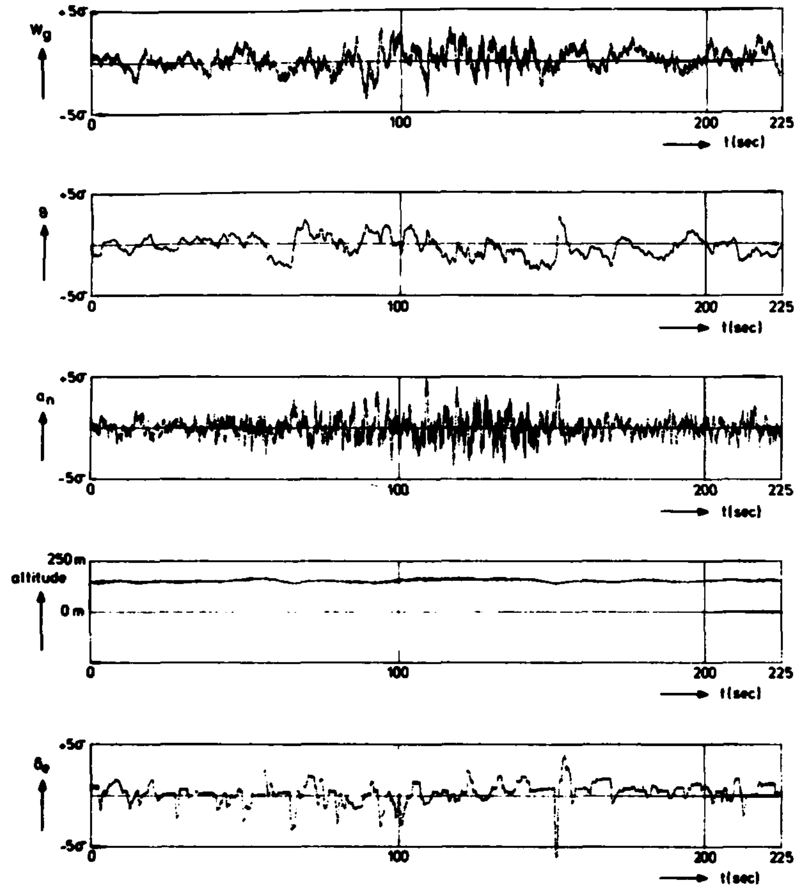


Fig. 21. Flight parameter records in non-gaussian turbulence, $P_\infty \approx 30$ (Pilot A).

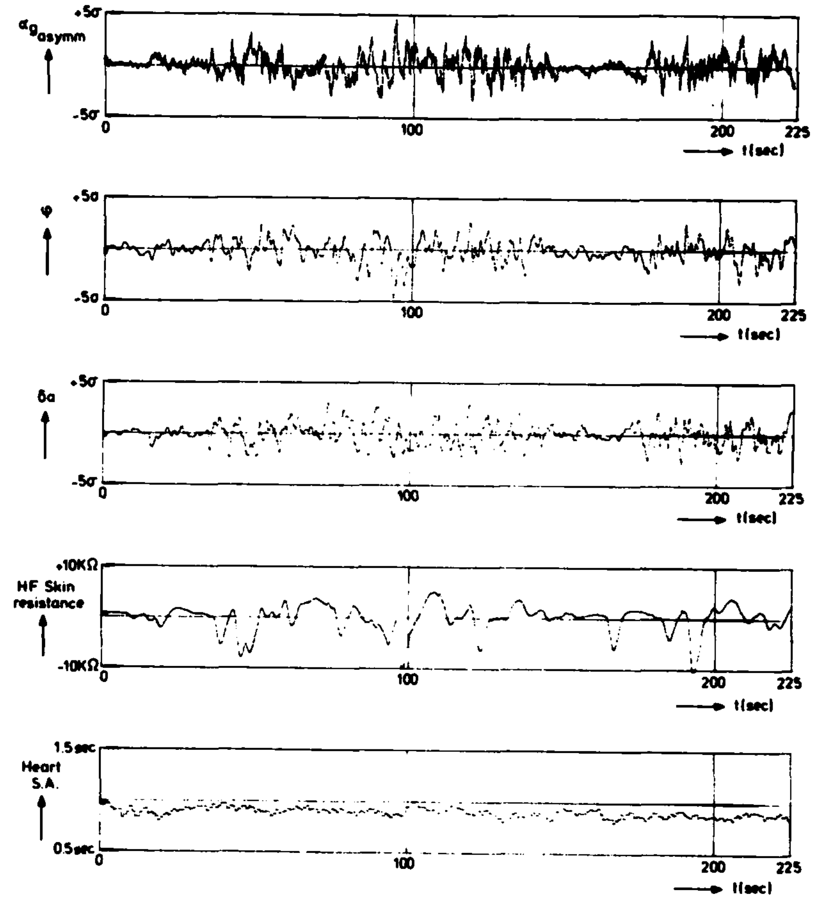


Fig. 22. Flight parameter records in non-gaussian turbulence, $P_\infty = 30$ and physological effects (Pilot A).

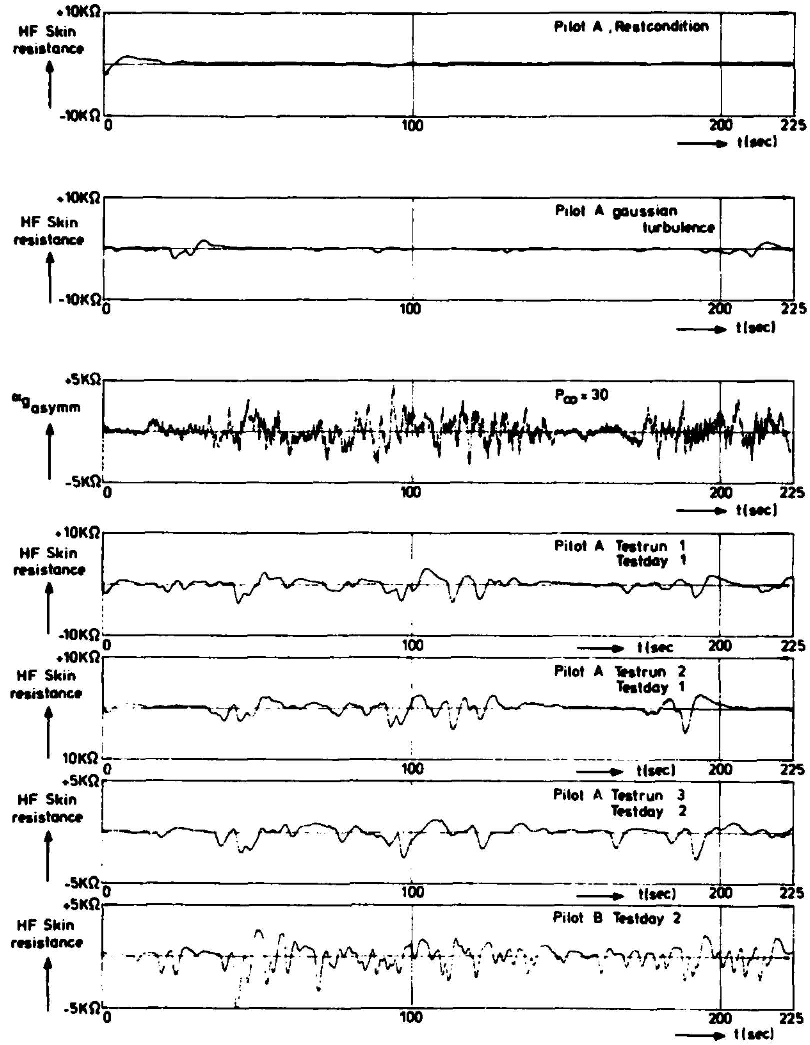


Fig. 23. Comparison of H.F. skin resistance results.

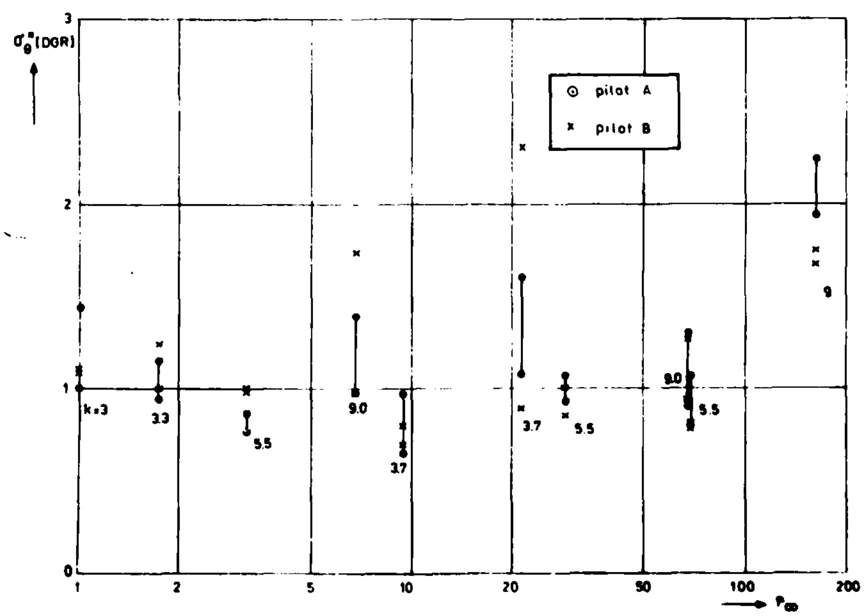


Fig. 24. Normalized r.m.s. values of pitch-angle as a function of patchiness.

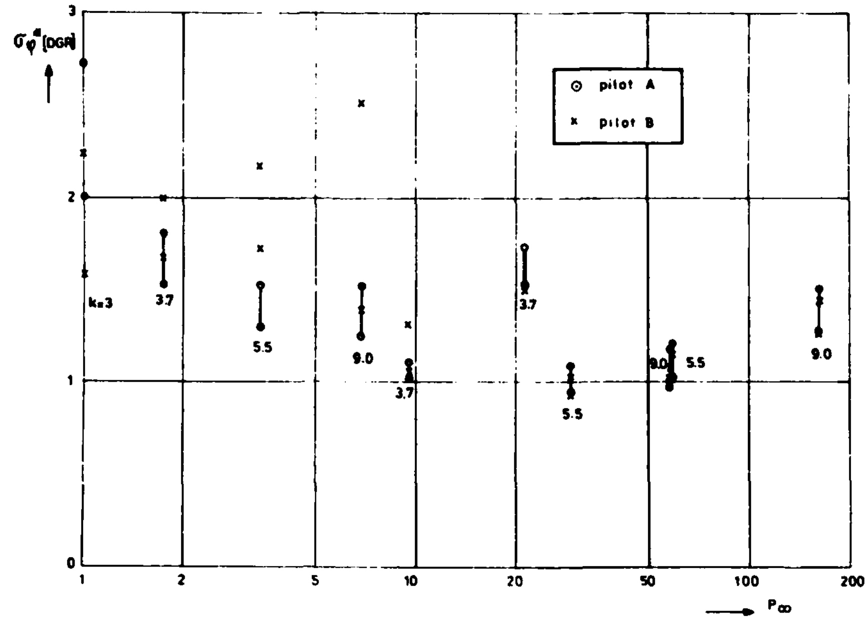


Fig. 25. Normalized r.m.s. values of roll-angle as a function of patchiness.

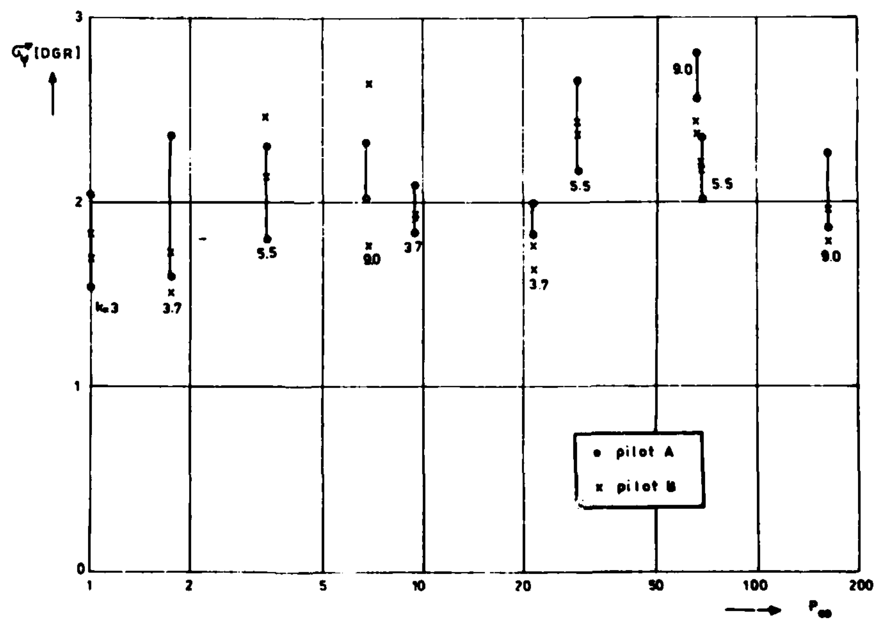


Fig. 26. Normalized r.m.s. values of yaw-angle as a function of patchiness.

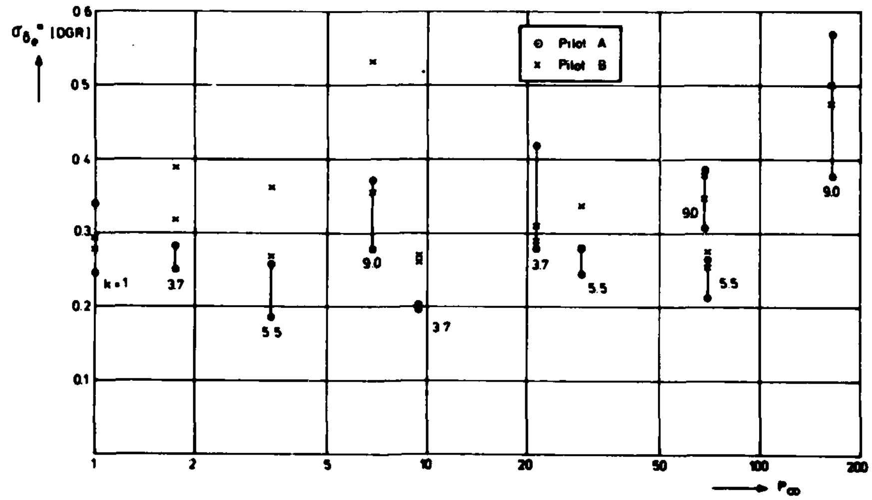


Fig. 27. Normalized r.m.s. values of elevator deflection angles as a function of patchiness.

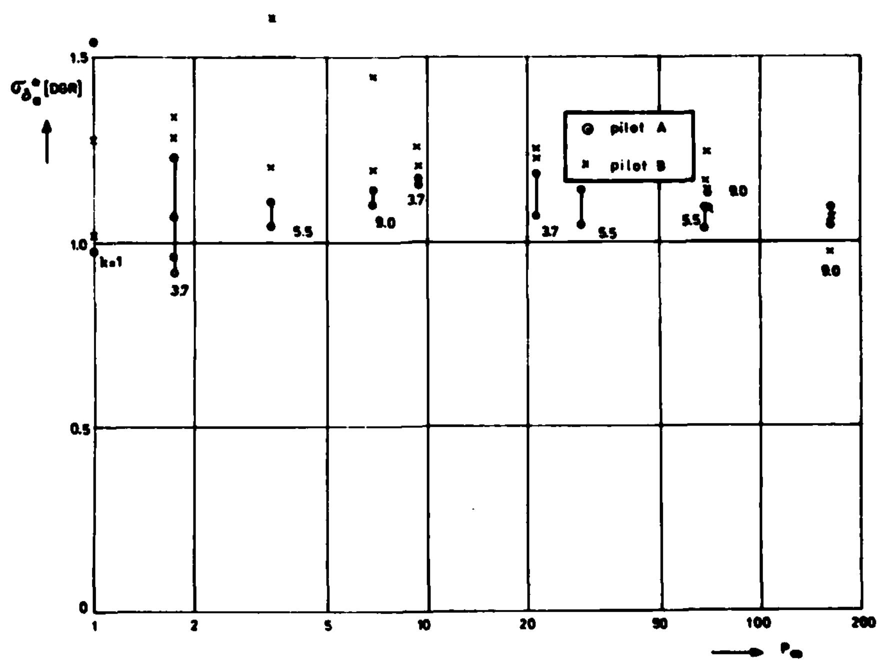


Fig. 28. Normalized r.m.s. values of aileron deflection angles as a function of patchiness.

HANDLING QUALITIES OF A SIMULATED STOL AIRCRAFT IN NATURAL AND COMPUTER-GENERATED TURBULENCE AND SHEAR

S.R.M. Sinclair
Flight Research Laboratory
National Aeronautical Establishment
Ottawa, Canada K1A 0R6

and

LTC T.C. West
Systems Research and Development Service
U.S. Federal Aviation Administration
Washington, D.C. 20591

1. INTRODUCTION

Aircraft capable of STOL operations generally have some common physical and operational characteristics which accentuate the influence of atmospheric disturbances on their flying qualities. Unassisted STOL performance demands, for example, that approach and departure flight segments be flown at relatively low airspeeds where the effects of windshear on the aircraft trajectory are magnified. When the short field performance is achieved through the use of power-induced lift or vectored thrust the handling characteristics of such a STOL aircraft operating in turbulence can be dominated by the vehicle's inherently low levels of aerodynamic damping and speed stability and the trajectory control task may be compounded by unconventional response associated with operation near the bottom or on the backside of the thrust-required curve.

Problems related to flight in turbulence are further aggravated by the STOL operational environment when this includes flight in confined or built-up areas. The topography of such STOLport environs provides a complex set of boundary conditions for the atmospheric flow and may favour generation of strong mechanical turbulence and windshears.

Over the past ten years the United States Federal Aviation Administration (FAA) has conducted a series of flight simulation experiments with the aim of identifying operational limits and minimum acceptable levels of flying qualities for powered-lift aircraft (ref. 1). The special significance of the interaction between aircraft dynamics and the dynamics of the atmosphere during low speed, STOL, flight has played an important role in the design of these experiments and has been borne out by the results of pilot evaluations. It has been necessary, however, to generate the turbulence inputs for the ground-based simulator experiments from computer models of atmospheric disturbances. The basis for the simulated turbulence has most often been the so-called "MIL-SPEC" model (ref. 2) which is a continuous spectrum representation with spectra of the Dryden or von Karman form and with gaussian amplitude distributions.

In contrast to these simple mathematical representations real turbulence is found to have distinctly non-gaussian velocity distributions and to exhibit intermittency and patchiness which are not present in the MIL-SPEC model. Predictability and monotony are often cited as unrealistic qualities of this modelled turbulence which is noticeably lacking in large amplitude excursions. To overcome these subjective deficiencies in the turbulence models used in flight simulation several different modelling techniques have been adopted (refs. 3 and 4 describe two of these); however, none of these statistical models includes a realistic representation of the low frequency wind variation upon which the turbulent motions are superimposed. In the real STOL operational environment these low frequency variations in wind either as a function of time or altitude may play an important role in establishing the pilot workload during final approach tracking. Simple geometrical shears are often introduced in ground-based simulator experiments but these are usually monotonic, localized disturbances which do not attempt to simulate the more complex wind variations of the real atmosphere.

The National Aeronautical Establishment of Canada has also conducted a series of simulation experiments to investigate handling qualities of powered-lift aircraft (refs. 5, 6). Although these airborne simulation experiments were designed to employ computer-generated rather than real turbulence so that specific experimental tasks could be accurately repeated, it was not possible to eliminate totally the influences of real windshears. Flights were planned to coincide with periods when the forecast winds were light and atmospheric conditions stable, nevertheless windshears were encountered from time to time and their strong influence on tracking workload was observed.

It was upon this base of experience in the simulation of powered-lift aircraft and their flight environments that the experiment described here was developed. A program was undertaken to measure naturally-occurring windshears and turbulence along the approach to an urban STOLport and to investigate the effects of these atmospheric disturbances on the flying qualities of a powered-lift STOL aircraft. The experiment entailed both an in-flight phase using the NAE Airborne V/STOL Simulator and a ground-based simulation phase which was performed on the Flight Simulator for Advanced Aircraft (FSAA) at the National Aeronautics and Space Administration's Ames Research Center. During the flight phase of the experiment the Airborne Simulator was flown in repeated instrument approaches to the Rockcliffe (Ottawa) STOLport. The simulator was programmed with the characteristics of a moderately backsided STOL aircraft and the flights were conducted in a variety of atmospheric conditions. The ambient winds and turbulence were measured and recorded during each approach using the Airborne Simulator's wind sensing system. The entire experiment was then repeated in detail on the FSAA, reproducing the simulated aircraft characteristics and injecting as disturbance terms in the simulator model the wind and turbulence time histories recorded during the airborne approaches. For comparison, additional approaches were flown in the FSAA replacing the taped atmospheric disturbances with computer-generated turbulence.

The specific objectives of the experiment were:

a) to document the characteristics of typical atmospheric disturbances encountered along the approach path to an urban STOLport;

b) to investigate the degrading effects of real atmospheric disturbances and computer-generated turbulence on the handling qualities of powered-lift STOL aircraft during approach tracking;

c) to compare the results of an evaluation of STOL approach handling qualities when the experiments are performed first in an airborne simulator and are repeated in a ground-based simulator with 6 degrees of motion freedom and a restricted-field, colour visual display.

2. THE SIMULATORS

The NAE Airborne V/STOL Simulator is an extensively modified Bell Model 205A-1 helicopter (Fig. 1). The right hand cockpit of the simulator, which is the evaluation pilot's cockpit, is equipped with a fly-by-wire control system with the full authority of the basic helicopter controls. The on-board simulation systems include a hybrid computing system, an array of high quality motion sensors and an electrohydraulic control force feel system. The computing system, in addition to performing the simulation model dynamic calculations, forms an integral part of the fly-by-wire system and provides the necessary simulator control and motion feedback signal processing. A dedicated micro-processor which is interfaced with the master computing system and through this link to the motion sensing systems, produces an on-line estimate of the ambient winds and turbulence components.

These systems and the way in which they are employed to perform airborne simulations of V/STOL aircraft are described in more detail in references 7 and 8.

The Flight Simulator for Advanced Aircraft has been a major source of experimental data on STOL flying qualities and was the primary experimental facility used by the FAA in its program to establish and evaluate tentative STOL airworthiness criteria. The FSAA is capable of relatively large amplitude motions in six degrees of freedom and is equipped with a Redifon colour visual display.

Physical and operational characteristics of the simulator are described in detail in reference 9. The simple model which was required for this experiment was readily implemented on the FSAA without approximation and the only inaccuracies in the final presentation to the evaluation pilots were the unavoidable ones associated with limited field-of-view and limited travel and frequency response of the motion system. The former affected only the short final segment of the approach task, however the effects of motion washout represent a more fundamental unknown pervading the ground-based experiment.

3. THE MODELLED AIRCRAFT CHARACTERISTICS

The STOL aircraft model which was implemented on both the Airborne Simulator and the FSAA was strongly backsided with a steepening flight path instability with decreasing speed (Fig. 2). The positive slope of the constant pitch attitude lines in the γ-V diagram is conventional in the sense that addition of thrust, with attitude constrained, produces an increase in airspeed as well as an increase in flight path angle. With power lever fixed, trim speed was very sensitive to attitude changes. This characteristic aggravated the speed control task when tracking in turbulence since the pilot could not close an effective inner speed loop on pitch attitude. These characteristics were deliberately designed into the model because they were considered to be typical of a class of handling qualities deficiencies prevalent in powered-lift aircraft.

The responses of the model to a longitudinal stick pulse and to a power lever step are shown in Figures 3 and 4. The model control system provided rate command/attitude hold modes in both the pitch and roll axes. The directional axis was augmented with good rate damping and directional stiffening based on inertial rather than air-referenced lateral velocity feedback. As a result of this inertial feedback, the system provided a degree of directional gust alleviation.

The modelled aircraft instrument panel provided only the basic information required for instrument-referenced flight. Tracking information was provided in the form of raw approach aid deviation signals displayed at the main attitude instrument. A small pointer at the right margin of the attitude instrument was programmed to display true airspeed deviations from the approach target speed of 65 knots, providing this vernier speed information at a sensitivity of 5 knots per dot and 8 knots full-scale.

4. THE EVALUATION TASK

Evaluation flights were conducted within the terminal control zone of the Rockcliffe STOLport which is located at the northeast corner of the city of Ottawa. The flying task is depicted in Figure 5. The evaluation pilot took control of the simulator in straight and level flight at 1800 feet above runway altitude, on-speed for the 65 knot STOL approach. At the model-engagement point the simulator was one dot (one degree) below the 6-degree approach beam of the microwave landing system and was positioned one dot (three degrees) left or right of the on-course. Glidepath capture and tracking to an altitude of 200 feet above ground were performed using instrument flight references and a final visual approach segment was executed to a zero sink rate flare over the landing zone of the active STOL runway.

Immediately following each run the evaluation pilot described the atmospheric disturbances during the approach and the effects of these disturbances on the difficulty of performing the tracking task. A standard questionnaire was used to provide a framework for this description and as part of this questionnaire response the pilot was asked to rate the IFR and VFR segments of the approach according to the Cooper-Harper scale.

In the airborne phase of the experiment, four pilots evaluated a total of 59 approaches on 17 separate experimental flights. These numbers do not include a series of initial approaches flown by each evaluator in relatively calm and stable atmospheric conditions to familiarize the pilot with the task and with the modelled aircraft and to establish a baseline task rating and performance level.

The FSAA experiment also provided a familiarization period for each evaluator during which approaches were flown with a very low level of computer-generated turbulence injected to avoid "mathematically smooth" flight conditions. Evaluation approaches were then flown using the recorded winds and turbulence from the airborne experiment. Each pilot was given, in the order in which they were produced, the full set of tapes which were generated during his flights in the Airborne Simulator. Following this, additional runs were flown, some with repeated tapes and some with computer-generated (Dryden or MIL-SPEC) turbulence.

5. CHARACTERISTICS OF THE MEASURED WINDS AND TURBULENCE

It was not possible to present each of the subject pilots with a wide variety of qualitatively different disturbance conditions nor was it possible to present the same sequence of conditions to all subjects. Nevertheless many different types and levels of atmospheric disturbances were encountered over the complete period of flight testing. Some specific cases are described in this section but before this is done, some of the terms which are commonly used to describe atmospheric motions are defined in relation to the measured and recorded quantities.

When the terms wind, turbulence, gust and windshear are used to characterize natural atmospheric disturbances, they are generally understood in a qualitative sense but they do not have precise or universally accepted definitions. In analyzing the measured disturbance time histories it was necessary to establish quantitative bounds for these terms to facilitate separation of the turbulence and wind from the total disturbance signal in a manner which could be mechanized for consistent run-to-run data processing. It was important also that these separated components correspond in a qualitative sense with the evaluation pilots' intuitive understanding of turbulence, gusts and windshear since the task questionnaire used these terms. The separation for each component of atmospheric motion was accomplished using a non-recursive filter which produced complementary (zero phase shifted) high-passed and low-passed signals. The effective crossover frequency where the high-passed and low-passed signal amplitudes are equal was set at .031 Hz. The high-passed signal was taken as a measure of the turbulence and the r.m.s. value of that signal was the number used to characterize the turbulence.* The low-passed signal, or wind, was scanned to identify and quantitatively characterize individual gusts or windshears which appear as variations in this wind time history.

The atmospheric disturbances encountered during the evaluation flights were often dominated by non-stochastic features - discrete events such as turbulence "level-switching"; stable, shallow layers of wind speed and directional shear, at times accompanied by embedded regions of increased turbulence activity; and extended, gradual shears in wind speed and direction. These characteristics are distinct from the "order-within-disorder" which has been identified as an inherent feature of low-altitude turbulence and which is associated with non-gaussian probability distributions of turbulence velocities and velocity increments (refs. 2, 3). Intermittency and patchiness are evident in the turbulence recorded in this program and non-gaussian distributions have been identified by statistical analyses of these measured time histories, however the entire turbulence pattern was often superimposed upon one or a few large-amplitude discrete events.

Some of these distinctive features are illustrated in Figures 6 through 10. For each of the approaches discussed below, the accompanying diagrams show wind and temperature profiles, and the variation with time and altitude of the r.m.s. level for the vertical and longitudinal turbulence components. (The r.m.s. values were calculated over sequential 16-second segments of disturbance time histories which had the low frequency drifts, shears or gusts removed by the filtering process described above.)

The approaches of flights 76-44, 76-51 and 76-174 are all examples of encounters with a frontal surface aloft. In each case the distinctive wind and temperature profiles, which are illustrated here for a single approach, persisted over the duration of the evaluation flight. The first and the last of these frontal structures exhibit the expected wind variation for a warm front approaching the STOLport from the west. The easterly wind at the surface is a normal occurrence in the cold air which recedes before the surface front. The southwesterly wind aloft in the warm airmass tends to decrease in speed with decreasing altitude before it begins to back in direction in the lower regions of the frontal shear layer. The cold airmass is generally very stable and turbulence is light and isolated to the last few hundred feet of the boundary layer. During repeated passages through the strong inversion layers of flight 174, there were occasional bursts of turbulent activity at the top of the shear layer which were not repeatable but were described as moderate turbulence when they were encountered.

The third of these shear layer encounters, flight 76-51, shows a much less ordered system with more low frequency content or gustiness in the wind variation. There was a constant temperature layer from 1000-1500 feet but no substantial inversion in this case, and the turbulence level was higher in the region above 1000 feet than below. Although the velocity profile was somewhat erratic, a distinct layer of directional shear was measured consistently on each approach of that flight.

---

* It should be noted that this is a somewhat severe filtering process. A significant part of the energy in a turbulence sample which does not contain drifts or windshears may be derived from frequencies below .031 Hz. If, for example, turbulence with power distributed according to the Dryden longitudinal spectrum and scale length 500 feet were sampled by a probe moving at 65 knots (the aircraft speed), an ideal "brick wall" highpass filter with breakpoint at .03 Hz would diminish the r.m.s. value of the sample by approximately 30 per cent. The r.m.s. of the filtered signal would more closely approximate that of the unfiltered sample as the scale length decreased.

The conditions which prevailed during flight 76-60 were in some ways the most interesting examples of the effects of atmospheric layering. There was no indication in the synoptic information available on the day of this flight that there was frontal layering in the local area. The measured temperature profile shows that there was a stable airmass throughout the lower 2000 feet with an isothermal layer from 1400 to 2000 feet. The region above 2000 feet was not probed, however the winds aloft were evidently very strong. The windspeed shear from 2000 feet down was almost linear but there was virtually no directional shear. The most disconcerting feature from the pilot's point of view, in what appeared to be an innocuous system, was the presence of two very distinct turbulence layers. Above 1600 feet the turbulence level was extremely low but suddenly "switched-on" at that altitude to a moderate and fluctuating level for the remainder of the approach.

The last of these special cases, flight 76-47, is representative of a number of evaluations which were flown on very gusty days. The atmosphere was cold and stable in the normal sense that it damped vertical turbulent motions, however there were strong fluctuating horizontal pressure gradients associated with an approaching storm cell. As a result the predominant impression was that of a gusty rather than a turbulent atmosphere and the pilots referred to large amplitude, low frequency "lifters" which required continuous compensation.

6. SOME RESULTS OF THE TRACKING EXPERIMENTS

Since the motion of the atmosphere in the vicinity of the approach path was the only significant objective variable influencing the task, the pilot ratings should provide an overall indication of the contribution of atmospheric disturbances to the task workload. Other factors, not related to the specific flight task, did however influence the experimental results. For example, the practice of having a subject pilot perform more than one approach during a single flight was found to produce a consistent "learning-curve"-type of run-to-run improvement in both performance and task rating for one of the evaluators. Extended periods of fine weather during the airborne testing phase resulted in protracted test periods and a lack of experimental continuity for some of the subject pilots. On the other hand each pilot completed his evaluations on the FSAA within a period of a few days and during any one simulator "flight" or session a pilot normally performed a large number of approaches. These contaminating experimental constraints can be expected to contribute to the scatter or lack of correlation in the experimental results.

The results discussed here, however, draw heavily upon the evaluations of one pilot who flew his complete airborne program in the final two weeks of that phase of the experiment. Coincidentally, this subject flew approaches in a relatively wide variety of atmospheric conditions, including a range of turbulence levels where shears were mild or undetected, as well as a series of structured windshears. Figure 11 presents the pilot ratings for the IFR approach segments plotted against the r.m.s. value of the filtered along track turbulence component. The runs which were flown in the presence of an identifiable, structured windshear have been highlighted with the bold symbol. (Again it should be emphasized that the numerical values of r.m.s. level for these filtered turbulence signals are smaller than r.m.s. values for an unfiltered sample of turbulence of equivalent subjective intensity. Measured values of the filtered turbulence r.m.s. of 2.5 or greater corresponded to conditions which were consistently described as "moderate" turbulence.) It is evident from the descriptions of the measured turbulence data that this r.m.s. turbulence level calculated over a large segment of the approach is a very poor metric for the natural disturbances encountered in these flights. For some of these approaches the pilot's workload was evidently influenced more by the presence of strong windshears than by the background level of turbulence.

The extreme values of the approach airspeed excursions for this same set of runs are plotted in Figure 12. Since speed control was generally a problem with this model and was described as a major preoccupation when flying the aircraft in turbulence, this is perhaps a good measure of the level of tracking performance which the pilot achieved on any given approach. The deterioration in performance with increasing turbulence level is apparent in these data although the level of correlation is not high. It is apparent that the points corresponding to approaches through windshears do not stand out from the general trend as they do in Figure 11. To track speed and glideslope in the presence of a windshear, the pilot is required to manoeuvre the aircraft trim point relative to the inertial reference frame. This is a qualitatively different control task from the stabilization required to compensate for turbulence upsets. Figures 11 and 12 indicate that the pilot was able to perform this low frequency manoeuvring task without diminishing his performance level but at the expense of a substantially increased workload.

The importance of low frequency gusts and windshear in establishing the tracking task workload is underlined by the subjective data gathered in the responses to the questionnaire. In addition to the task ratings and some general comments on handling characteristics of the modelled aircraft, pilots were asked to provide a description of "the effect of each of the following atmospheric disturbances on the difficulty of accomplishing the indicated approach segment tracking task:". The disturbance categories which followed were mean wind, windshear and turbulence - and space was provided for both a verbal response and a "quick-check" indication that the effect was "negligible","slight", "moderate" or "great".

Figure 13 summarizes the responses of one pilot to this question. The approaches were first sorted according to pilot rating. For each rating increment the distributions then indicate the number of approaches for which the effects of turbulence and shear respectively were considered to be "negligible", "slight", "moderate" or "great".

The distributions clearly show that the pilot considered windshear to be an important contributer to the overall task workload. This would be a trivial point if these observed windshear contributions were related in all cases to the presence of strong, measured shear layers of the magnitude and type illustrated in Figure 7. However this was not the case. In many instances the contribution of windshear to the task difficulty was acknowledged when the measured shear was relatively weak.

The third distribution in each group in Figure 13 illustrates, in a simple heuristic way, that the combined effects of the high and low frequency disturbances are reflected in the task rating. The numerical values 0 through 3 were associated respectively with the adjective ratings "none" through "great" and the contributions due to shear and turbulence were added to arrive at a "combined disturbance index". The centre of gravity of the distribution shifts consistently to higher index values as the pilot ratings increase, suggesting that the "difficulty" added to the task by the individual elements of the disturbance was assessed in a manner consistent with the task rating. The concept of the "combined index" should not, however, be accorded undue significance since the subject pilots were unaware of the numerical scales at the time of the evaluation.

During the ground-based experiment each pilot flew a separate series of approaches with the atmospheric motions simulated by Dryden model (MIL-SPEC) turbulence superimposed upon steady, light head-wind and crosswind components. The data from these runs were distinguished by the presence of highly correlated variations of pilot rating and performance with the r.m.s. level of the computer-generated turbulence.

7. CONCLUDING REMARKS

The atmospheric motions measured during the approaches to the STOLport generally contained low frequency variations which could not be considered part of a continuous spectrum of turbulence. In the simplest cases the low frequency content resulted from passage through stationary boundary layer windspeed shears and geostrophic directional shears. Under the more extreme conditions of atmospheric stratification associated with frontal surfaces, the low frequency variations were localized to a shallow altitude band which contained large wind velocity gradients.

The experimental data show that low frequency gustiness or windshears played an important role in the evaluators' assessments of the approach task workload. The atmospheric models which are used in flight simulator experiments to investigate STOL handling qualities should incorporate a realistic presentation of low frequency wind variations as well as representative continuous spectrum turbulence.

A second and quite different feature of the measured disturbances is the phenomenon which was described above as turbulence "level-switching" but which might be generalized to include less dramatic cases of varying turbulence level. The horizontal "patchiness" which is observed in constant altitude surveys of low altitude turbulence is a special case of this type of level variation. In more extreme cases where the intensity suddenly changes between two very distinct levels, the phenomenon is associated with the presence of stable strata in the low altitude atmosphere.

The influence of these disturbance modulations on the pilot's tracking task includes both the unsettling effect of the change in aircraft ride qualities and an increase in workload associated with the necessity to reassess the control strategy for turbulence compensation. Without these, the tracking task in the ground-based experiment with Dryden turbulence appeared to "scale" in a simple way with the r.m.s. level of the turbulence.

Finally, many facets of the experiment have not been addressed in this limited and selective presentation. The run-to-run comparison of the VFR phases of the experiment in the two simulators, for example, provides some insight into the importance of the rich visual cue environment of the real world in the final stages of a manual controlled landing. These subjects will be considered in a final report on the project which will be published by the FAA and NAE.

8. REFERENCES

1. Identification of Minimum Acceptable Characteristics for Manual STOL Flight Path Control. U.S. Dept. of Transportation, Federal Aviation Administration Report No. FAA-RD-75-123, June 1976.

2. Chalk, C.R.; Neal, T.P.; Harris, T.M.; Pritchard, F.E. — Background Information and User's Guide for Mil. Spec-F-8785B (ASG), "Military Specification - Flying Qualities of Piloted Airplanes." Air Force Systems Command, Wright Patterson Air Force Base AFFDL-TR-69-72, August 1969.

3. Tomlinson, B.N. — Developments in the Simulation of Atmospheric Turbulence. Royal Aircraft Establishment Technical Memorandum FS-46, September 1975.

4. Reeves, P.M.; Campbell, G.S.; Ganzer, V.M.; Joppa, R.G. — Development and Application of a Non-Gaussian Atmospheric Turbulence Model for Use in Flight Simulators. NASA CR-2451, September 1974.

5. Doetsch, Jr., K.-H.; Gould, D.G.; McGregor, D.M. — A Flight Investigation of Lateral-Directional Handling Qualities for V/STOL Aircraft in Low Speed Manoeuvring Flight. NRC/NAE Aero Report LR-549, National Research Council of Canada, October 1971.

6. Doetsch, Jr., K-H.; Laurie-Lean, D.W. — The Flight Investigation and Analysis of Longitudinal Handling Qualities of STOL Aircraft on Landing Approach. Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base AFFDL-TR-74-18, March 1974.

7. Sinclair, S.R.M.; Roderick, W.E.B.; Lum, K. — The NAE Airborne V/STOL Simulator. Proceedings of the AGARD Flight Mechanics Panel Symposium on "Rotorcraft Design", May 1977.

8. Sinclair, M.
Hindson, W.S.
The Wind and Turbulence Measuring System of the NAE Airborne V/STOL Simulator. Quarterly Bulletin, DME/NAE 1977(4), National Research Council of Canada, January 1978.

9. Sinacori, J.B.
Stapleford, R.L.
Jewell, W.F.
Lehman, J.M.
Researcher's Guide to the NASA Ames Flight Simulator for Advanced Aircraft (FSAA). NASA CR-2875, August 1977.

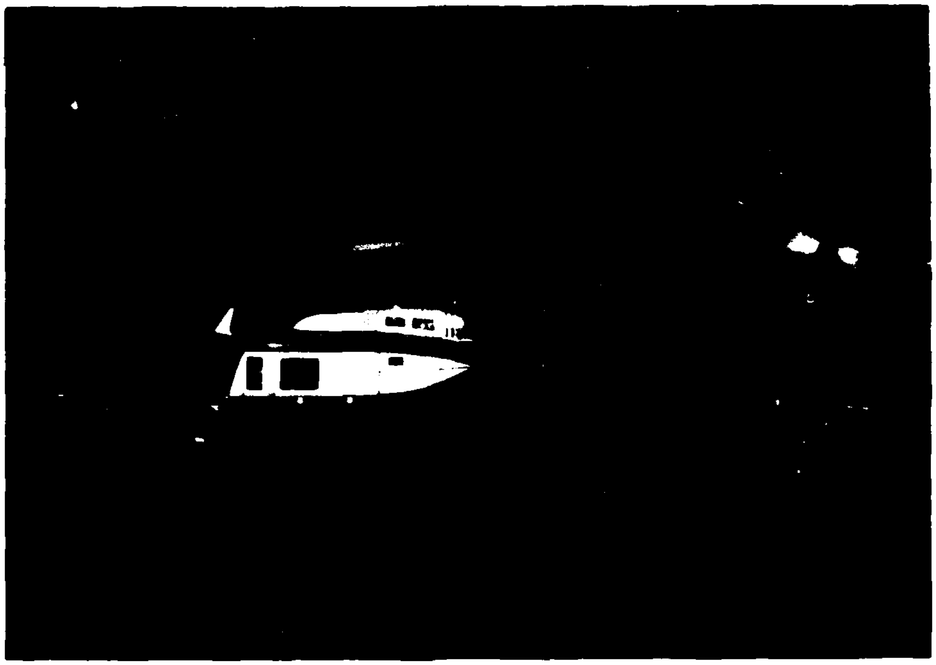


FIG. 1: THE AIRBORNE V/STOL SIMULATOR

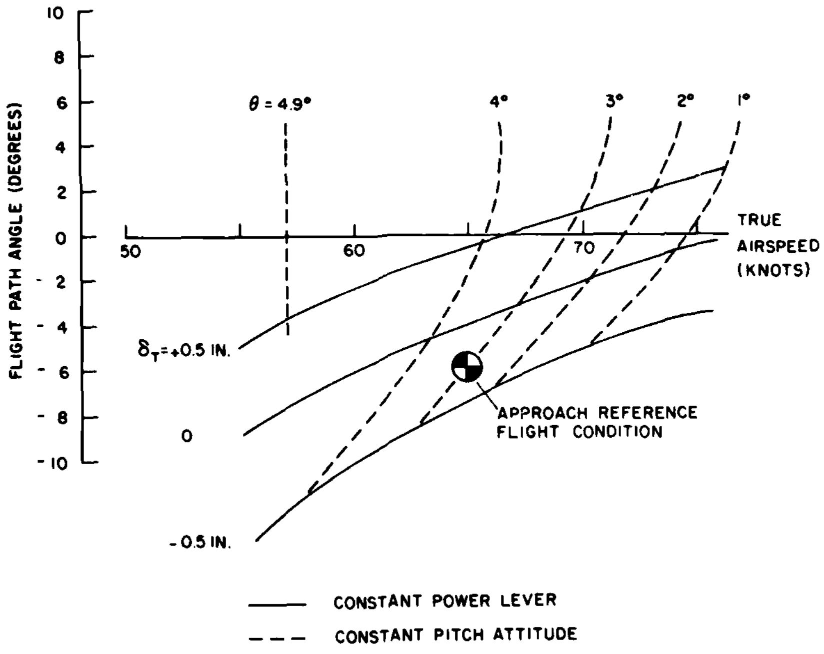


FIG. 2: FLIGHT PATH ANGLE - SPEED DIAGRAM FOR MODEL

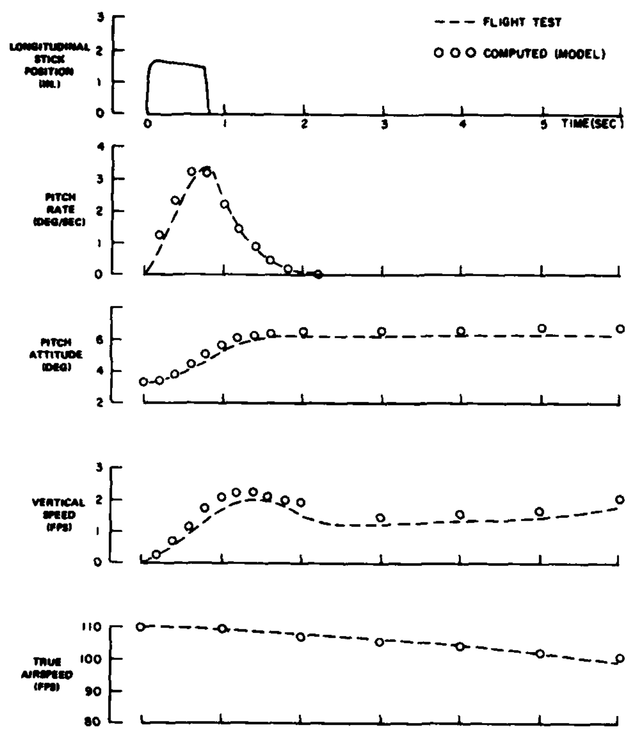


FIG. 3: MODEL RESPONSE TO PITCH CONTROL PULSE

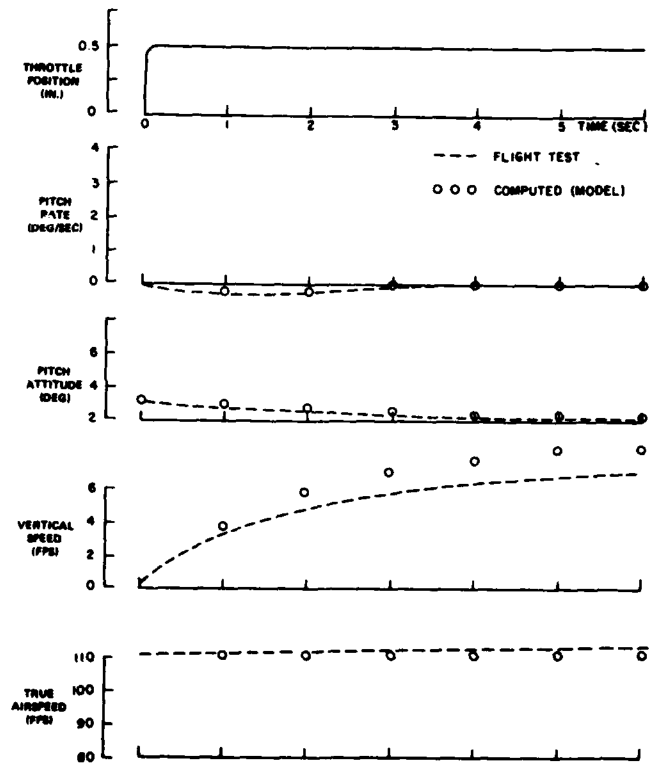


FIG. 4: MODEL RESPONSE TO THROTTLE STEP

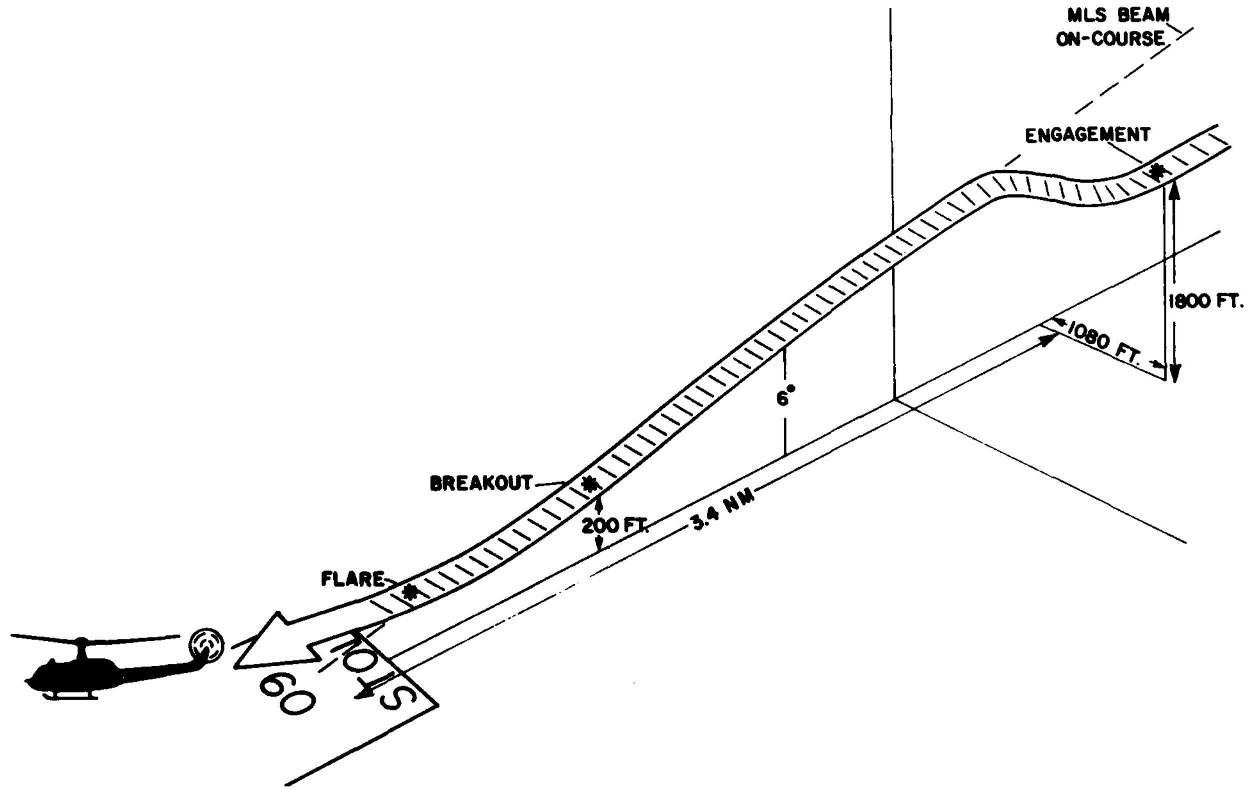


FIG. 5: APPROACH TRACKING TASK

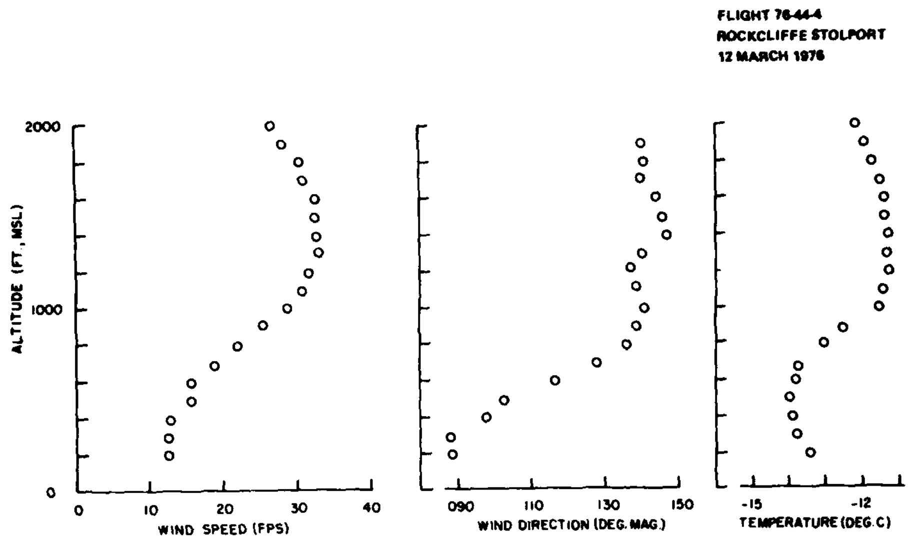


FIG. 6(a): WIND AND TEMPERATURE PROFILES

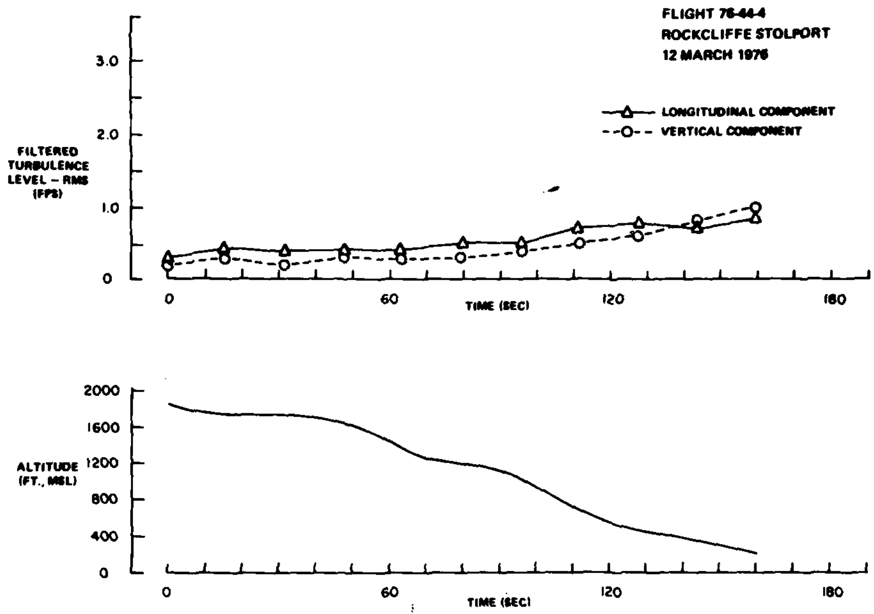


FIG. 6(b): TURBULENCE LEVEL VARIATION DURING APPROACH

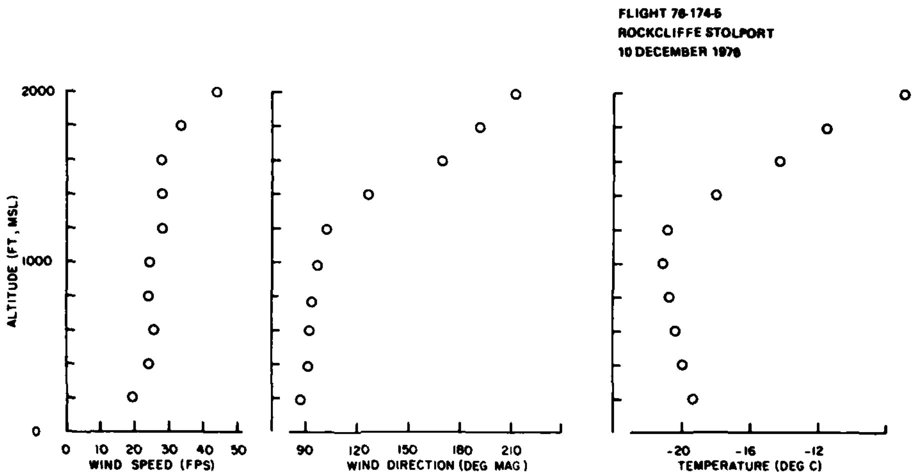


FIG. 7(a): WIND AND TEMPERATURE PROFILES

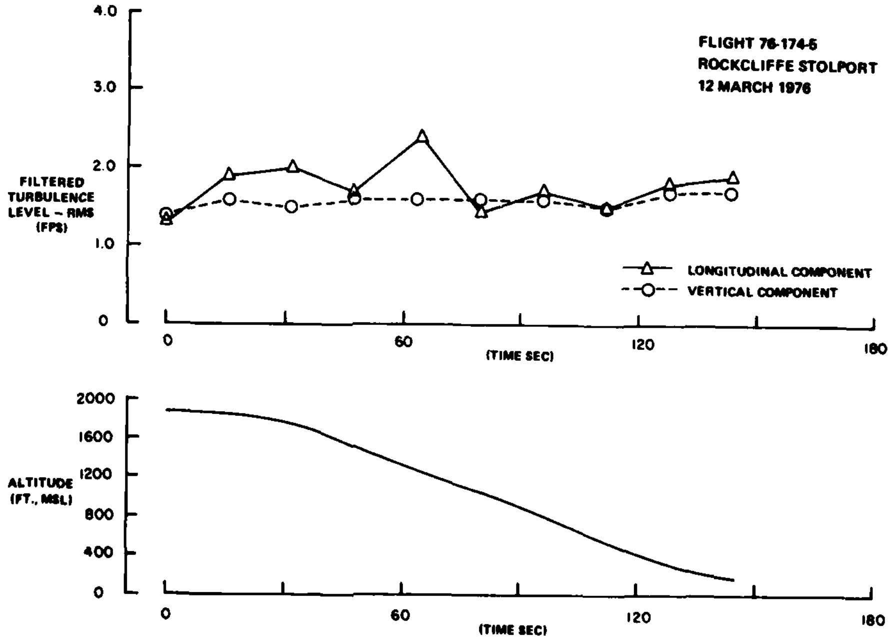


FIG. 7(b): TURBULENCE LEVEL VARIATION DURING APPROACH

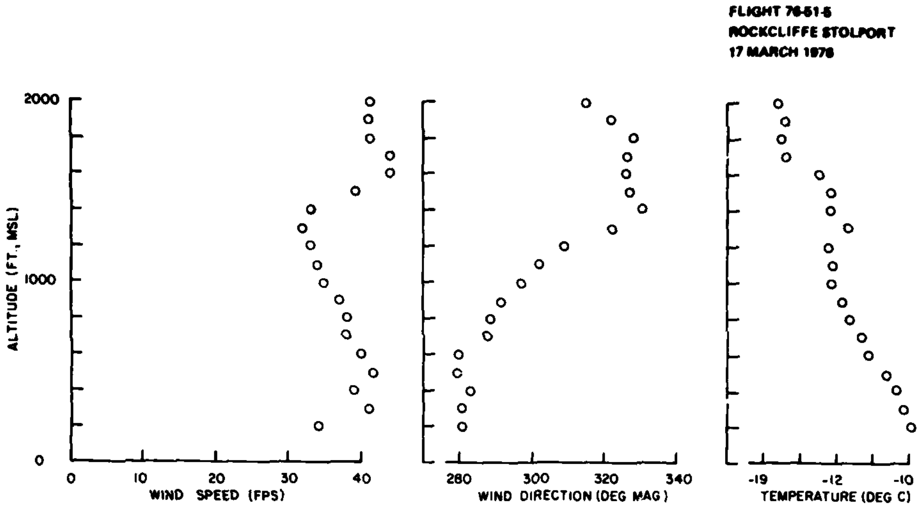


FIG. 8(a): WIND AND TEMPERATURE PROFILES

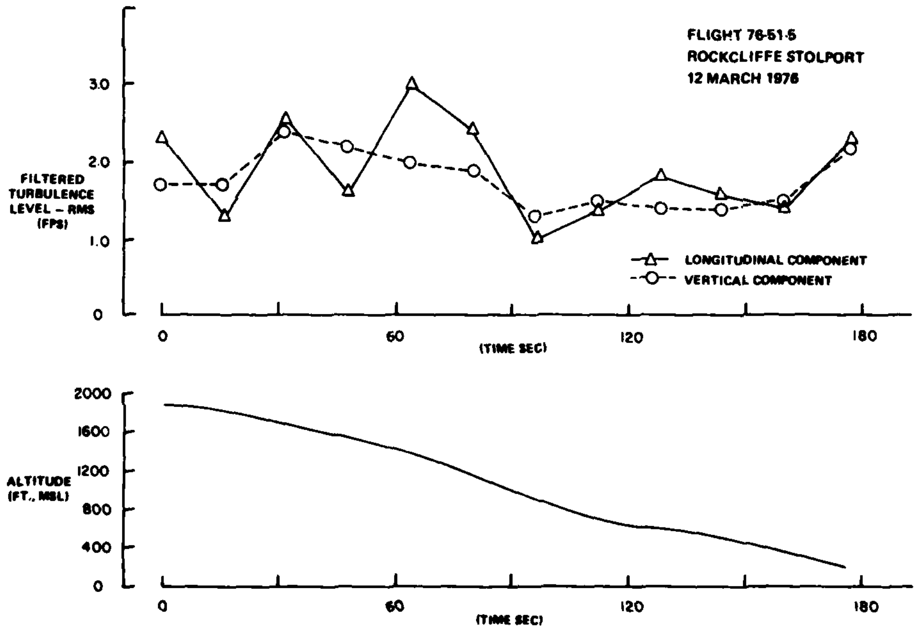


FIG. 8(b): TURBULENCE LEVEL VARIATION DURING APPROACH

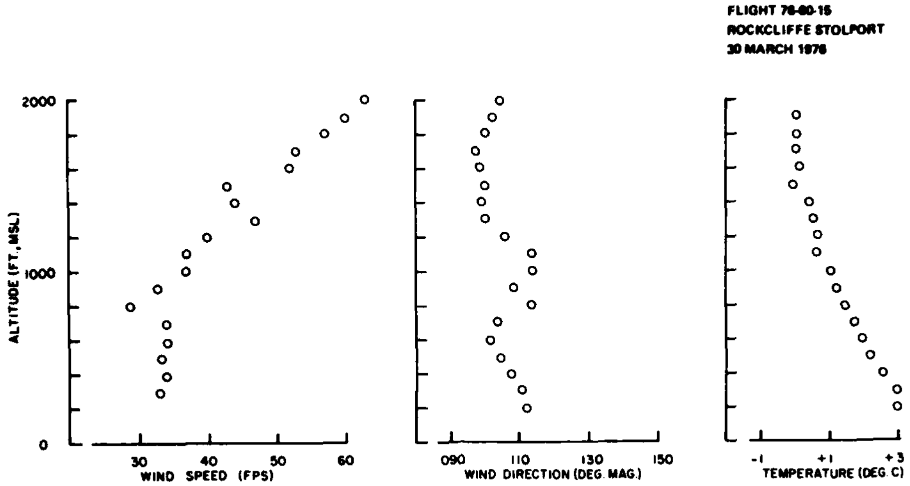


FIG. 9(b): WIND AND TEMPERATURE PROFILES

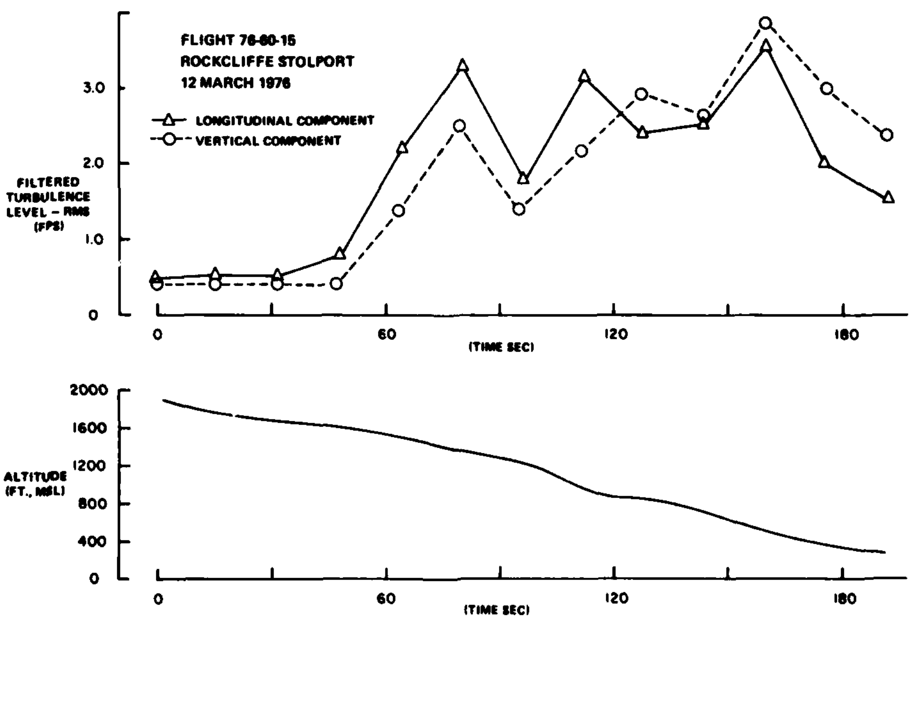


FIG. 9(b): TURBULENCE LEVEL VARIATION DURING APPROACH

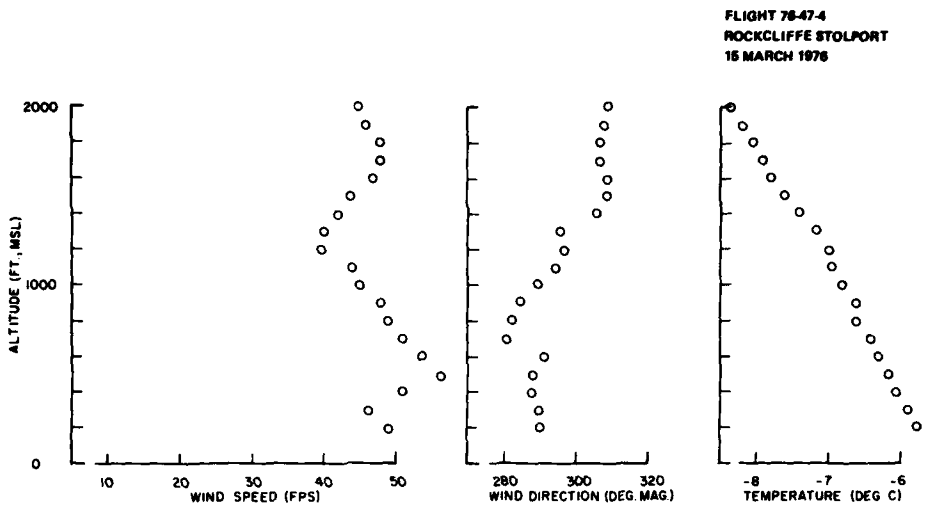


FIG. 10(a): WIND AND TEMPERATURE PROFILES

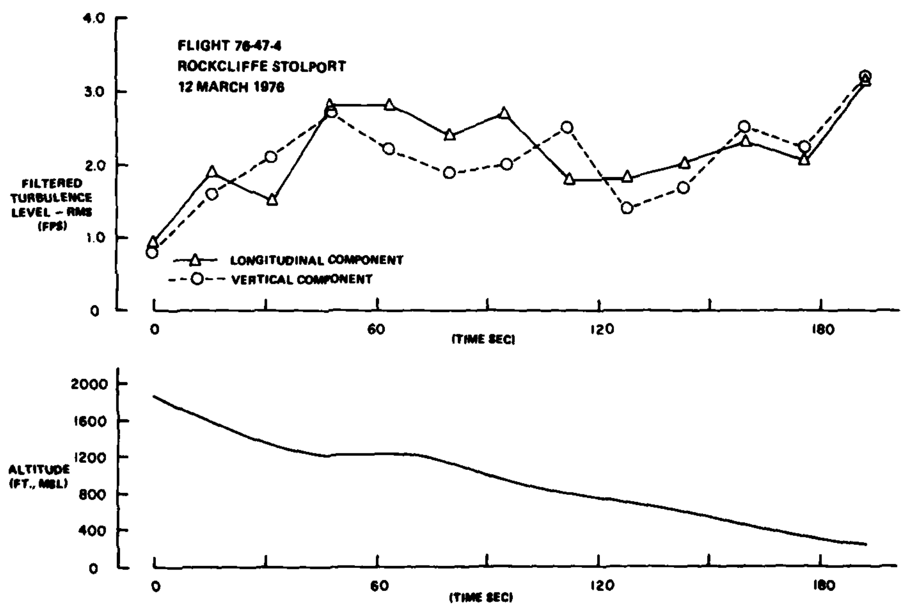


FIG. 10(b): TURBULENCE LEVEL VARIATION DURING APPROACH

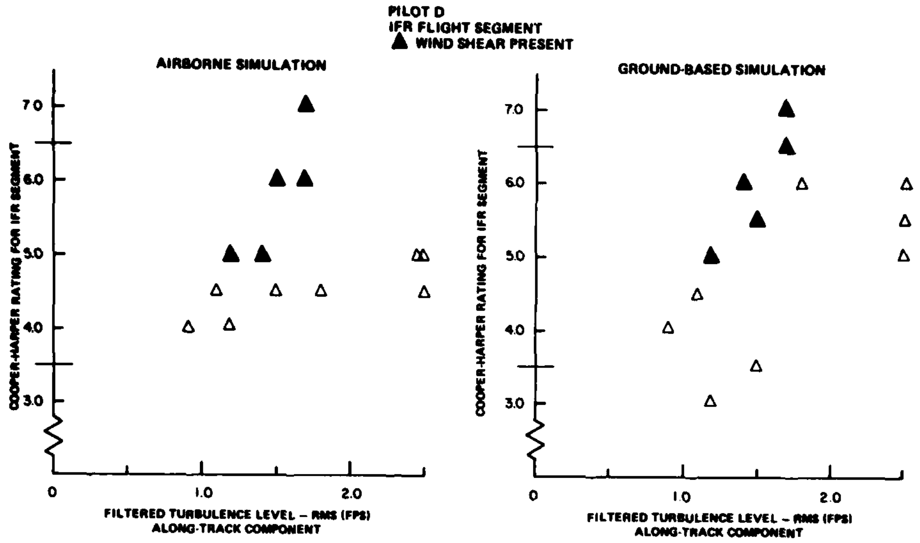


FIG. 11: PILOT RATING FOR APPROACH TASK

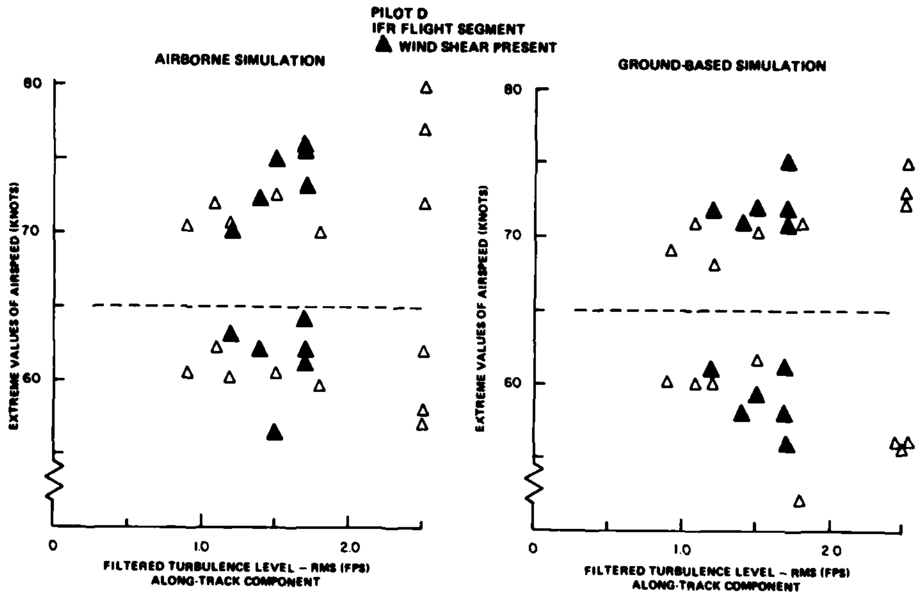


FIG. 12: AIRSPEED TRACKING PERFORMANCE

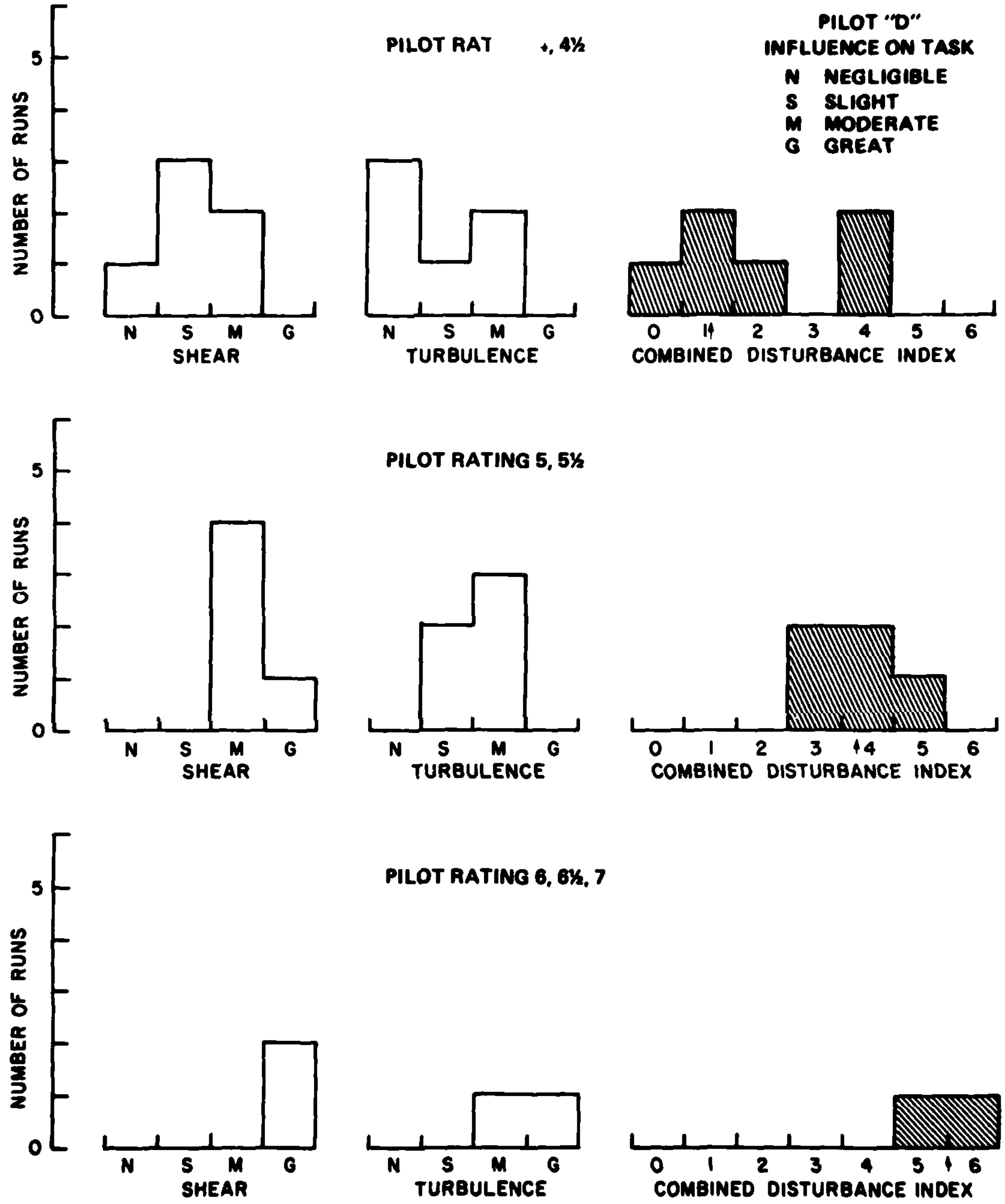


FIG. 13: VARIATION OF PILOT RATING WITH DISTURBANCE LEVEL

VISIBILITY MODELLING FOR A LANDING SIMULATOR
WITH SPECIAL REFERENCE TO LOW VISIBILITY

by

D. Johnson

Royal Aircraft Establishment
Farnborough, Hampshire, England

SUMMARY

When a simulator is used to demonstrate or investigate the effects of restricted visibility on a pilot's ability to land an aircraft it is important that the visual sequence displayed is as realistic as possible.

In this paper the characteristics of the visual world by day and by night are described. In particular the topics of contrast, the apparent horizon and the perception of the lights are considered.

A brief account is also given of the characteristics of some of the more commonly encountered fogs whose effects could usefully be represented in simulating low visibility conditions. These include shallow fogs and those with marked vertical density gradients.

Various ways of simulating the outside world in general are briefly described and discussed in relation to fog and vision.

1 INTRODUCTION

The use of flight simulators for approach and landing requires the visual world to be adequately represented. For studies of all-weather operations, it is essential that all visibility conditions including low visibilities caused by haze, fog and low cloud should be portrayed correctly. These reduced visibility conditions are not uncommon.

Experience has shown that it is not good enough, if serious studies are being made, to use unsophisticated representations of such conditions even though to do so may seem realistic to people who have not experienced actual landings in fog.

2 *THE VISUAL WORLD*

2.1 General

The visual world by day, as seen from an aircraft on the approach to landing consists of the ground and all the ground features within the range of visibility, such as the runway, markings, trees and buildings. If the approach and runway lighting system is in use, some of the lights may also be visible.

As daylight decays into twilight, the ground features become less discernible and lights more evident. By night in limited visibility when it is truly dark, the scene consists solely of the perspective pattern of the ground lighting system and lights on roads and buildings in the immediate vicinity. In good visibility at night the true horizon may be seen if the luminance of the sky is greater than the ground, as happens when light from a distant town or city is scattered in the atmosphere.

In general the limit of vision and the conspicuity of objects and lights depends, as will be explained below, on the attenuation of light by the earth's atmosphere as for example, in conditions where fog and mist exist. The degree of attenuation can be represented by the quantity 'σ', the extinction coefficient. However, in everyday language we speak of the distance over which vision is possible in given conditions. Meteorologists specify this distance as the meteorological visibility (met vis). Its value can be computed from extinction coefficient (σ) by an accepted relationship, met vis = $3/\sigma$ and if the atmospheric attenuation is uniform the meteorological visibility will be the distance at which black objects of a particular size have a 5% contrast with the sky horizon, and also the distance that the observer will judge to be the limit of visibility.

The relationships that govern the visibility of both objects and lights are complex. In this paper it is only possible to refer to general and pertinent aspects. A considerable amount of information, based on work by Koschmeider, Allard *et al* has been collected and discussed by Middleton[1]. More recently, Douglas and Booker in a comprehensive monograph[2] on visual range in aviation have usefully reviewed and described the basic concepts.

2.2 The day scene

By day an object displays a particular brightness or luminance as a consequence of the incident illumination and the reflective properties it possesses. It is visible when it contrasts sufficiently with its background or other objects having a different luminance. For the purpose of explanation, let the object when situated in the near field have an inherent luminance L_0, and an apparent luminance L_x when viewed from a distance. Also, let the luminance of the horizon sky be L_h.

Koschmeider showed that if the inherent luminance of the object is not zero, then L_x and L_0, with reference to L_h, have the relationship:

$$L_x = L_0 e^{-\sigma x} + L_h(1 - e^{-\sigma x})$$

hence

$$C_x = C_0 e^{-\sigma x}$$

where $\frac{L_x - L_h}{L_h} = C_x$

and $\frac{L_0 - L_h}{L_h} = C_0$

and C_0 and C_x are the inherent and the apparent contrast ratios respectively. From these relationships the variation in luminance with distance can be computed.

Contrast ratio decreases exponentially with distance and this explains why the objects that make up the visual picture in the field of view of an observer in an elevated position, become lighter in tone with distance until they all merge into the background. In fog, the apparent horizon occurs where the contrast ratio tends to zero.

In considering these matters it is convenient to compare the visual range of black objects with the visual range of other objects for the same conditions. A black object has an inherent luminance of zero. Therefore,

$$C_x = e^{-\sigma x} .$$

As such an object recedes into the distance it only remains visible until C_x becomes numerically equal to the threshold contrast ratio (Σ), at which point,

$$\Sigma = e^{-\sigma x} .$$

Detailed investigations made in the USA and reported by Blackwell showed that the contrast threshold varies with the object size. This data is illustrated in Fig 1 by two curves, one representing daylight viewing conditions and the other bright moonlight. The contrast threshold by day varies from 10% for objects corresponding to fine detail, to 3% for objects subtending 3 minutes to 30 minutes of arc, and tends to a limit of 1.5%. It is suggested that the absolute limit of visual range in overcast conditions corresponds to $\Sigma = 1.5\%$ or thereabouts which implies by way of an example, that in a meteorological visibility of 300 m ($\sigma = 0.01\ m^{-1}$) the limit of vision occurs at a range of 420 m. Objects subtending 3 minutes to 30 minutes should remain in view up to 350 m range, whilst fine details may only be visible up to 230 m. In this example the apparent horizon would be not less than 0.25 degrees below the true horizon to an observer standing at ground level and not less than 1.5 degrees to the pilot 40 ft above the ground.

For moonlight conditions the data in Fig 1 indicates that the contrast threshold is substantially greater than it is for day conditions. Care must be exercised in applying such data since the perception of objects to which it refers could be affected by the presence of ground lighting.

As shown by Douglas and Booker[2] the visual range V' of objects having an inherent contrast C_0 with the horizon sky, compared with the visual range to extinction (V) of black objects has the relationship

$$\frac{V'}{V} = 1 - \frac{\ln C_0}{\ln \Sigma} . \qquad (1)$$

When C_0 applies to an object against a terrestrial background of luminance L_b it can be shown (see Ref 2) that:

$$\frac{V'}{V} = \frac{\ln \left[1 - \left(\frac{L_b}{L_h}\right)\left(1 - \frac{C_0}{\Sigma}\right) \right]}{\ln 1/\Sigma} . \qquad (2)$$

Fig 2 shows for a detection contrast threshold Σ of 3% the variation of V'/V with L_b/L_h for a range of contrast ratios and represents equation 2. When $L_b/L_h = 1$ it also represents equation 1.

Typical values of L_b/L_h under overcast sky conditions are: Snow 1, white markings 0.9, dry concrete 0.75, damp concrete 0.5, grass 0.25, desert 0.15. The contrast ratios of white marks to dry concrete and to damp concrete are roughly 0.3 and 0.8 respectively, hence in these two conditions white marks of constant subtense when $\Sigma = 3\%$, will disappear at 58% and 74% of the visual range of a black object. Runway threshold markings are large objects and will be visible to a longer range than other markings because a smaller contrast threshold will apply.

2.3 The night scene

With the exception of a perceptible horizon, this will consist of a random array of lights from sources such as houses, roads and those parts of the approach and runway lighting system that are visible. What will be seen will depend on the visibility conditions. There are basically two approved systems of airfield lighting and these are described in ICAO documentation[3], together with particulars of the beam characteristics, angle settings and colours of the lights. One of these systems is illustrated in Fig 3.

Experience with flight simulators used for approach and landing has shown the critical importance of simulating all ground lights including those sources which are not part of the approach and runway system but which help to define the ground plane.

The visual range (R) of lights depends on the extinction coefficient, the intensity and the threshold eye illumination E_T which in turn depends on the luminance of the background. These are related by Allard's law as follows:

$$E_T = \frac{I}{R^2} e^{-\sigma R} .$$

Typically $E_T = 10^{-4}$ lux for daylight viewing and 10^{-6} lux on a dark night.

Operationally, all the lights in any component part of the lighting system have identical light outputs but at any instant each will display different luminous intensities toward the pilot because of the beam characteristics and graded setting angles of the individual light units.

Providing the performance and dispositions of lights in the ground system and the slant visibility between the aircraft and the ground is known, it is possible using Allard's law to determine which lights will be visible and the intensity of each directed towards the pilot. A computer programme[4] has been written to do this, and it has been used extensively to determine visual sequences, in some cases for simulation.

The ratio of the illumination E_1 at the eye of an observer due to light at a distance R_1 to the illumination E_2 due to a light of the same luminous intensity at a greater distance R_2, according to Allard's law, can be expressed as follows,

$$\frac{E_1}{E_2} = \frac{I}{R_1^2} e^{-\sigma R_1} \Big/ \frac{I}{R_2^2} e^{-\sigma R_2}$$

which reduces to

$$\frac{E_1}{E_2} = \left(\frac{R_2}{R_1}\right)^2 \left(e^{\sigma(R_2 - R_1)}\right) .$$

This ratio for lights at distances of 1000 m and 250 m in 1000 m met vis ($\sigma = 0.003\ m^{-1}$) is nearly 150/1. In 100 m met vis ($\sigma = 0.03\ m^{-1}$) lights at 300 m and 75 m from an observer give a ratio approaching 15000/1. These two examples represent respectively a day fog situation in which a 10000 cd light has a visual range of 1200 m and a night condition when a 10000 cd light has a visual range of 350 m.

If the two lights are to be correctly simulated on a TV monitor, as in the system described in section 4.3, then the effective intensity (area of spot multiplied by the luminance of the spot) of each should have the appropriate ratios. In the case of the model board simulation described in section 4.1 the inverse square effect is built into the model. However, it will be appreciated that high intensity ratios cannot be represented in simulation on a standard TV display.

Unless all simulated runway lights can be given the correct relative intensity (see section 2) the lights may merge together to form a line which is much brighter than that which occurs in the real world. This problem might possibly be alleviated by increasing with distance the spacing of the lights in the simulation. Adjacent lights do augment one another to create an effectively higher intensity[2] but the intensity of runway inset lights decrease with distance because the angle of view gets progressively further from the beam axis.

3 FOG

3.1 Visibility conditions and visual sequences

Reduced visibility conditions, in the context of this paper are confined to those caused by fog and low cloud, but they can also arise due to rain, snow and dust. The characteristics of all these natural phenomena are complex and variable. For the purpose of simulation it is necessary in the interests of economy to select those that are representative of the conditions most commonly encountered. The choice of fog situations to be represented can be helped by experience gained from fog characteristic measurements and experience gained in actual approaches and landings made at RAE Bedford. It is suggested that for simulation purposes the following conditions described below are representative of fog conditions.

3.1.1 Low cloud

This can have a well defined cloud base 100 ft or more above the ground. It will probably have a top well above the height at which decision to land has to be made. The cloud may be assumed to be very dense, the equivalent meteorological visibility being of the order of 30 m ($\sigma = 0.1\ m^{-1}$). Between the cloud base and the ground the visibility is not necessarily very good, in fact it can be as little as 1 mile ($\sigma = 0.0005\ m^{-1}$) or so. Low stratus cloud may have a ragged base and it is a relevant condition but is not included here since it cannot be described sufficiently well.

3.1.2 Unbroken fog

This, for want of a better name, is relatively mature fog which extends without any gaps in it over an extensive area. The depth of the fog can be 100 ft from ground level to the top but the depth sometimes exceeds 1000 ft.

A feature of this form of fog is that, more often than not, the density and hence the extinction coefficient increase with height[5], which means that visibility, and slant visibility, decrease with height above the ground. Fig 4 illustrates how the ratio slant visibility/ground level visibility can possibly vary with height in 100m and 600m meteorological visibility, at two levels of probability. It will be noted, as an example, that in 100m equivalent meteorological visibility near the ground ($\sigma = 0.03\ m^{-1}$) the slant visibility between a height of 60 m (200 ft) and the ground is one half of the horizontal ground level visibility ($\sigma = 0.06\ m^{-1}$).

However, more recent fog data suggests that beyond 600 m visibility vertical fog gradient tends to decrease and that fog becomes fairly uniform when the visibility exceeds 1500 m (p = 50%) and 3000 m (p = 10%).

Two illustrations in Fig 5 show how the visual range of approach and runway lighting varies with pilot eye height during final approach and landing, for two fog conditions - a fog with a strong vertical gradient and uniform fog with no gradient. These are known as visual sequence diagrams. Such diagrams and the associated fogs were described and discussed at a previous AGARD meeting[6]. The middle curve in the lower diagram shows that visual contact is made with the approach lighting at a height of 100 m (330 ft) at a range of 400 m, the first light being seen in the near field, just ahead of the ground cut-off by the aircraft cockpit and nose. At a height of 70 m (220 ft) the visual range has increased to 450 m but the first 250 m is obscured by the aircraft, leaving a visual segment of 200 m. At a height of 50 m (165 ft) there is a sharp decrease in visual range as the runway lights, which are less intense than the approach lights, begin to come into view. Below this discontinuity the visual segment increases again to 350 m of runway lighting.

These examples emphasise the fact that fog gradient can have quite a profound effect on the visual sequence. As an example, the horizontal visual range from a height of 100 ft to the farthest visible light in 200 m ($\sigma = 0.015\ m^{-1}$) meteorological visibility, is shown to be 230 m in a 10% gradient fog and 400 m in uniform fog. In severe gradient situations as will be seen by comparing the two diagrams in Fig 5, a rapid increase in the visual segment occurs once the visual contact is made with the ground lighting.

3.1.3 Shallow fog

This type of fog generally arises in the early stages of radiation fog and mainly occurs at night. It is usually dense fog with the visibility being less than 100 m ($\sigma = 0.03\ m^{-1}$), possibly 30 m ($\sigma = 0.01$) and up to 100 ft deep. The fog density has in the past been considered to be uniform, but recent fog measurements have shown that it generally increases with height, the top may be sharply defined or tenuous with the density decreasing over 20 m or so to that of the atmosphere above the fog. During approaches when this type of fog exists, the slant visibility decreases with height and becomes a minimum near the fog top. The slant visibility at twice the height of the fog top will be approximately twice the slant visibility between the fog top and the ground. The danger with this type of fog is that the pilot may see the ground and/or ground lighting quite clearly during the early part of the approach but the visual setment will decrease as the fog top is approached and the pilot, unless he has been informed of the ground level visibility may assume that he has sufficient visual segment to land, whereas in fact that may not be the case.

3.1.4 Temporal and spatial variations in fog

The fog characteristic pertinent to roll-out after landing is the change in visibility due to spatial variations in the fog. This complex topic is still not very well understood and is outside the scope of this paper. However, in the interests of simulating landings including roll-out, the following characteristics should be noted. Firstly, analysis of fog data shows that somewhere along the length of a runway the local visibility in extreme cases may double or halve. Most changes will be well within these limits and the pilot should be aware of the situation as a result of verbal visibility reports based on runway transmissometers. Secondly, at night in radiation fogs, large undetected patches of fog up to say 400 m across and 30 ft deep can exist on a runway. The meteorological visibility in such patches is typically 50 m ($\sigma = 0.06\ m^{-1}$). It is possible that one patch of this size or one very much smaller could be encountered at night during landing.

4 SIMULATION

There are three basic ways of generating the picture of the real world and these are discussed below in the light of the material in the preceding sections.

4.1 Camera - model board

This system comprises a board, sometimes a wide moving belt, on which all necessary features of the ground plane are constructed in detail at model scale and texture added to make the model look realistic. A micro-optical head of a television camera follows the computed path of the aircraft in height, pitch, roll and yaw and the scene is presented in raster scan form on a TV display, either in black and white or in colour.

The vertical resolution that can be achieved between the scan lines of the display is about 0.1 degrees. This is not well suited to the display of runway and approach lights since the angle subtended by adjacent lights at a distance along the runway is less than the angle corresponding to the line spacing. For example, at a range of 400 m adjacent runway lights having a 30 m spacing subtend 0.1 degree at the eye of an observer 10 m above ground level; the inclusion of ground lighting at model scale in a form that can be televised is undoubtedly a difficult problem. Because of the large angles subtended by lights at short ranges it is possible to represent lighting in low visibility conditions but possibly not the intensity ratios (see section 2).

Perhaps the most important feature that should be included in any realistic simulation of the visual world is the reduction of contrast from the near field up to and including the horizon, as a function of distance. There are various ways of doing this but it may be advantageous to grade the illumination of the model to assist in reducing contrast with range and to enhance this with veiling luminance introduced into the optical system. Flight tests have shown that in restricted visibility conditions by day the contrast of fine details on the runway in the very near field has a considerable influence on pilot landing performance and decision making.

The apparent horizon should be well represented and faint ghost images of the true horizon should not be displayed. Masks have been used in some simulators to limit the range of vision but the horizon so produced has to be diffused. This method has the disadvantage of cutting off any ground features that extend upwards above the apparent horizon.

4.2 Films

The picture is provided by a ciné film of the visual scene recorded from the cockpit during actual approach and landings, but it may be constructed as a cartoon film, using perspective drawings and models. The system is known as the visual anamorphic motion picture technique (VAMP). In the projection process the picture can be modified to be correct when the pilot makes limited excursions from the path to which the original picture refers.

Filming of low visibility approaches and landings can be done during automatic landings but it is necessary to know the exact approach path and the visibility conditions. Therefore such films would only be produced at flight centres that have all the required facilities for autoland and monitoring visibility and approach paths. Such films of approaches in fog have been made and realistic pictures have been obtained by RAE at Bedford. However, it has proved difficult to make satisfactory films of lighting systems in moderate and good visibilities at night because the lights, especially bright lights, 'flare' and appear larger but dimmer than they actually are. Moreover, the relative intensities of the lights in a projected film are not realistic.

4.3 Computer generated images (CGI)

This system or technique has developed very rapidly over the last few years. One form of display is the beam penetration tube which is best used for coloured night scenes. Up to several thousand spots of light are used singly or collectively to form the lights of the approach and runway lighting system and any other lights in the ground plane. Texture can be painted faintly on the runway and horizon glow can be depicted realistically.

Another form of display is by raster scan. This has particular application for producing daylight CGI scenes but the resulting picture tends to have a cartoon-like appearance.

It would seem that both systems can produce the day and night characteristics that have been described in this paper.

The effects of reduced visibility on the simulated picture can be produced in two ways. The limit of visual range for any visibility condition can be programmed as a function of height or range from pre-calculated visual sequences, and some attempt made to diminish contrasts and intensities with distance. Alternatively these effects can be computed by direct application of the physical laws, thus relative contrasts and intensities etc are determined automatically and the far point of vision is a product of this process.

At night in fog the background luminance is increased by the forward scattering of light from the runway and approach lights, and this could be simulated to create a more realistic situation. In low visibility night conditions with the lighting at maximum setting the background luminance is typically 30 cd/m^2 but when the visual range exceeds 600 m, a setting of 1/10 maximum is adequate and this, combined with the decrease in fog density, results in background luminance of about 3 cd/m^2. By comparison the background luminance on a relatively clear moonlight night is of the order of 0.01 cd/m^2. As fog density increases the lights should be made progressively more diffused so that they have no sharp outline in the very low visibilities.

A night landing simulator of this type at RAE Bedford, capable of displaying only the lighting system, has been used to study landing performances in reduced visibility conditions[7,8]. For this purpose the visual sequences in gradient fogs described in section 3.1.2 were pre-computed, stored and displayed, the contrast ratio between lights in the near field and the farthest visible lights being about 30/1. These sequences added realism to the visual scene and provided a proper but limited basis for study of approaches and landings in fog.

5 DISCUSSION AND CONCLUDING REMARKS

It is evident that accurate modelling of the day and night scenes of the visual world for landing simulations is a difficult design task. An attempt has been made in this paper to provide a brief informative introduction to the subject of the conspicuity and visibility of lights, markings and objects that make up the ground plane, and to direct the reader to better sources of information.

The contrast of objects with their surroundings and background is obviously an important aspect of simulation of the real world. Especially vital are the exponential reductions in contrast and tones that occur due to attenuation of light by the atmosphere as distance increases from the observer. Another important matter outlined in the text is that the range of visibility of objects depends on the angle subtended by the objects.

The range of contrast and particularly the range of intensity of lights between the near and far field of vision can be very large, especially in low visibility. Ideally the range of intensity should be correctly modelled but this is not feasible and therefore compromises have to be made.

It is also appreciated that distant lights when scaled correctly are too small to be displayed, especially on a raster scan, and therefore some of the simulated lights have to be larger than life. In low visibility conditions, size has to be exaggerated to represent the appearance of lights diffused by fog. On the other hand, there is a tendency for distant lights to merge together in good visibility conditions to form bright continuous lines and therefore the number of simulated lights may have to be decreased and the spacing increased. This is another possible area for compromise that requires consideration by the designer.

The various fog conditions described in this paper are limited but they have been proved by use in the RAE landing simulator to give very representative visual sequences. Further fog and reduced visibility conditions that can be simulated to advantage will undoubtedly result from the fog studies currently being concluded at RAE. However, the present information should be of help to the designer in deciding on ways and means of simulating reduced visibility conditions and fog.

REFERENCES

1 W.E.K. Middleton Vision through the atmosphere. University of Toronto Press

2 C.A. Douglas and R.A. Booker Visual range: concepts instrumental deterioration and aviation application. US NBS Monograph 159

3 Aerodrome manual and annex 14. ICAO 1976

4 A.W. Puffett A method of computing the visual range of lighting patterns during approach to landing. Unpublished RAE papers

5 D. Johnson and A.W. Puffett An attempt to relate slant visibility with horizontal visibility and height based on limited data from various experimental studies of fog. Unpublished RAE papers

6 A.J. Smith and D. Johnson The improvement of visual aids to take-off and landing. AGARD Conference Proceedings No 160

7 J.C. Penwill and R.J. Packwood Digitally generated outside world display of lighting pattern used in conjunction with an aircraft simulator. RAE Technical Memorandum FS 45 (1975) AGARD Conference Proceedings No 198 on 'Flight Simulation/Guidance Systems Simulation', The Hague, Netherlands 1975

8 R.J. Packwood A computer generated night time visual display for an aircraft research simulator. To be published

Copyright
©
Controller HMSO, London
1978

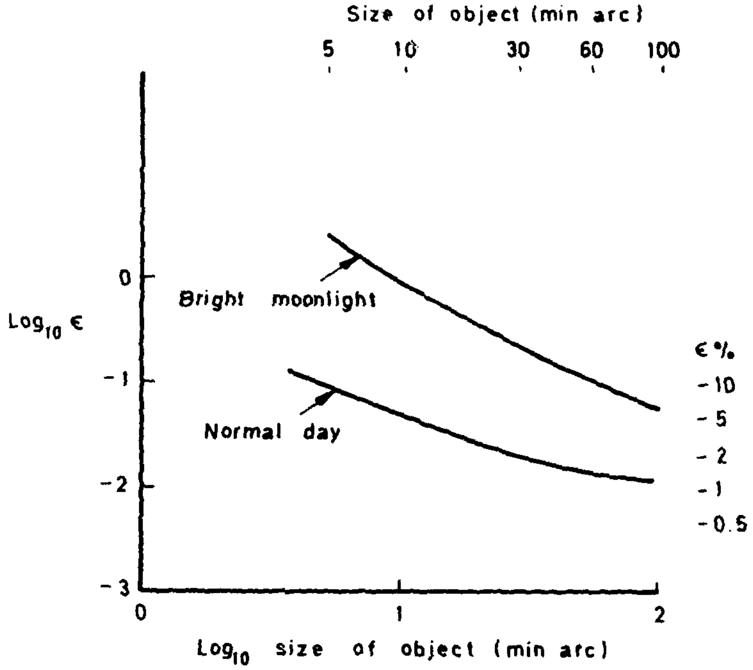


Fig 1 Variation of contrast ratio with size of object

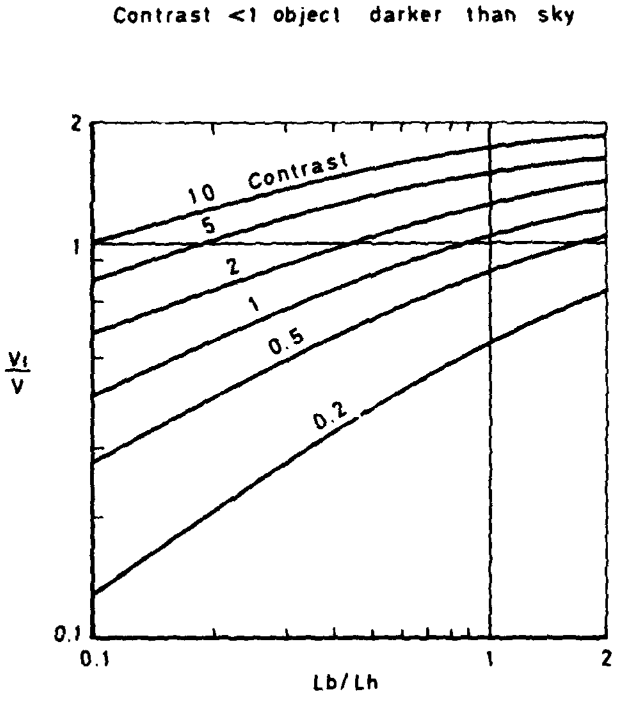


Fig 2 Variation of V1/V with Lb/Lh for a range of contrast ratios

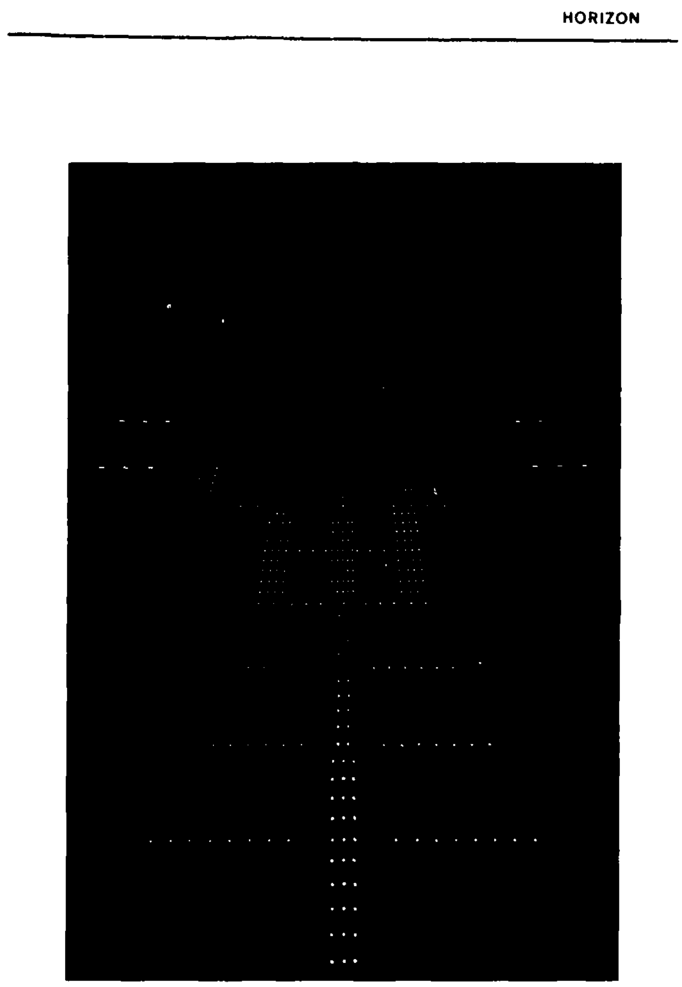


Fig 3 Perspective of Category 2 approach and runway lighting

Vs slant visibility

Vr ground visibility

$\bar{\sigma}$ mean σ corresponding to Vs

σ extinction coeff corresponding to Vr

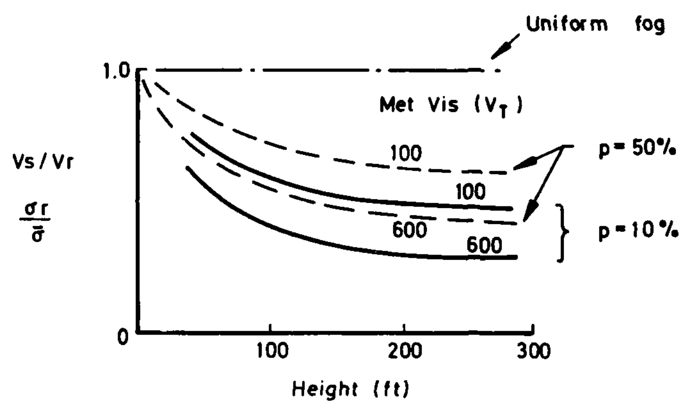


Fig 4 Variation of slant visibility with height due to vertical fog gradient

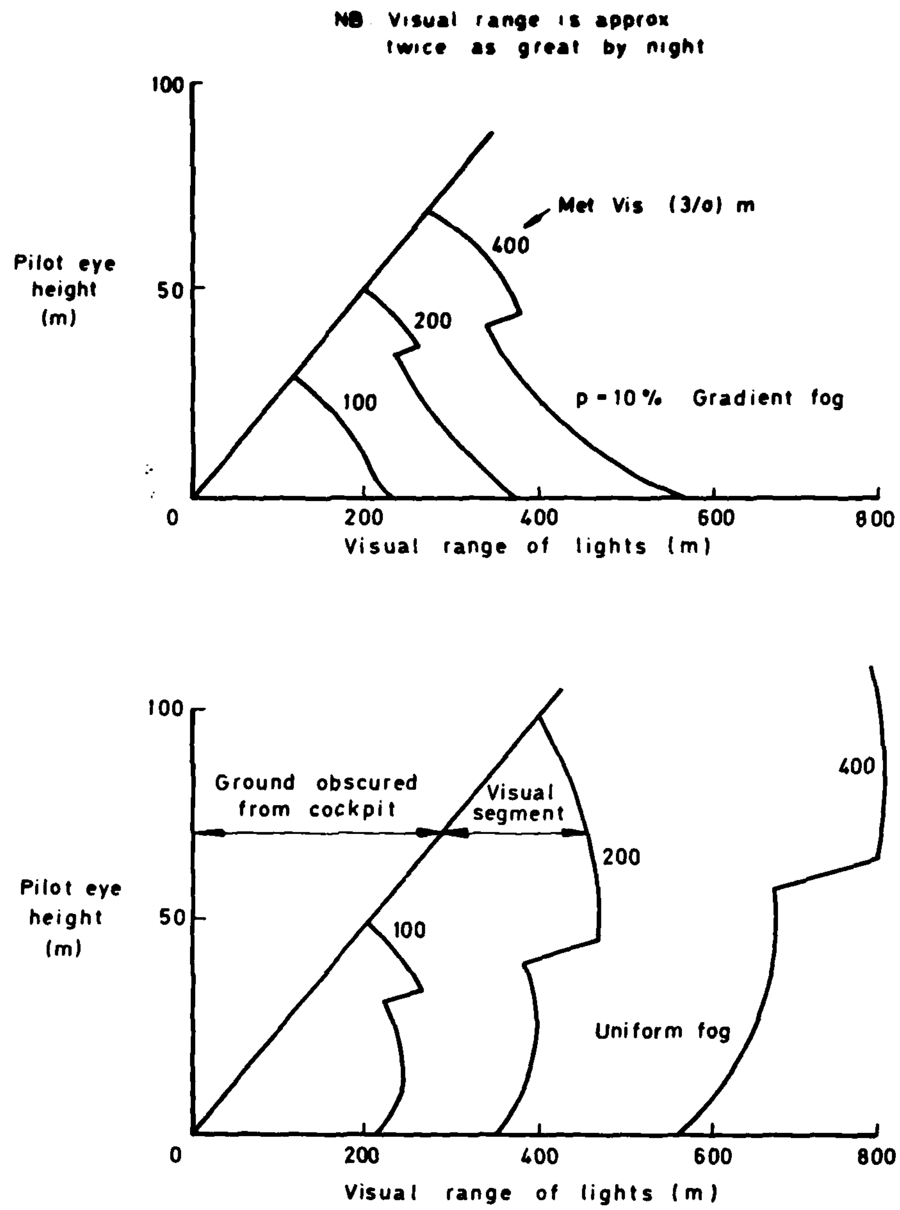


Fig 5 Visual sequences in fog by day

VISUAL SIMULATION REQUIREMENTS AND HARDWARE

John C. Dusterberry
Research Assistant to the Director
NASA-Ames Research Center
Moffett Field, CA 94035 USA

Summary

Requirements for any out-of-the-cockpit visual simulation system can easily lead to a set of system specifications which are clearly beyond the visual scene that can be produced by current technology. Therefore, the requirements of any proposed system must be assessed in light of the expected simulated aircraft and missions, experiments on pilot response, and available image generation and display hardware. A review is made of some of the recent experiments, and the results are related to aircraft and missions with particular emphasis on research and development simulators. Recent visual simulation hardware is considered in light of extending the range of applications of piloted aircraft simulators, and a method of design approach is proposed.

Introduction

The setting of requirements of a simulator visual system and the trade-off of these requirements with available visual system hardware is a vexing problem. The initial approach is usually to determine the gross performance of the human visual system and then to set the requirements of the ideal visual system to match the performance of the human eyes. Such an ideal visual system would, in fact, have to exceed the performance of the eyes. Man has two eyes which are to a degree independently controllable in direction. They have variable focus and f-stop. The maximum acuity of the eye occurs only in the cone of foveal vision, a cone of about 3 degrees, but this cone is mounted in movable eyeballs which are, in turn, mounted on a movable head, which is, in turn, mounted on a movable body. Even neglecting the binocular cues, these eye characteristics make the initial requirements of any simulator visual system to be the foveal vision capability over a 4π steradian field-of-view, with perhaps a few subtractions where the vehicle geometry prevents any crew member from seeing out from any operating position. To fill completely a sphere with the resolution obtainable in most present training simulators would require about 23 television monitors and the equivalent image generation capability. To match the nominal one arc second per line pair resolution of the human eye would require about a hundred-fold increase in the number of display devices.

The requirement for a complete reproduction of the crew's available visual cues will be compromised as surely as would a proposed requirement that the pilot's available motion cues be totally duplicated. The objective is simulation of the visual world; it is not duplication. It is intuitively understandable that to duplicate the pilot's motion cues would require a simulator motion system physically approaching the volume through which the actual aircraft would fly, and that, therefore, duplication of motion cues is not technologically or economically feasible. It is less obvious, but equally true, that duplication of the pilot's available visual cues in a simulated mission is not currently technologically feasible. If it were technologically feasible, full duplication would be employed in a brute force approach only because the understanding of the visual cues necessary for a given simulated mission are not well understood. One would duplicate them because he had no idea how to simulate them economically.

Current visual simulation systems make several different kinds of compromises. The resolution is almost always compromised, and even the highest resolution is presented over a small portion of the possible area--usually forward-oriented. This area is, in many systems, surrounded by a low resolution field. Attempts have been made to steer the limited, high-resolution portion of the picture to the area of greatest interest to the pilot, either by head-tracking or by a logical system determined by the known task and a prediction of the pilot's control actions.

Those who set requirements and determine specifications of simulator visual systems find themselves on the horns of a dilemma. The technology will not allow them to provide the "ideal" system. The science of understanding how a human uses the visual information in a simulator is enough less than perfect to give them no clear guidelines on how to make the trade-offs. However, the increasingly successful use of visual simulation equipment for training and for vehicle research and development has stimulated the development of better equipment and provided data and insights into system requirements. The growing importance of simulators as training devices has led to the design and operation of simulators for research and training techniques and for studies of the relative importance of the several visual system parameters. The increased interest in the field has attacted the attention of psychologists and other scientists interested in human performance and behavior, and they have conducted studies using both simulators and laboratory apparatus. As a result there is an increasing body of information available directly applicable to the problem of making trade-off decisions from aircraft mission requirements into human performance requirements and finally into simulator engineering specifications. In addition to discussing some available visual system hardware and some of the recent studies giving insight into how pilots use visual cues, a system to lead from requirements to design will be proposed.

Visual Simulation Hardware

All simulator visual systems may be viewed as a series of three elements in series: (1) an information storage subsystem; (2) an information retrieval and processing subsystem; and (3) an information display subsystem as shown in Figure 1.

They can be viewed as three elements in series, and in the best systems, there will be an information pass-band match between the various elements. It is probably easiest first to describe generically the various simulator visual systems, and to discuss their advantages and disadvantages.

Camera-Model Systems: The information storage in camera-model systems is in the form of a three-dimensional physical model of the area over which the simulated vehicle can fly. Servomechanisms translate a television camera over this model, and, generally, rotational freedom is provided by a servoed optical probe. Display is provided by television monitors or projectors.

Considerations of ease of modeling and of probe design dictate a large-scale model. However, space requirements, model lighting requirements, and translation servomechanism design requirements favor a smaller scale. Although these conflicting factors can be rationally traded off, this trade-off will, in turn, heavily influence the probe design.

The retrieval of the information is accomplished by viewing the model with a television camera through an optical probe. The intersection of the three mutally perpendicular probe rotational axes must occur at some node in the optical system. This nodal point is the scale equivalent of pilot eye height, so minimum model scale ratio is set by the relationship:

$$\text{Minimum model scale ratio} = \frac{\text{On-the-ground eye height in simulated vehicle}}{\text{Closest approach to model of probe optical node}}$$

In addition to keeping small the distance of the closest approach to the model, it is desirable to keep small the physical dimensions of the probe, particularly in systems used to simulate helicopters or other VTOL aircraft. Large physical size will make the model scale unreasonably large, or make unreasonably small the maximum allowable model terrain slope. The desire for a small probe, however, makes lens design more difficult by affecting adversely T-numbers, geometric distortion, resolution, and depth in focus. Even pin-hole cameras can become diffraction-limited.

The television camera presents another set of problems. RGB simultaneous color cameras are large and heavy, require more model lighting, and are more difficult to maintain. High resolution black and white cameras seem attractive (if one can conclude color is not important), but the electrical noise ("snow") associated with the necessary higher electronic pass band may actually result in a picture with a lower sharpness factor. Consentino reporting on an experimental, 800 scan line, field sequential color camera, noted the picture noise to be subjectively less when, he viewed the black and white monitor through the color wheel than when he viewed the monitor directly[1]. Avoiding a loss in sharpness factor by the use of multiple cameras to view the probe image offers possibilities that have not been thoroughly investigated, but it is not clear that such an approach will offer advantages that will outweigh the foreseeable problems it will introduce. Shaping and shrinking of the camera raster have been used to overcome some of the above problems, but one must investigate carefully the effect of the resulting geometric distortions to the picture.

Collimation is generally concluded to be an important characteristic of the display device. There is much subjective, and a small amount of objective evidence, which will be considered later, to support the conclusion. Refracting collimating lenses are low in cost, lightweight, and of high transmissivity; but, generally, they have relatively high distortion. The mirror-beamsplitter collimating system has little distortion with the proper input device, but it weighs more and has a 25 percent maximum transmissivity. Pancake window collimating systems, used on several developmental simulators, fold the optical path reducing the weight and moment of intertia problems. However, their very low transmissivity has so far restricted their use to high-brightness black and white display tubes.

The cost and moment-of-intertia problems associated with collimating optics often force the system designer to the compromise of presenting a real image on a screen at some distances from the pilot, usually in the range of 6 to 20 feet. Some amount of eye accommodation is then required of the simulator pilot as he moves his attention from inside to outside of the cockpit.

Both television monitors and television projectors can be used as the input device to the display system. Projectors have more light flux, and the measured resolution can be high. However, the contrast ratio of the shadow mask monitor tube is generally higher, and the total simulator display is less likely to suffer from secondary reflections that may further reduce the sharpness of projected displays.

Computer-Image Generator Systems: The second major category of simulator visual systems is computer-image generator (CIG) systems. These systems generate a cartoon-like picture of the outside world. There are two major types, calligraphic and raster scan. The calligraphic type draws lines. Original designs made it useful primarily for night scenes, although recent developments have extended the technique to provide day scenes. The raster scan type uses a television-scanning format and can provide shaded planes and graduation in shading in the same plane. Advantages of both kinds of CIG systems include an infinite depth of field, a conveniently changeable generated field-of-view, and an ability to produce simultaneously a multi-window scene from the same view point. Although analog systems exist, almost all systems are digital. Advances in large-scale integration (LSI) promise rapid advances in the hardware performance and large reductions in cost.

The information storage in a CIG system is in computer memory. A number of points are stored as x, y, and z positions in space; lines are stored as connections of two such points; and planes are defined by such lines. The definitions of the points, lines, and planes can include brightness and color information. There are scaling problems, because for a given size memory, only a given amount of information of these kinds can be stored. If this amount of information is used to describe a fly, the system can produce a magnified picture of a fly that is better than one can see with the naked eye. If the same amount of storage is used to describe large areas of terrain, the simulator pilot's view point can get close enough to the ground so that it appears to be a featureless plane. Peripheral memory devices, disks or tapes, can alleviate this problem. Recent developments have made semi-automatic the tedious mapping. Techniques are also available for semi-random presentation of terrain and obstacles, and for insertion of texture.

Retrieval and processing in CIG uses computer techniques. The computer receives information on the position and altitude of the simulated airplane. Knowing the simulated field-of-view, it determines which of the objects stored in memory are in the field-of-view, their positions projected on a two-dimensional map, and which ones occult others. It then computes digitally the resulting picture, either in calligraphic or raster scan format. This picture information is then converted to analog form to drive the display device. Computing techniques are also used in raster scan system to provide shadows and sun shading, edge smoothing (to make round objects appear round and not appear formed from planes), and to suppress scintillation and stair-stepping. Usually, a small general-purpose digital computer is part of the system, but since many of the calculations are repetitive, special purpose computing hardware is added to increase speed. These calculations can be made for the generation of more than one window scene at the cost of additional computer capacity or lesser individual scene content. This class of systems eliminates the lag of servomechanisms, but the time required to compute the picture introduces a similar pure transport lag into the system.

Since the nature (and in raster-scan systems, the format) of the input signal to the CIG system display device is the same as in television camera-model systems, the display hardware available is generally the same as that described in the Camera-Model section of this paper. One exception to this is the use of beam penetration color tubes in several calligraphic systems. These tubes have the advantage of being self-registering, but will not produce the range of hues available in color kinescopes.

The digital nature of these systems would seem to make them likely candidates for the rapidly developing field of digital matrix array displays such as light-emitting diodes, (LED), liquid crystals, and thin-film electro-luminescent (TFEL) displays. Presently, the displays themselves can not match conventional television display devices in resolution. However, the resolution is constantly improving, the power densities are low, and very high brightness seem attainable. Perhaps the greatest hope lies in the good potential match between the image generation hardware and the image display hardware.

Other Systems: Cine systems store their data in motion picture film taken from an aircraft flying a pre-programmed path. The data is extracted by choosing the frame and portion of the frame to be projected, and is processed by television (raster distortion) or optical (servoed anamorphic lenses) techniques. The amount of processing that can be done without subjectively disturbing distortions provides a usable picture only when the vertical objects in the scene have a height that is small compared to the height at which the picture was taken and when the simulation aircraft position does not deviate by substantial percentage from the position at which a given cine frame was photographed. The cost of making the film is high, and film-handling in the projector is a difficult mechanical problem. The preprogrammed nature of the film is not a limitation in CTOL training simulators, but it is generally too severe a restriction in an aircraft R&D simulation.

Point light source or deFlorez systems store the information in a planar transparency, often with three-dimensional objects. Processing is done by servoing this model or transparency in 6 degrees of freedom with respect to the pilot's viewpoint. Extraction and display is accomplished by placing a point light source at this viewpoint and projecting on a screen a little larger than the forward hemisphere with respect to the pilot. The picture is generally quite good but very dim; attempts to make it brighter result in the light source becoming large with respect to a true point source. This lowers resolution. There is a severe limitation on translation dynamic range, and lack of stiffness in the storage transparency makes it necessary to mount the system rigidly; it can not be carried on a motion base.

A special class of point light source projectors, the earth/sky projector, does a good job of presenting rotational cues only. The information storage is in a servoed, essentially spherical transparency which is small and rigid. The upper half of the sphere is usually blue with enough white clouds to give heading cues. The lower half of the sphere is a greenish-brown featureless earth, and the tilting horizon can be projected over an almost 4π steradian spherical screen. Since there are no high resolution objects in the scene, the deviation from the point light source is not disturbing to the observer. The projected picture is somewhat dim.

Epidiascopes, providing a direct optical projection of a scale model, have seen limited use. The large illumination requirements seem to prevent its use for most applications, but the technique has recently been successfully applied to a target aircraft image in a combat maneuvering simulator[8].

Lasers are being employed in several new experimental simulator visual systems both as laser-scan television cameras and laser television projectors. One of these systems[2] employs a charge-couple device (CCD) television camera[3]. Head-slaved systems with the image projected on the visor are also under development[4].

Requirements and System Choice

The bewildering array of elements available for visual simulation systems would seem to make the design of a system a straightforward engineering process. However, despite rapid changes in the technological feasibility, particularly in computer image generation, it is still not possible to assemble the perfect system usable for all aircraft and all missions. Trade-off decisions will have to continue to be made to provide a solution that is feasible, both technically and economically. These trade-offs can be made best by an iterative process that considers the aircraft and mission requirements of the simulator, the resulting apparant visual scene requirement, a review of the available psychophysical literature that will influence the engineering specifications, the making of a tentative design, and the assessment of the risks associated with this design. The results of the assessment must then be weighed against the original mission requirement to determine whether they should be further reduced. Figure 2 illustrates this process in a more formal manner than the manner in which it is usually carried out.

Aircraft and mission requirements of the simulator are perhaps the most difficult to set, particularly in simulators used for aircraft research and development. Since foresight is limited, one can not always predict with great accuracy the specific aircraft type and mission that will be of greatest interest during the lifetime of the simulator visual system, particularly when the visual system development period may approach that of a new aircraft. An attempt not to confine aircraft and mission types to those of the greatest interest can only result in a system that will do nothing well. An early and ruthless setting of priorities of aircraft types to be investigated in the simulator and of the mission segments of those aircraft is important. In training simulators, this is an almost automatic decision. However, both in research and development simulators and in training simulators, priorities of mission segments most likely to produce effective simulator results should be considered. From the priorities a set of general visual system requirements can be set. For example, wide field of view will be imperative in an air-to-air combat simulator.

The translation of these requirements into engineering specifications will inevitably lead to the specification of a system beyond the technology unless these simulator requirements are carefully assessed in terms of human requirements. Two kinds of information are valuable in this process. The first is the subjective opinion of pilots on what cues they use in flying aircraft and what deficiencies they have found in the visual systems of simulators they have flown. One should listen carefully to this subjective pilot opinion, and then carefully evaluate how it can be used. Pilot complaints are always valid; if the pilot says something is wrong, there is something wrong. However, the nature of the complaint and the suggested solution may not always be correct.

The second kind of information to be considered is the available psychophysical literature. The successful use of visual simulation systems has led to an increasing number of investigators searching for the characteristics of these systems important to the illusion. The literature they have produced should be investigated carefully to determine what car be used to make the engineering specifications less stringent. It is always permissible to fool the simulator pilot; it is never permissible for the simulator designer to fool himself when he trys to fool the pilot.

One factor that must be considered is that the intent of the visual system is not always to improve the performance of the simulator pilot. Palmer and Petitt have shown one effect of a collimating lens on a simulated landing scene is to decrease the accuracy with which pilots can make angular size judgments[5]. However, the decreased accuracy resulting from adding the collimating lens better matched the poor accuracy that subjects achieved when viewing a real-world scene. The effect of collimating was not to increase the accuracy of angular size judgment; it was to make it more like it was in the real world.

Studies of peripheral cues represent another class of investigations that are useful in determining visual system specifications. Armstrong's flight study of the landing of conventional aircraft shows performance was virtually unaffected by reduced peripheral vision[6]. Simulator studies by Junker[7] show peripheral vision to have an important effect on the pilot's ability to control in a roll tracking task, but that he apparently used the information the same way he used simulator roll motion. The experimental and analytical work of Young, and his colleagues, tie together these senses and indicate how they may reinforce or substitute for each other[8].

Other studies give some insight on how the limited number of edges and planes available in computer image generated systems might be used to advantage. Studies of viewing of computer-generated images by Crawford[9] indicated the differing levels of the texturing used had little effect on ability to judge distance from the runway. Ritchie also offers additional hope for a full acceptance of computer image generation by citing studies showing faster recognition time of cartoon drawings than of photographs[10]. The implied result is that if the characteristics of the visual system are not as good as the characteristics of the human eye one can change the picture content to make the performance of the operator the same as in the real world. This is what Kraft has done by a carefully controlled change in simulated runway light brightness[11] and Palmer has done by adding poles to the side of the runway[12].

Contrast as well as resolution is an important factor in the ability of a human to see an object. This factor is often overlooked by investigators who assign Snellen ratings to simulator visual scenes. Campbell and Maffei have made direct physiological measurements of evoked potentials on humans at various combination of resolution and contrast.[13] Their results at threshold values compare well with the psychophysical literature. A possible implication of this work to the visual simulator designer is that the contrast of small objects in the simulator visual scene can be enhanced artificially to make the perception of them the same as in the real world. Such a technique would be especially applicable to computer image generation, where contrast could be controlled conveniently as a function of range (and, therefore, of spatial frequency).

A valid training requirement can lead easily to an invalid simulator requirement, invalid in the sense that the requirement adds unnecessarily to the cost or design risk. While it is necessary to train pilots to differentiate between friendly and unfriendly tanks or aircraft, this training may not have to take place in the simulator that is used to train them for destroying those unfriendly targets. The human requirements of resolution and contrast needed to differentiate between targets may lead easily to engineering specification that current visual equipment cannot meet. One solution that should be investigated is possibility of building a separate, high-resolution, high-contrast visual trainer, perhaps using a slide or cine projector, to train for recognition of targets, and of using the flight simulator to train for pursuit and destruction of the unfriendly targets.

Reference to work of the kind described above can provide the imaginative person, psychologist or engineer, with insight and ideas that can greatly reduce the technological requirements of the simulator visual system and allow a engineering design to meet the system requirement.

A trial design to meet the derived specifications must then be made. Whatever this trial design, it then must be tested for design risk, for first cost, for operating cost, for effect on other subsystems (such as motion), and for possibilities of system growth. The trial design must then be evaluated against the simulator requirements. Together all participants of the simulator requirements and design team must decide whether the proposed design is feasible, technically and economically, and whether it meets the system requirements.

Conclusion

The process I have described implies a more formal procedure than the manner in which this requirement setting and design process is likely to be carried out. In fact, if the procedure was carried out entirely in a rigorously formal manner it would probably fail. However, I believe that a recognition that a process, at least of this type, is being followed will reduce considerably the early confusion of producing a workable system. The individual tasks of simulator requirements, human requirements, and preliminary design, although they may be led by disciplinary specialists, should be shared to some degree by all members of the team so that team members influence each other to the maximum extent. The growing body of literature on human response to simulator systems and the rapidly advancing state of electronic devices off great hopes of producing simulator visual systems to meet increasing range of simulator requirements. The result in training can be to produce a better aviator more safely and at lesser cost. The result in aircraft development can be to produce a better and more economical aircraft.

References

1. Cosentino, Alfonso, A High Resolution Color TV System for Visual Simulation, Proceedings of the Eighth NTEC/Industry Conference, Orlando, Florida, November 18-20, 1975, NAVTRAEQUIP IH-275, pp. 67-76.

2. Walker, Joe L., An Opaque Target Optical Projection System, Proceedings of the 1977 IMAGE Conference, Williams Air Force Base, Arizona, May 17-18, 1977, pp. 73-82.

3. Oharek, Frank J., 360° Nonprogrammed Visual Display, Proceedings of the 10th NTEC/Industry Conference, Orlando, Florida, November 15-17, 1977, NAVTRAEQUIPCEN IH-294, pp. 311-318.

4. Kocian, Dean F., A Visually-Coupled Airborne Systems Simulator (VCASS)--An Approach to Visual Simulation, Proceedings of the 1977 IMAGE Conference, Williams Air Force Base, Arizona, May 17-18, 1977, pp. 15-23.

5. Palmer, Everett and John Petitt, Visual Space Perception on a Computer Graphics Night Visual Attachment, Proceedings of the AIAA Visual and Motion Simulation Conference, Dayton, Ohio, April 26-28, 1976, pp. 88-95.

6. Armstrong, B.D., Flight Trials to Discover Whether Peripheral Vision is Needed for Landing, RAE Technical Report 70205, November 1970.

7. Junker, A.M. and D. Price, Comparison Between Peripheral Display and Motion Information on Human Tracking About the Roll Axis, Proceedings of AIAA Visual and Motion Simulation Conference, Dayton, Ohio, April 26-28, 1976, pp. 63-72.

8. Borah, Joshua, Laurence R. Young, and Renwick E. Curry, Sensory Mechanism Modeling, AFHRL-TR-77-70, October 1977.

9. Crawford, Billy M., Donald A. Topmiller, and Malcolm L. Ritchie, Effects of Variation in Computer Generated Display Features on the Perception of Distance, Proceedings of the 1977 IMAGE Conference, Williams Air Force Base, Arizona, May 17-18, 1977, pp. 271-289.

10. Ritchie, Malcolm L., Illusion., Distance, and Object in Computer-Generated displays, Proceedings of the 1977 IMAGE Conference, Williams Air Force Base, Arizona, May 17-18, 1977, pp. 225-239.

11. Kraft, Conrad L., Charles D. Anderson, and Charles L. Elworth, Light Size and Perception of Glide Slope in Computer Generated Visual Scenes, Proceedings of the 1977 IMAGE Conference, Williams Air Force Base, Arizona, May 17-18, 1977, pp. 51-69.

12. Palmer, Everett, Op. Cit.

13. Campbell, F. W. and L. Maffei, Electrophysiological Evidence for the Existence of Orientation and Size Detectors in the Human Visual System, Journal of Physiology, vol. 207, no. 3, pp. 635-652, May 1970.

Acknowledgement

Dr. Robert H. Wright, Aeromechanics Laboratory, U.S. Army Research and Technology Laboratories, provided valuable and helpful suggestions in the preparation of this paper. Prof. Laurence R. Young's question stimulated additional thoughts on training applications.

VISUAL SYSTEM ELEMENTS

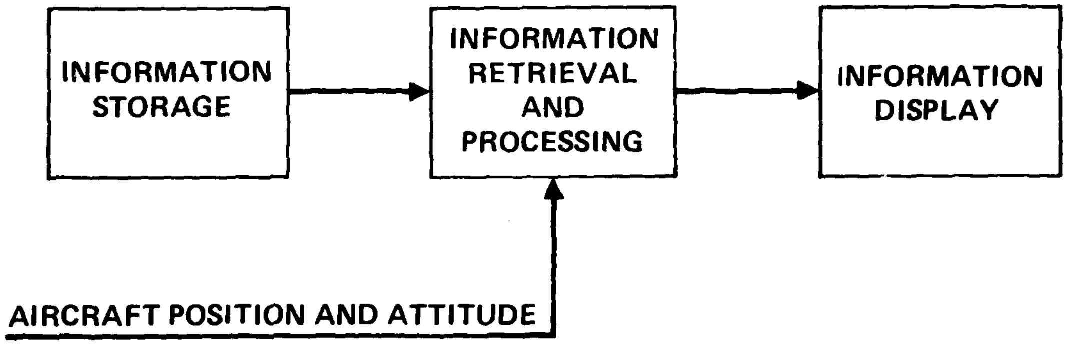


FIGURE 1

DESIGN PROCEDURE

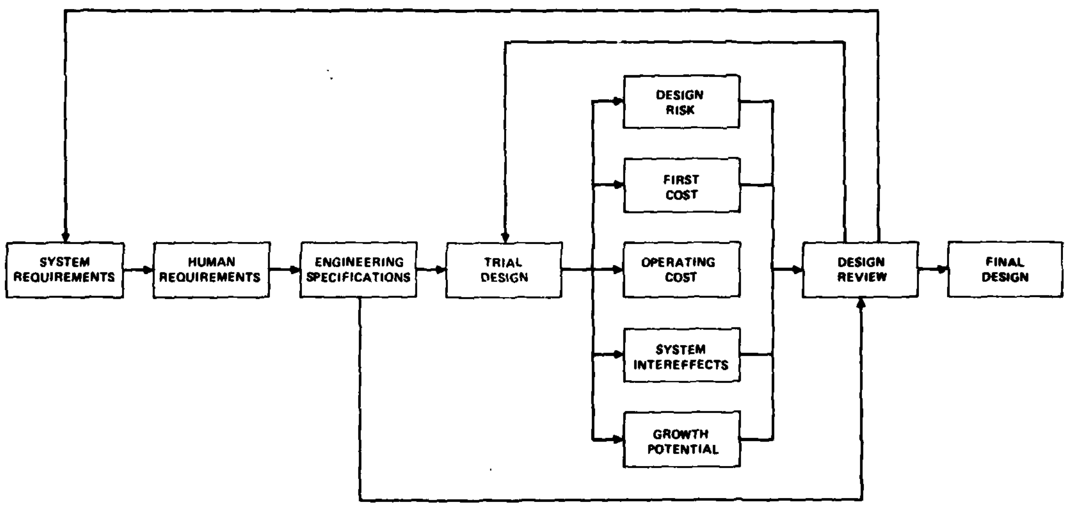


FIGURE 2

LOW BUDGET SIMULATION IN WEAPON AIMING

by

P. Manville and E. D. Whybray
Royal Aircraft Establishment, Farnborough, Hampshire, England

SUMMARY

For a number of years Flight Systems Department at RAE Farnborough has been effectively operating and developing a low budget research simulator, designed to explore aiming sequences, accuracies and real time usage in air-to-ground weapon delivery from low altitude.

Work completed has shown the value of this basic facility in providing fundamental data for assessment purposes and for the optimisation of pilots' tasks.

As a result, the simulator has been expanded to permit the aiming sequences of air-to-air combat and air-to-ground designators to be evaluated.

The description of the techniques and equipment employed illustrate how accuracy and fidelity can be achieved within modest resources.

1. INTRODUCTION

We are all aware of the cost effectiveness of training flight simulators, whether they be full mission machines costing several millions of pounds or procedure trainers costing an order less. What perhaps is less publicised are the significant benefits that can accrue from relatively cheap special purpose research simulators used as design tools. With the ever increasing cost in terms of time and money of modifying military aircraft for flight trials research and the relatively low flying rate achieved with such vehicles, a research simulator is an essential equipment for the weapon system designer.

Such a simulator requires to be flexible, reliable and cheap both in capital cost and running effort, in order to prevent the facility ascending to principal importance over the problem.

The purpose of this paper is to describe a special purpose research simulator that has been developed, in Flight Systems Department at RAE Farnborough over the last 10 years, to study the close interaction of the crew and system during the vital moments prior to weapon delivery.

2. ORIGINAL SYSTEM

A paper presented at the 16th Symposium of the Guidance and Control Panel in June 1973 discussed the reasoning behind the choice of system and the general principles employed in its design. A fixed, base, single seat cockpit with a HUD sighting system was accurately referenced to an outside world visual attachment derived from a 35mm film projector (Fig 1). The whole system was controlled by a general purpose analogue computer and much of the original equipment was obtained from surplus sources. Emphasis during development was placed upon the quality and positional accuracy of the visual system in order to provide as much 'on line' realism and data reduction as possible. Use of the facility during the last five years or so, has demonstrated the value of the basic layout; surprising, on occasions, even its most ardent admirers. Much fundamental aiming data has been produced and used for assessment purposes and for the optimisation of piloting tasks; and of nearly equal importance, the facility has provoked many stimulating discussions during demonstrations of new ideas and concepts.

As a result, it was decided to extend its basic capability to cover two important areas for future study. These are:

(a) The simulation of narrow field of view designator sights with auto tracking devices for use in air-to-ground weapon delivery.

(b) The simulation of the aiming sequences in air-to-air weapon aiming.

3. EQUIPMENT EXTENSIONS

In our original concept of the Weapon Aiming simulator, it was postulated that for manually flown low level attacks in high speed aircraft, the typical acquisition ranges of small targets would limit the lateral travel required from the simulation to quite modest levels. The high positional accuracy with limited freedom offered by a film system was therefore judged to be ideal. However, for the A/A attack sequences and for aiming weapons having an offset capability, a much wider degree of flight and target coverage is required together with target portrayal showing the correct orientation.

3.1 Designator simulation

Interest in air-to-ground designation systems has grown rapidly in the last few years, as the need to improve aiming accuracy and stand-off range increases. In simple terms, the sight consists of a narrow beam laser, an electro-optical camera with narrow field of view facilities, coupled by stabilization optics that provide a high degree of space stabilization and wide angular cover. Developments in technology now permit a range of these devices to be realised in a military package. The optimisation of the equipment in conjunction with the human operator, especially for autonomous low level operations, continues to be a challenging area where simulation is needed.

The basis of the designator simulation is shown in Fig 2. Essentially, it comprises a small model viewed by a TV camera having a zoom lens. The camera can be controlled to look at any part of the model within limits, and its output is displayed to the pilot in the cockpit.

The model is built to a scale of 200:1 using relatively simple conventional techniques. Models are readily available at this scale and a limited, but not unrealistic scenario can be set up. Motion can be incorporated by the use of simple pulleys and lines attached to the targets. To represent aspect, the whole area is carried upon a rotary table that can be turned through ±150°, in azimuth. At the ranges of interest, the lack of elevation aspect change proves not to be a serious worry, *ie* between 10 km and 1 km, the depression angle changes from 6 mrad → 60 mrad when flying at 200 ft.

The TV camera viewing the model uses a 25mm vidicon tube and a 20.1 zoom lens. The zoom is driven at a scaled rate under computer control to simulate closing range. Picture degradation to allow for atmospheric effects is an important consideration for narrow field of view sensors. This can be achieved relatively simply by the well established Hollywood technique of the use of a chiffon scarf in front of the lens. Alternatively, if resources allow, a picture processing unit can operate on the digitised video output to model the effects more precisely. To provide simulation of the pilot's aiming task without a mechanised pan and tilt head, the TV camera control unit has been modified to produce a shrunken or reduced raster which can be deflected in X and Y axes in response to input demands. The loss of picture quality inherent in this process is not serious for this application.

The harmonisation and target location are well controlled and enable the more basic characteristics of auto lock follow (ALF) systems to be represented, without recourse to the use of actual ALF equipment.

3.2 Air-to-air simulation

The A/A facility consists of a mixed projection system, employing a TV projector to give a sky/ground image and a special purpose epidiascope target projector to provide a high quality target image in colour, if necessary. Obviously with a fixed base cockpit and a visual field of view of about 50°, a full combat simulation is not possible. However, what has been produced is a visual attachment which by the virtue of the positional accuracy and response of its projected image, allows study to be made of the close aiming and sight line tracking problems in A/A using precise 'on-line' measurements of the pilot's aiming performance.

The layout of the current facility is shown in Fig 3. The sky/ground projector provides a fully manoeuvrable attitude indicator for the aircraft, on the viewing screen. The target projector inserts a correctly orientated and scaled target image into the pilot's forward field of view wherever the target is so located.

3.2.1 Target projector

Although the concept of using a gimballed model is not new, its application for this simulator is novel. A main structure is 3 m long and supports three units; the optical system, the gimbal system and the moving carriage (Fig 4).

The gimbal system (Fig 5) consists of a model scaled 1000:1 mounted on a probe, either from its tail for 'head-on' attacks or from its nose for more conventional attack sequences. This probe in turn is mounted on a pitch servo carriage which tracks around the outer ring. A roll servo is included on the carriage, and rotation of the outer ring provides the final degree of freedom, *ie* target heading changes.

The servos are all conventional dc electric motor drives and slip rings are incorporated to take the signals to the moving carriage.

This construction allows 360° of roll and ±135° of target elevation and heading change. Illumination is provided by two lamp houses containing 250 watt quartz halogen lamps focused on to the model. The complete gimbal assembly and lighting units are mounted on a base plate to allow precise location on the target projector carriage described below.

The target projector (Fig 6) incorporates very simple principles. A 50mm *f*0.95 lens mounted in a focusing slide, forms an approximately constant brightness image of the model in the plane of the 150mm projection lens. This image is then projected onto the screen via two mirrors. The first mirror is mounted at 45° to its shaft and hence produces a 1:1 angular displacement with rotation in the pitch plane of the viewing screen. Normal to the axis of the lens is a second mirror which is vertically pivoted to produce a lateral displacement of the screen image. In this case, the normal 2:1 relationship applies between image angular shift and shaft rotation.

Finally in order to retain the correct rotation of the image in the presence of aircraft roll and the 1:1 mirror rotation, a roll prism assembly has been designed to fit between the two lenses used. A 2:1 optical rotation is thereby achieved in the projection path by a relatively small unit.

Range change is achieved in the rather obvious way of carrying the gimballed assembly on the projector rails mentioned above. As set up, a scale change of 18:1 can be achieved which, with the model sizes chosen provides a maximum range of about 5 km. Whilst this is less than other A/A simulations, it is adequate for most aiming applications.

Two problems stem from the fact that the model is required to approach close to the relay lens. Firstly, there is a depth of field limit whereby at the closest ranges, all parts of the model are not retained in sharp focus. High levels of illumination help here by allowing the lens to operate a lower stop and under the high dynamic rates usually associated with the very shortest ranges, the problem is rarely noticed. The second problem, linked to the first, is the need to hold focus at all ranges. This problem has been overcome by a mechanical linkage that controls the precise position of the lens using a non-linear cam drive. A continuous loop of wire is attached to the carriage. As the carriage moves, a windlass is rotated by the wire and positions the cam against a linear slide carrying the lens, to continually adjust focus.

Advantages offered by this complete electromechanical approach to target projection are:

(a) the quality of the image - it being limited by the resolution of the optics and the skill of the model maker,

(b) the precise control of image position and orientation: the original aim of better than 1 mrad being achieved,

(c) the brightness of the image with colour to enhance the overall effect.

3.2.2 Sky/ground projector

Having produced a high quality target image on the screen, it is essential in A/A work to provide an outside world to give a dynamic reference for the target. For low level engagements, the original cine film can be used in some instances.

However, in general, a fully dynamic image is needed. Fig 7 shows the layout of the equipment design to fulfil this role. A monochrome TV projector is mounted above the target projector and harmonised with the screen. At a remote site, the image is generated by a commerical TV camera and lens viewing a coloured glass sphere shaded to represent sky and ground. Although the projection is monochromatic, a coloured sphere is more readily produced than a shaded grey version.

The camera is mounted in a roll cradle and controlled by the aircraft roll angle. Full 360° rotation is available. The glass ball is produced from two glass hemispheres approximately 100 mm in diameter and 5 mm thick. The sky and ground representation is painted on each half respectively prior to them being cemented together. A grinding process is then undertaken to remove spherical imperfections and to produce a matt finish which enables the camera to view the scene without surface glare problems.

Pivots are attached to the polar axes of the 'globe', thereby enabling it to be held in a frame. Rotations about these pivots, simulating aircraft heading changes directly, are accomplished by a rubber wheel drive about the horizon line. A friction drive suffices here, since small errors or slippages are not ever detected on the projected image. The frame is capable of rotation about its centre as shown, by conventional servo drive. Continuous motion is available about each axis.

To avoid the frame from being seen at the nadir and zenith flight condition, the polar pivot points are carried through the frame's bearings and fitted with 'polar caps'. These caps are faired to the profile of the frame and matched in colour and texture to the polar areas. The frame is therefore never seen by the camera, the only discernible feature being a slight loss of focus in the cap areas. True 360° continuous motion is achieved about each axis without any non-linear effectr at the poles, or support features being seen.

The TV chain employs a magnification of about ×50 from the ball to the screen and hence only coarse features can be represented. In addition, this form of simulation is limited to angular effects only. Whilst flying above and away from the horizon, these are quite realistic with the impression given of flying up into the bright beyond. Also of good quality is the horizon itself and clear attitude information is given. What is missing are any clues concerning height loss during the aiming phase. Regrettably, in terms of our simple simulation, no solutions are in sight.

4 APPLICATIONS

The updated facility can be coupled together in a considerable number of ways, each of which yields benefits to a specific weapon aiming problem. Table 1 has been produced to illustrate some of the possibilities, but clearly those given are not exhaustive. The aim of this paragraph therefore is to state briefly what capabilities are provided by the options rather than to list possible attack sequences which could be evaluated.

4.1 Air-to-ground

Four air-to-ground permutations are shown. A/G 1 represents the original system and provided for HUD attacks against film based targets. Experience covering many years has demonstrated the value of the facility for low level delivery and it is limited only by the availability of film.

The addition of the designator in A/G 2 provides a natural extension to take on the narrow field of view sensor attack for a wider range of weapon options. A film target is still needed for any visual phases under examination. Options A/G 3 and A/G 4 utilize the target projector in an air-to-ground role. Typical ground targets can be projected into the film scene to give a number of useful benefits.

(i) Offset targets can be more accurately represented since correct geometry can be portrayed to the pilot in terms of angular position, correct perspective and target orientation.

(ii) Moving targets can be simulated with the direction of motion not related to the film.

(iii) Multiple targets can be used, within certain limits imposed by the target projector.

In these cases, the film is used as an attitude indicator only, to aid flight path control. Exercises have been conducted using modes A/G 3 and A/G 4 with considerable success and at least 50% of operations now employ the target projector in this mode.

4.2 Air-to-air

For air-to-air, the target projector is always used with an aircraft target. The choice has to be made concerning rear and front hemisphere attack, but having chosen, the full capability of the system becomes available.

The background is usually provided by the sky/ground projector although for some low level applications, the high quality film background is valuable. Most work involves the use of the HUD although the cockpit is fitted to receive a helmet mounted sight.

5 CONCLUSIONS

The simulator has now reached a relatively advanced state of development in its ability to represent the capabilities of airborne sighting systems in typical surroundings, and at first sight, the title of this paper may no longer appear applicable. However, sophistication has been limited to a relatively small area and in terms of the capital invested and the resources required to maintain and run the facility, the cost remains relatively low.

The techniques used have been chosen because they provide quality in the very demanding attack processes. To provide an aircraft simulation to the same high standard in all departments would be an extremely expensive undertaking. Clearly such advanced facilities are required, but it is the belief of the authors that a valuable contribution can be made, especially in the early stages of system conception, by using the type of simulation outlined in this paper.

Table 1

Facility → mode ↓		HUD/HMS	HDD	Film	Target projector	Designator	Sky/ground
Air-to-ground	1	√	-	√	-	-	-
	2	√	√	√	-	√	-
	3	√	-	√	√	-	-
	4	√	√	√	√	√	-
Air-to-air	1	√	-	-	√	-	√
	2	√	-	√	√	-	-
	3	√	-	√	√	-	√

Copyright
©
Controller HMSO London
1978

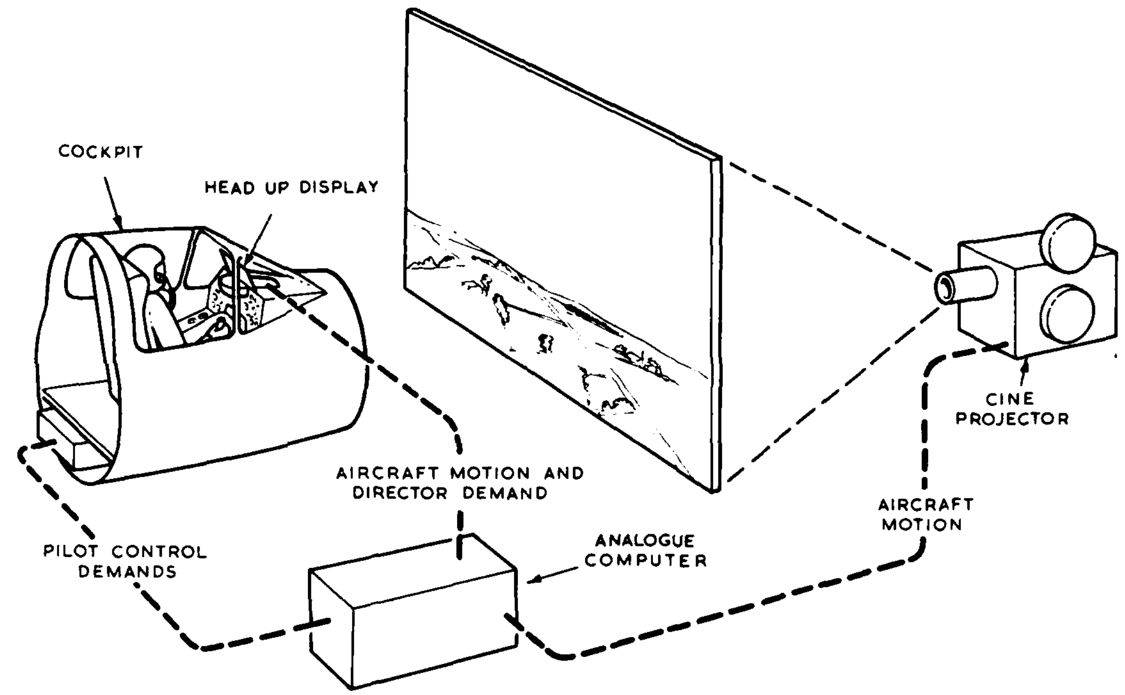


Fig 1 **Original weapon aiming simulator**

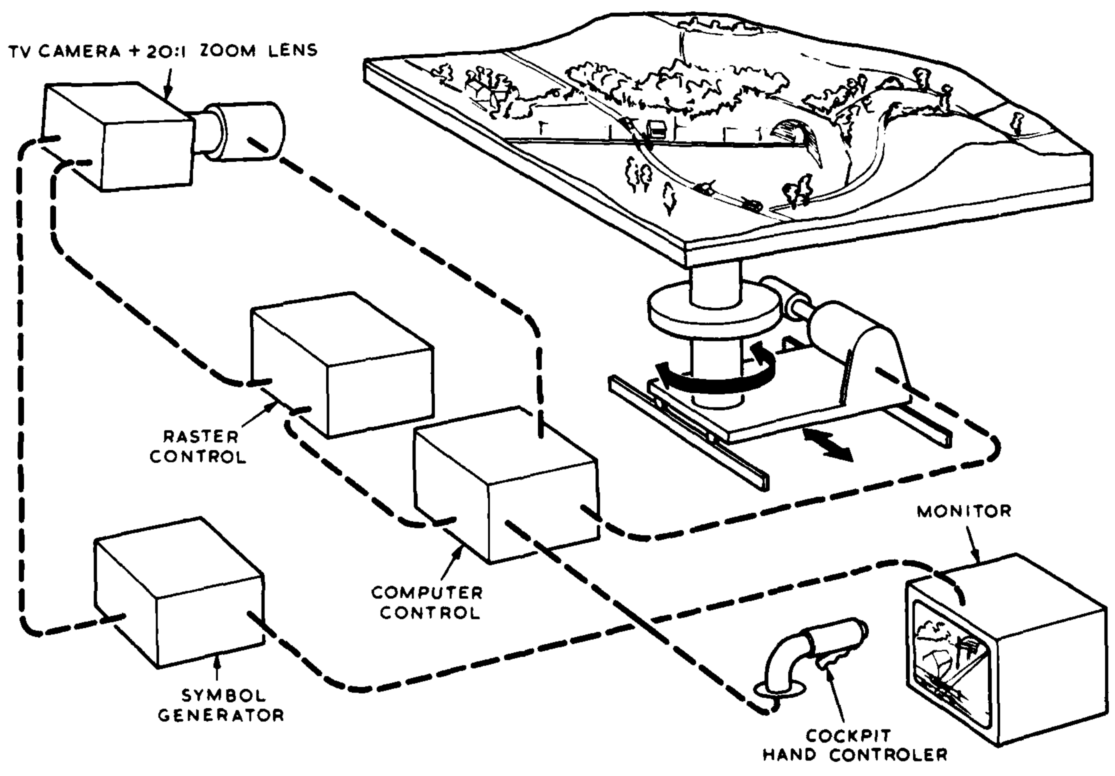


Fig 2 **Auto-lock designator simulation**

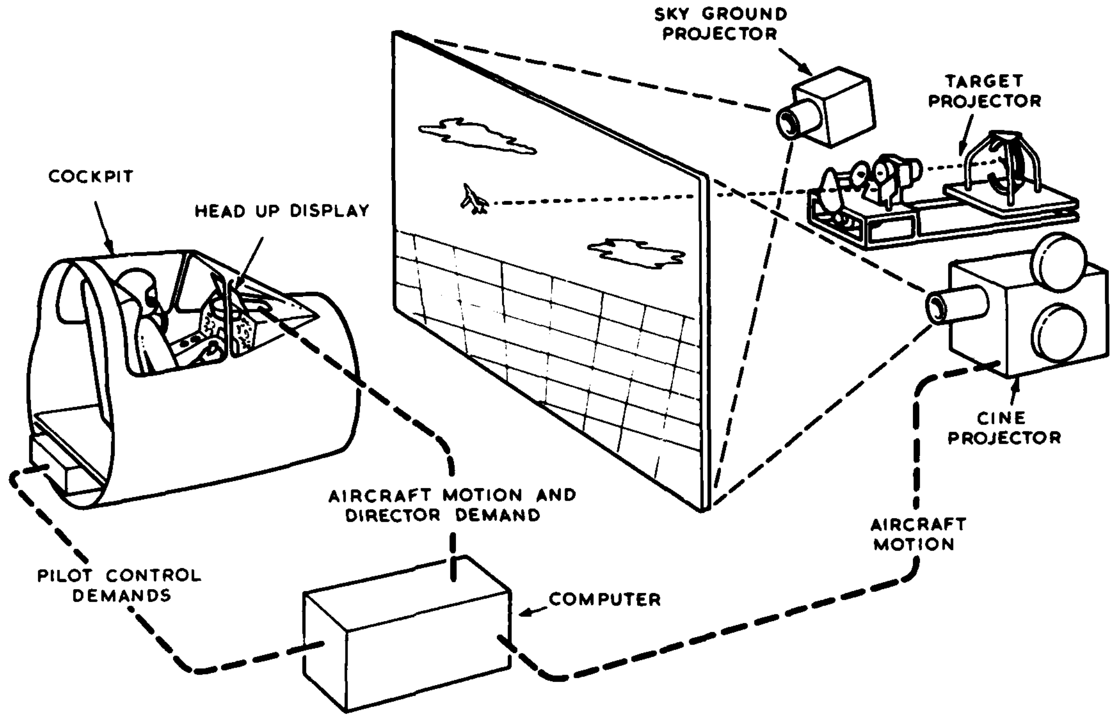


Fig 3 Updated weapon aiming simulator

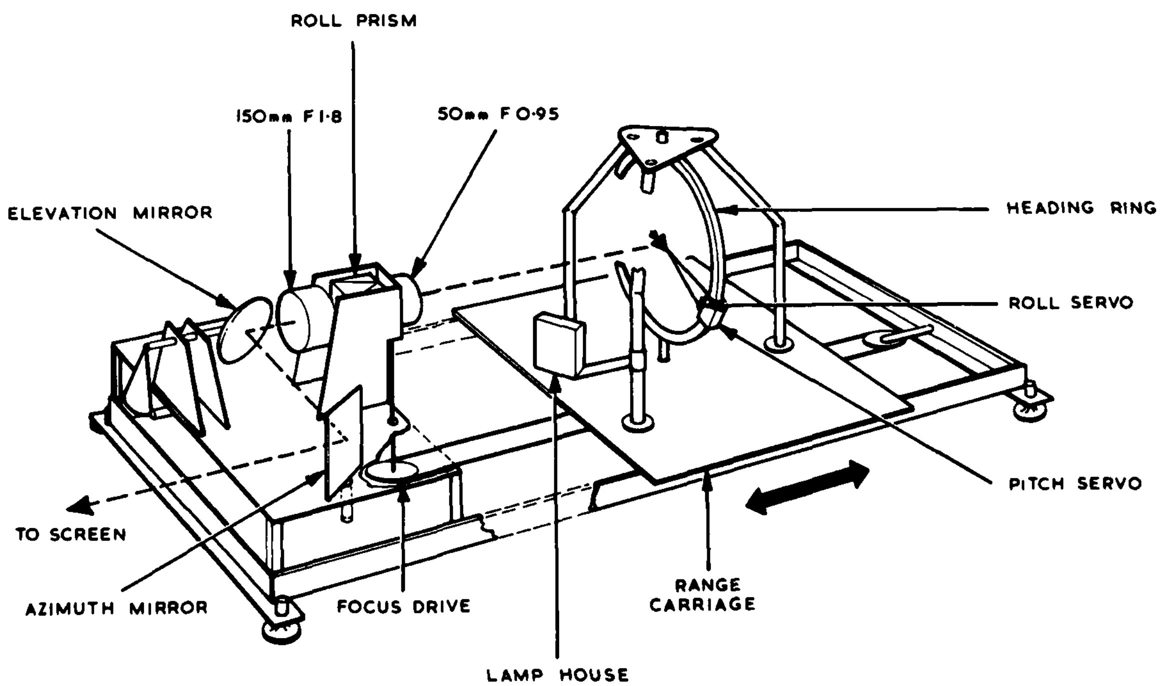


Fig 4 Target projector

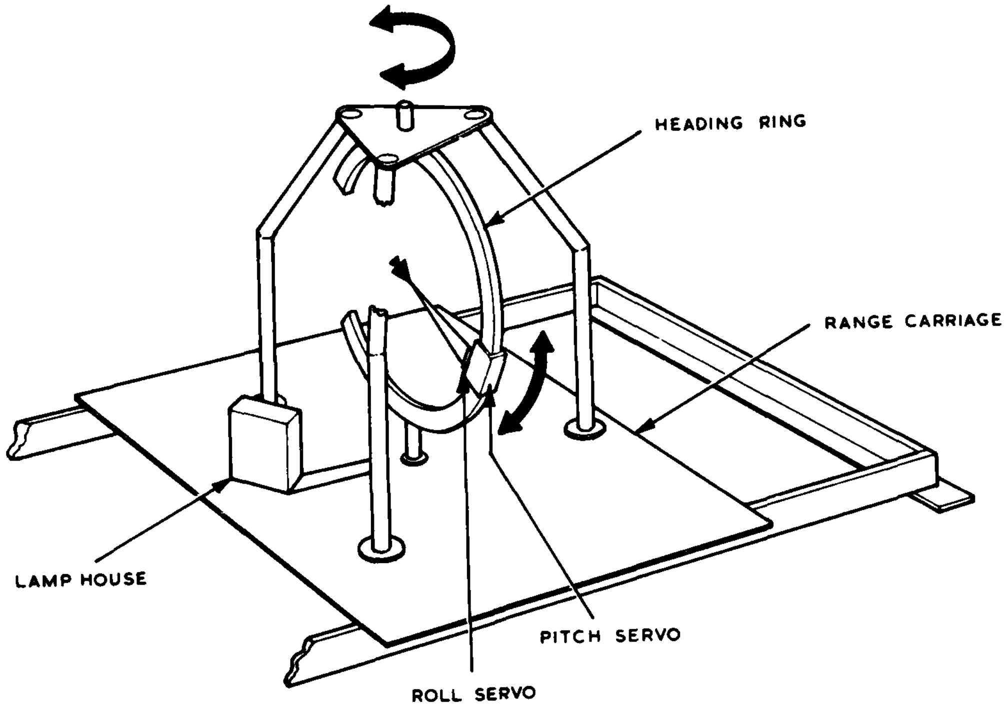


Fig 5 Target gimbal system

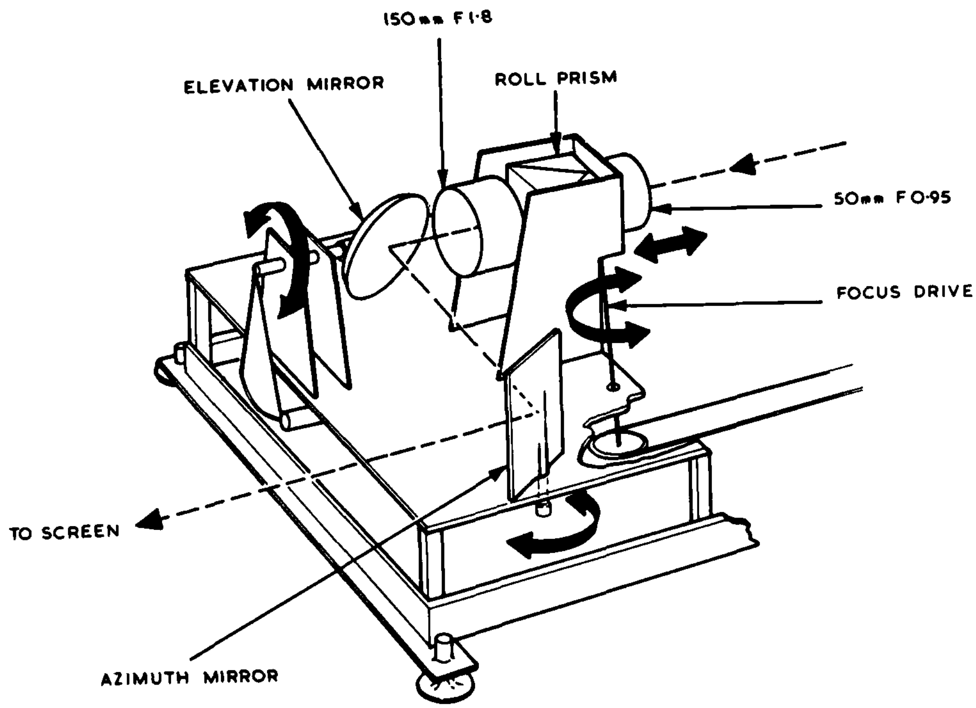


Fig 6 Target projector optics

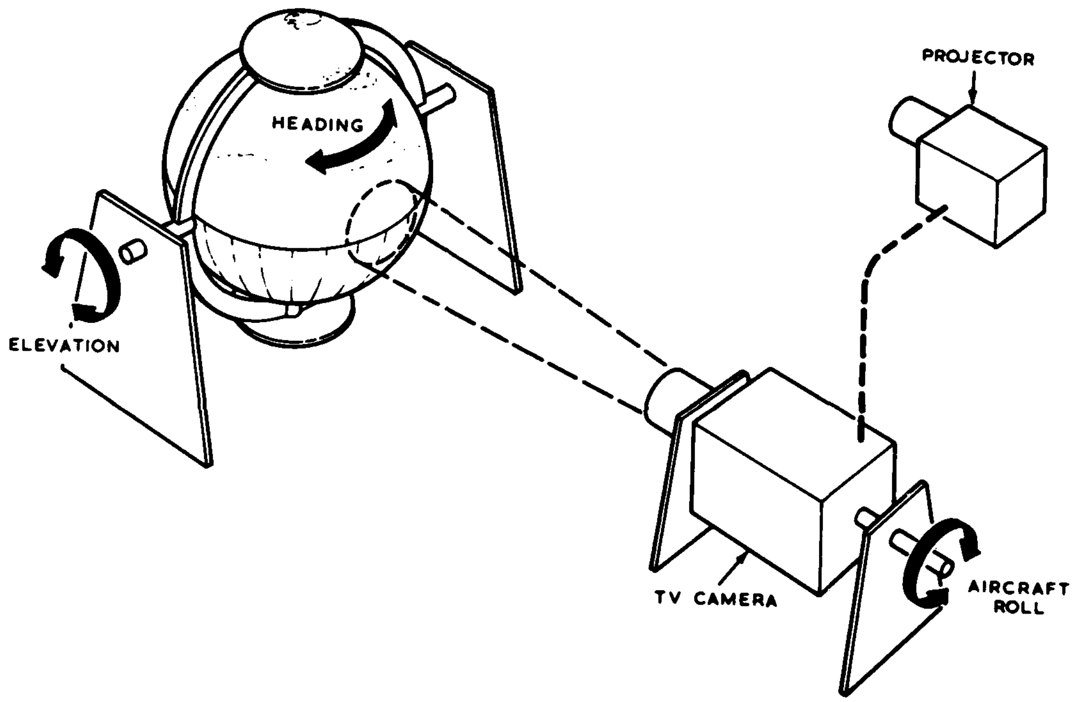


Fig 7 Sky/ground generator

THE LUFTHANSA DAY/NIGHT COMPUTER GENERATED VISUAL SYSTEM

Dipl.-Ing. M. Wekwerth
Deutsche Lufthansa AG
Dept. NT 3
6000 Frankfurt/M. Airport
Germany

Summary:
After defining some CGI terminology, the paper roughly outlines the functioning of the system in a block diagram manner. The capabilities of the system with respect to display and computational capacity are discussed. The layout of the computer landscape model, the training aspects that influenced the positioning of objects, the colouring and the colour saturation are covered. A comparisation between a conventional rigid model closed circuit television system and the CGI reveals the high flexibility of the CGI and its adaptability to varying training concepts. But it also shows up the shortcomings of computer generated imagery with respect to realism and picture detail. Mention is made of the first half year of operation experience as well as of pilot's acceptance of the new system. The paper closes with remarks on future system requirements and improvements with respect to higher content (texture) and larger fields of view.

Definition of Terms

When the first computer generated visual systems were available on the market, the airline community was searching for objective criteria to assess picture quality and scene content. This problem was relatively easy for the pure night visual systems, because the number of lights, that could be presented to the pilot as an "out-of the window" scene was an adequate means for judging picture complexity. But as soon as dusk or daylight CGI's were available, new criteria had to be found. Words like "edges, scene visible edges", "faces", "polygons" etc. were created and after a while nobody knew how to compare apples with apples.

This presentation restricts itself to just two of these words, namely "polygons" and "displayed polygons". They are defined as follows:

Polygon : A polygon is a plane, convex region defined by its edges and 3-dimensional vertex coordinates. The average number of edges in a polygon is four.

Displayed Polygon: A polygon, that has passed the back face, field of view and the perspective area test and is partly or completely presented to the pilot.

The number of displayed lights and the number of displayed polygons are sufficient to describe the scene complexity of the DLH system.

Functioning of the DLH CGI (Block Diagrams)

The Lufthansa Day/Night CGI is a dual channel image generator. Dual channel means, that the image generator produces video outputs for two independent viewpoints simultaneously, so that two flight simulators can be connected to it at any one time.

The image generator consists of a general purpose DEC PDP 11/45 computer and nine racks of special purpose hardware (see fig. 1)

The tasks of the general purpose computer are as follows:

- Receipt and handling of data blocks from the host computer
- Decoding of data blocks
- Control of the moving models
- Computation of data base reference points for continuous landscape presentation
- Data base management
- Control of flashing sequence for lights
- Control of light directionality

These tasks occupy the PDP 11/45 to such an extent, that only very limited time for background work is available.

The main task of picture generation is accomplished in the special purpose hardware. The required picture update rates and hence the high computing speeds make it necessary to use special purpose rather then general purpose computers.

In general, the special purpose hardware can be divided into three main units, namely:

- the geometric processing section
- the segment processing section and
- the display output section.

The geometric processing section performs the following tasks:

- Data base storage
- Elimination of back facing polygons
- Coordinate transformation and perspective division of vertices and polygons
- Clipping of picture information to the required field of view and
- Sorting of picture information into display plane coordinates.

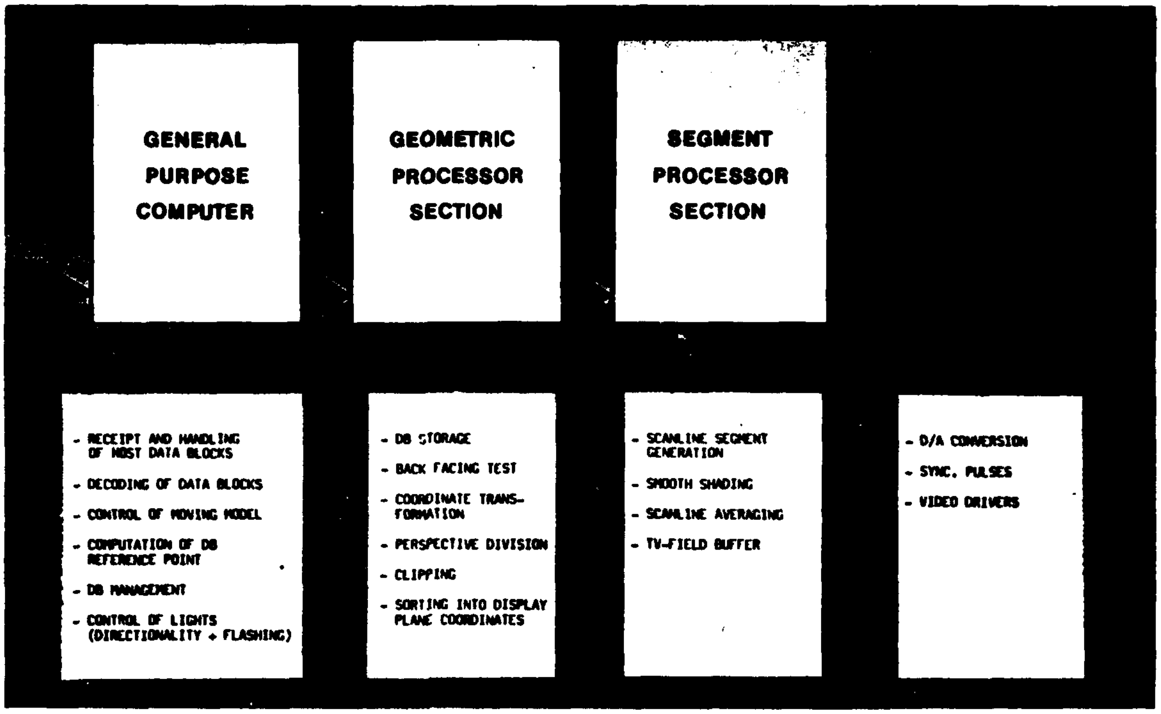


Fig. 1: Day/Night CGI Block Diagram

As soon as these tasks are accomplished, a picture exists in the computer, which is an exact replica of what the pilot will eventually see in front of his cockpit window. But before it can be displayed, it needs to be formatted in order to cope with the requirements of raster scan television signals. This is why the following computation block performs the tasks of

- Generating scan line segments
- Shading of objects
- Scan line averaging and
- Storing the information of one complete TV field in a buffer, ready for output.

The final section, the display output section, then converts the digital information of the field buffer into analog voltages and produces sync pulses to drive the display units.

System Capacity

Image Generator Capacity

When Lufthansa purchased the Day/Night CGI in 1975, it was still unknown, how much scene detail would be required to satisfy pilot's needs. This is why at the beginning of the project, a six month study was performed in order to find an acceptable match between picture detail and training value. The result of this study produced the following values:

- Total data base (in memory): 2000 polygons
- Displayed polygons: 200 per channel
- 2000 lights per channel
- 120 light strings per channel
- 50 special purpose lights
- Update rate: 50 Hz
- Positional resolution: 1/16 foot

It was felt, that if the available polygons and lights were put in the right places in the data base, the picture would have an acceptable level of complexity to achieve good training value. In fact, it seems, that the number of polygons is not as important to the acceptability of a CGI picture as is the strategic placing of objects within the confines of image generator capacity.

Special Effects

Apart from high scene detail, a picture can be enhanced by introducing special effects. As most of the simulator visual training is performed at low visibilities, emphasis was placed on good fog simulation. The Lufthansa CGI system applies a fog attenuation function to the picture elements, so that distant objects tend towards the fog colour thus disappearing in fog, whilst objects in the near field maintain their original colour. The application of the fog function is done on an element by element basis, so that long objects that extend into the distance (hangars, terminal fingers etc.) gradually and continuously disappear in the distance.

The simulation also includes variable fog density with altitude, so that effects, which are commonly referred to as "ground fog" can be introduced.

Under "clear day" conditions, the visibility is 40 nautical miles maximum. Any objects beyond that range are not computed. To make the picture more realistic, a horizon haze band is introduced.

An interesting and valuable feature of the Day/Night CGI is the control of the landscape illumination. This is accomplished by varying two illumination components, namely

- direct sunlight and
- ambient light

A combination of both produces effects for "sunny days", overcast and low visibility.

As soon as a cloudlayer is introduced, the direct sunlight component is reduced, thus reducing overall contrast and colour saturation in the picture. When the simulated aircraft climbs through the clouds, the direct sunlight component slowly increases so that the displayed picture becomes continuously brighter until eventually the aircraft breaks clouds and the sun component takes over completely.

A special technique is used to smooth out sharp discontinuities between polygons. This technique is called "smooth shading" and is used on the runway tyre marks, curved roofs of hangars and also on the horizon band.

In addition to the special effects which enhance the picture presentation, there are two effects which greatly improve picture quality.

Data base management is a technique which handles scene detail as a function of size of the displayed object. In the Lufthansa CGI each modelled object exists only once in the data base. The decision, whether an object is displayed on the screen once it is within range and inside the viewing pyramid or rejected is purely based on the perspective area of this object. If the area is smaller than for instance one "quarter of a picture element", then the object is not displayed, but as soon as its perspective area exceeds this size, it is slowly fed in, so that no popping-in of objects occurs.

The second important feature is a full 3-dimensional range priority. This means, that the hidden surface problem and the occultation of objects is solved by means of testing their range to the observer rather than introducing separating planes at the time of modelling. This technique greatly facilitates the work of the modeller and enables the pilot to fly freely over the data base without ever coming to a point where he can see through mountains or other 3-dimensional objects.

The DLH CGI Data Base

The "Anytown" Airport

It was mentioned earlier, that at the beginning of the project an extensive evaluation was made to find the number of displayed polygons which would be adequate for pilot training. As this number turned out to be 200 displayed polygons per channel it was also noted that this number would not be sufficient to model a real world airport. In order to achieve a certain degree of realism, whereby a pilot can actually recognize, that the scene he is looking at is - let us say - Frankfurt Airport, requires picture detail far in excess of 1000 polygons. So, the decision was made to model an "Anytown" airport, which incorporates topographical features that are pertinent to certain training maneuvers.

A special set of ground stations was overlayed and approach charts as well as take-off data sheets were prepared in order to bring the documentation for the "Anytown" airport to the same level as for any real-world airport.

Airport Layout

Before the process of digitizing the airport could start, a team, consisting of Lufthansa training pilots and engineers, defined a list of items, which should be included in the "Anytown" training airport.

This list included (see figure 2)

- a parallel runway system to facilitate training of swing-over maneuvers
- an upsloping runway, so that optical illusions, which occur during an approach to a sloping runway, can be trained.
- an overwater approach
- mountains in the take-off area to give second segment weight limitations
- fields and 3-dimensional objects in the approach area for better speed and height perception during final approach
- a truck, that crosses the runway on a predetermined path upon instructor's request, so that the student initiates a go-around maneuver.
- flashing hazard lights, a rotating airport beacon, road lighting and scatter lights to enhance dusk and night scenes.

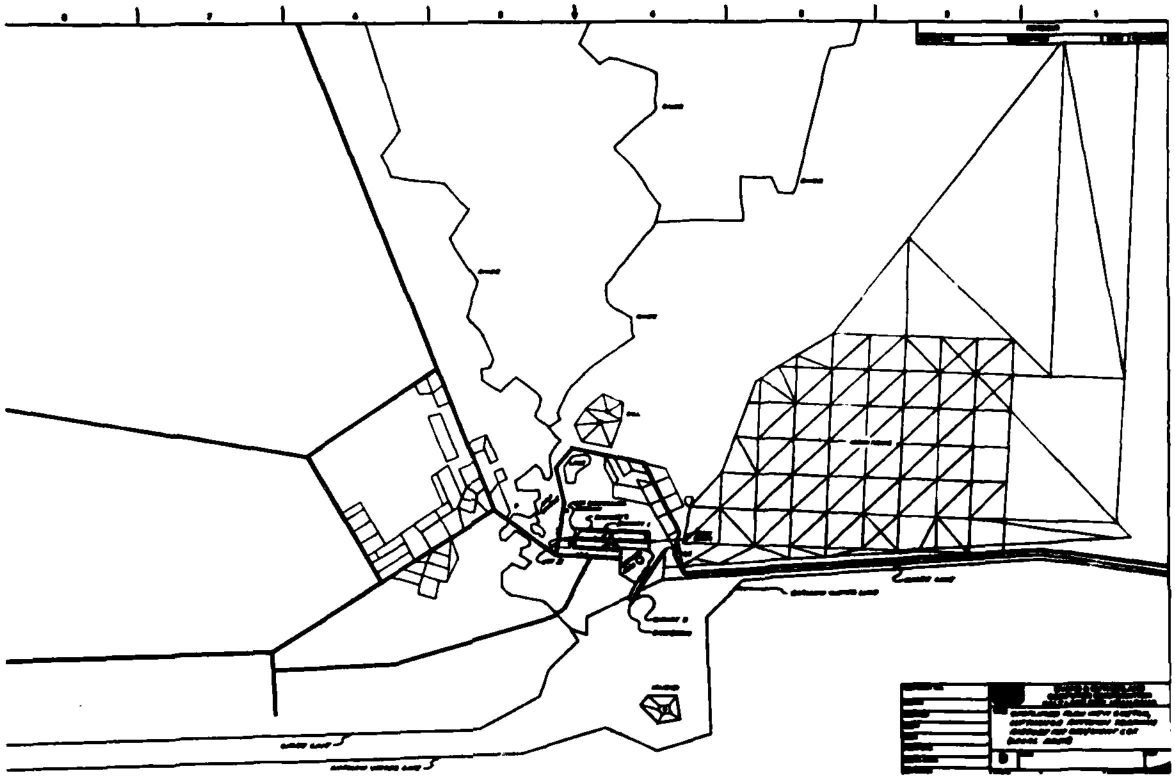


Figure 2: Data Base Design Study

Once this was defined, digitizing could start. The trial-and error method was used to place objects into strategical places and each time one digitizing session was completed, the modeled landscape was viewed and evaluated on a line drawing system. After this was completed, colours were assigned to each object and the anytown airport was now viewed on the image generator for the CAORF (Computer Aided Operations and Research Facility) facility at Kingspoint, New York. A set of approximately 50 aerial photographs, showing landing and take-off scenes, was used to tune the colours.

The landscape - as it stands today - contains 2000 polygons and 2000 lights. 41 colours were used for polygons and 6 colours for lights.

Polygons, that have identical colour coding, may not appear to have the same colour, if the values for intensity and reflectivity of the polygons vary.

Rigid Model / CGI Comparisation

When comparing the TV rigid model technology with the CGI, there are certain advantages of the CGI, which are fairly obvious. These are presented in tabulated form below.

	CGI	RMV
Focus	complete picture in focus	focus problems with depth of field at low altitudes
Stability/Repeatability	very stable and repeatable	degradation of electro/mechanical components causes instabilities. Scene repeatability low.
Gaming Area	large gaming area (up to 4000 x 4000 nm)	gaming area relatively small (8 x 3 nm)
Reduced visibility	reduced visibility very realistic, look-through effect for lights is possible	curtain effect, poor look-through capability
Over-the-coulds scenes	yes	yes (only with separate model)
Environment Flexibility	allows various airport layouts to be programmed	one fixed environment
Terrain Height	the CGI can provide the host computer with aircraft height above terrain for GPWS and radar altimeter applications	not possible

	CGI	RMV
Lightpoint Presentation	small pointlights	model scale determines minimum size of lights
Side Window Displays	possible	impossible, due to camera restrictions
Resolution	more than 700 picture elements per line	600 picture elements per line
Availability	99,7% of scheduled training time	98% of scheduled training time
Maintenance Effort	Low, due to high reliability and diagnostic readiness checkout	very high
Energy Consumption	approx. 25 KW	approx. 150 KW

But there are also disadvantages of the CGI, namely those, which concern picture content and realism.

In the CGI all displayed objects have strict geometric shapes, lines are clear and sharp, polygons are coloured uniformly and no texture is provided. These facts make the picture look artificial, whilst the picture provided by a rigid model visual system can be made to look very realistic, if careful modeling is applied.

It was this argument of an artificial picture, which brought up the very serious question of pilot acceptance. Although the two training pilots, who accompanied the whole project right from the beginning, were very optimistic, the big test for the system came, when it was put into operation,

Pilot Acceptance of the CGI System

Synthetic Appearance and Picture Detail

The dual channel CGI went into operation on Sept. 15, 1977. A few weeks before that date all pilots were briefed on the system and were provided with the necessary information material for navigation and flight planning. They were also asked to comment on the system, negative or positive.

Today, after half a year's operation, we can say, that pilot acceptance of the CGI system has been very good. Many positive comments were made on the clear and sharp picture. The synthetic appearance and the lack of scene detail did not influence the generally positive attitude towards the system. It seems, that in a high workload traning environment the pilot concentrates on very few, but very significant items in the outside scene. These are the runway and its shape and position within his field of view. The rest of the environment model is of less importance to him.

Training Value

When the CGI was installed, it increased the visual time during a training shift from 40% to 80%. This in itself is a great improvement to simulator training. But the CGI also enabled pilots to fly certain maneuvers under visual conditions, which they could not perform with the closed circuit television/model board system. These are all high altitude maneuvers and emergency descents. They can now be flown above clouds with a good horizon reference.

It is almost certain, that due to these improvements a reduction in actual aircraft flight training can be expected, although at the present time no definitive figures can be quoted.

It should also be noted, that the high availability of the CGI (average 99,7% over the last six months) compared with that of the rigid model visual system (average 98%) produces an additional 80 hrs of visual time per year.

Future Requirements

The future requirements can be divided into two major areas. The first relates to improvements of the picture generator itself, the second one to improvements of the display system.

Picture Generator

Although the CGI picture generators are capable of producing sufficient polygons and lights to make a scene "flyable", the scene that is presented to the pilot lacks one important feature, namely texture.

The polygons, which are calculated by present day CGI's are of uniform colour and intensity. It is very difficult to position such a polygon in space just by judging its size and perspective area. Adding texture to the polygon surface facilitates the task of judging the distance between observer and object, thus enhancing the threedimensional effect of the picture.

If texture is added to all displayed polygons, the picture becomes richer and more realistic. It should be noted, however, that, if texture is introduced into future CGI's, it must be treated in the same way as polygons with respect to positional and perspective calculations.

Display System

When using rigid model visual aids, the camera is normally the weakest link in the video chain, that means, picture quality depends on the quality of the TV camera and its associated optics. With the advent of CGI's the camera was eliminated, so that now the display system is the limiting factor with regards to picture quality.

One disadvantage of present display systems is the interlace technique with which the video information is written on the screen. This interlace technique produces "staircase" effects whenever a displayed object moves vertically across the CRT surface. This effect has always been present, even with closed circuit television systems, but it has become more apparent with the clean pictures, generated by the CGI.

The second disadvantage of TV raster scan displays is the fact, that one picture element is written once per frame only. This means, that the presentation of light points with respect to brightness is not as good as on calligraphic displays, presently used on night visual systems. A combination of raster scan and calligraphic displays seems to be the ideal display for the future.

Finally, I would like to mention the ever increasing demand for wide angle displays, which allow a horizontal field of view of 180 to 210 degrees. This demand could not be met with closed circuit television systems due to optical problems in the TV camera. Nowadays the CGI image generator can produce scenes for large viewing angles, but the displays presently on the market cannot produce a collimated, continuous wide angle field of view.

If the above requirements can be met in the future, we will be one step closer to "zero-flight-time" training.

RECENT ADVANCES IN TELEVISION VISUAL SYSTEMS

by

Brian L. Welch
CAE Electronics Ltd.
P. O. Box 1800
St. Laurent, Montreal
Quebec H4L 4X4 Canada

SUMMARY

A closed circuit television (CCTV) model board visual system, which was designed for a CH-47 helicopter, is described herein. The attributes and deficiencies of the system are discussed in an attempt to show how a model board based visual system suitable for full mission simulation in Nap of the Earth (NOE) environments could be designed. A new computer generated image (CGI) visual system which makes extensive use of texture is presented as an alternative to the model board approach. The importance of realism in full mission simulators as distinct from flight and weapons trainers is also discussed.

INTRODUCTION

The modern battlefield has become a highly lethal place for both fixed and rotary wing aircraft. The formidable array of weapons which can be used against aircraft has forced pilots to abandon their normal operational altitudes in the vicinity of a battlefield. The only airspace which can be considered relatively safe is below 100 feet and only then if a sufficient amount of ground cover is available. The term 'Nap of the Earth' (NOE) has been coined by the helicopter community to describe operations in which they fly at speeds of up to 60 knots only a few feet above the ground and fly around obstacles rather than over them. Whether or not this type of flying led to helicopter units being called Air Cavalry is not known but it very accurately describes the NOE flying technique. Aircraft such as the A10 whose primary role is to kill tanks on the battlefield operate at only slightly higher altitudes than helicopters but at speeds of about 300 knots. Even multirole aircraft such as Tornado and F16 must operate at these low altitudes when used for close air support. The environment for the pilots flying these missions is full of trees and bushes, hills and valleys, which although offering protection from the enemy are lethal to the unwary pilot. Whereas the high flying pilot can obtain adequate height cues from size and shape of known objects the low flying pilot must make use of texture and parallax. This then is the environment which the simulator engineer must try to duplicate.

In a closed circuit television model board system the probe has to be able to 'fly' in NOE terrain, the camera and projector must be able to pick up and display high resolution color imagery, and the gantry must be able to move the probe smoothly at all operational speeds with very little lag. The system about to be described does all these things, not well enough for a full mission simulator but sufficiently well to show how one should be designed. The field of view, 38° x 50°, is completely inadequate, the dynamics of the gantry leave a lot to be desired, and the flying area is far too small, but the basic video chain provides imagery which seems to be of sufficiently high quality to allow NOE flight.

SYSTEM DESCRIPTION

The system which will be described in some detail was designed for a CH-47 simulator and will be used by the Imperial Iranian Army Aviation (IIAA) at Isfahan. The simulator was not designed to have a full mission capability but the techniques used have shown how a full mission simulator could be designed. The design of a CCTV visual system can be broken down into the following areas:

a) TV Camera

b) Optical Probe

c) Display

d) Model

e) Model Illumination

f) Gantry

g) Special Effects

No one area can be considered to be the critical component. When the designer is using state of the art technology a poor design in any of the above areas can have a serious effect on system performance.

TV Camera

The TV camera is perhaps the most unusual aspect of CAE's design as it is based on a field sequential color technique rather than the normal simultaneous system used by the broadcast industry. The normal color TV camera has three image tubes, each receiving a red, blue or green image. The resulting video signals from each of the tubes are essentially kept separate and used to drive the corresponding guns of a color CRT or some other display device using separate color channels. The three separate color images are then optically combined to give a full color display. The significant difference in the field sequential technique is that only one image tube, one video channel and one display channel are used. The color is obtained by placing a color wheel containing red, blue and green filters in front of the image tube and rotating it in synchronism with the field rate such that successive fields receive red, blue and green images. A typical color wheel is shown in Figure 1.

The display device uses a similar color wheel to project sequentially colored fields. The field rate must be three times the normal TV rate and a correspondingly higher bandwidth must be used. Both the camera and the display have the distinct advantage of not having any of the color registration problems which plague high resolution simultaneous systems.

Some visual systems have tried to eliminate the registration problem inherent to simultaneous TV by using a high bandwidth luminance channel and low bandwidth chrominance channels. This has been justified on the assumption that the eye has a much lower acuity in the red and blue portion of the spectrum than in the green. However the resolution of most visual systems is 3 to 6 times worse than that of the normal eye which renders the assumption quite irrelevant. In actual fact the acuity of the eye in the red and blue is only about 10 percent lower than in the green and yellow. The resolution of a field sequential system is of course equal in all three colors.

Care must be taken in the design of a field sequential camera to obtain good colors. It should be apparent that any lag in the image tube will cause desaturation of the color by mixing different color information in successive fields. The color wheel is the most critical component, assuming that a low lag camera tube is chosen which has a reasonable response across the visual spectrum. The size of the color wheel, its center of rotation, the shape of the color filters and the width of the spokes are carefully chosen to ensure that the electronic scanning beam follows the spokes down the picture and always lies exactly behind the spoke. This ensures that only light of the correct color is integrated by the image tube target in each field.

The optical characteristics of each filter depend to a large extent on the spectral characteristics of the model illumination, the optical probe and the image tube. The design goal should be to obtain equal video signals from all three color fields when imaged on a white test chart. Although the color gains can be electronically adjusted any large difference in the gain of one color will accentuate the desaturation of the color due to lag which can never be entirely eliminated. This usually means that the cut-off frequencies for each color are not where one would normally expect them to be. The red filter for CAE's camera, for example, has a decidedly orange appearance; however, the coloring of the model is also under the designer's control and can be used to compensate for this effect.

Very few image tubes offer high resolution, low lag, low noise and high sensitivity, all of which are obvious requirements for a visual system camera. The RCA Image Isocon type 4827 is probably the best compromise and was chosen for this system. The standard 4827 was found to be too noisy, however, and several tubes were obtained with different target to mesh spacings which effectively control the tube sensitivity and noise characteristics. A spacing of .002 inches seems to be optimum in that it allows a reasonably noise-free picture yet has sufficiently low lag to give good color. A recent tube which might offer superior performance is the Philips Plumbicon type 45XQ. The modulation transfer function (MTF) of the camera using a 4827 Image Isocon with .002 inch target to mesh spacing is shown in Figure 2.

A limiting resolution of 800 TV lines is readily obtained with high modulation at the intermediate frequencies. The SYNC standard chosen for this system is 735 lines at 150 fields/second. Slightly higher image quality could be obtained by going to 925 lines but any higher line rate than this would probably result in poorer picture quality due to the higher bandwidth resulting in a decrease in signal to noise ratio.

The noise produced by an Isocon is almost entirely due to Photon noise and can be readily calculated from a knowledge of the faceplate illumination and the noise equivalent bandwidth. The predicted signal to noise ratio was 32 dB and the achieved value was 30 dB. It should be noted that the integration time of the eye is considerably longer than the integration time of the camera at the light levels associated with visual systems. This becomes the controlling factor in determining the displayed signal to noise ratio.

Optical Probe

The design of the optical probe is an extremely important task in any model board system. The probe used in an NOE visual system must be able to cope with several situations not normally encountered in model board systems. It must be able to fly very close to both the ground and vertical objects, go between trees spaced only two or three rotor widths apart and it must have a sufficient depth of focus to provide good imagery for all objects within the field of view. Tilted optics have been used with considerable success to provide a well focused image of a runway at ground level by rotating the image plane of the runway as a function of altitude and pitch to keep it coincident with the face plate of the camera image tube. Unfortunately, vertical objects are no longer in focus and very close vertical objects are considerably defocused. This effect is shown in Figure 3.

The CH-47 simulator has a nontilt probe with a 0.7 mm aperture and a variable focus mechanism. Figure 4 shows the depth of focus when focused at 100 mm. This has been found quite adequate when flying at or below tree top level. It could be argued that a tilt probe could be operated in a nontilt mode when flying NOE, however a tilt probe has considerably lower transmission and slightly lower MTF.

The actual point at which the probe is focused varies with altitude, pitch and velocity and was determined empirically. A significant improvement in this regard could be obtained if the probe was focused at the point at which the pilot was looking. This would require a knowledge of both head position and eye position. Although such a concept may sound a little far-fetched, head trackers and eye trackers will probably become quite commonplace in both aircraft and simulators in the not-too-distant future. As a fairly detailed knowledge of the surface of the model is held in computer memory to prevent probe crashes - a subject which will be dealt with later - the orientation of the pilot's head and eyes will enable the probe to be focused at the optimum distance. The acuity of the eye drops off quite rapidly outside the fovea so it is possible that the pilot would be unaware of any out-of-focus imagery existing anywhere in the field of view.

The optical performance of the CH-47 probe particularly from the point of view of transmission and MTF is extremely high and little improvement can be expected in this area. The MTF curve is shown in Figure 5. Part of the design concept of the visual system was to provide a view through the 'Chin Bubble' of the CH-47. This was deemed necessary by the IIAA for sling load operations in sandy conditions as the forward and side views were usually completely obscured. To meet this requirement a wide field of view probe was used allowing the forward view and 'Chin Bubble' view to be picked up by two separate cameras. Figure 6 shows the sizes and relative position of both views. Although the 'Chin Bubble' view has proven to be of little value in general simulation use the technique has shown how a relatively wide field of view could be provided by using multiple camera systems with a multiple output probe. The configuration shown in Figure 7 uses three cameras to cover 110° by 50° and is probably the optimum configuration as it matches the performance of the probe to that of the cameras. Each of the probe outputs would have an identical mapping function obviating the need for complex scanning and shading circuitry in the camera or display systems.

Display System

Current display technology is the limiting factor in the design of visual systems. The television industry has been unable to produce a display device to match the performance of the Eidophor light valve which has been around for over thirty years. Various attempts have and are being made to produce higher resolution displays but none have been successful. One of the reasons for choosing a field sequential color television system was to allow the use of the field sequential Eidophor.

The projector used on the CH-47 is basically a monochrome EP-8 with a color wheel inserted in the optical path and an electronic system operating at the required line rate and bandwidth. The monochrome GE light valve has a similar performance to the Eidophor in regard to resolution and could be converted to the field sequential color mode. A significant number of systems would have to be purchased, however, to make this conversion a commercially viable proposition.

The lack of reasonably priced high performance television displays has forced the simulation industry to consider 'Area of Interest' (AOI) systems. In this type of display system the displayed image is slaved to the pilot's head position allowing imagery to be seen wherever the pilot looks. This technique is not new having been used before on the LAMARS simulator. The advantages of the head slaved display are fairly obvious; a relatively small field of view can be used for each display channel allowing good resolution to be obtained and at the same time several channels can be mosaicked together to give a reasonably large field of view.

The optical probe in an AOI visual system 'looks' where the pilot looks instead of always being aligned with the aircraft axis. The actual technique used for slaving the displayed imagery to the head can vary from simply slaving a complete projection system inside a dome screen to the use of a head mounted display. The head mounted display would appear to be the ultimate 'Area of Interest' system. The pilot will have the impression that he is wearing a pair of goggles which restricts his field of view to that of the display. The actual design of head mounted displays is outside the scope of this paper but CAE and Farrand Optical Company are making such a device having a field of view similar to that shown in Figure 7 and hope to have it working before the end of this year.

Although head mounted displays have many obvious advantages they suffer from one serious drawback in that it may be impossible to provide high resolution target imagery. The resolving power that appears to be possible with helmet mounted displays is of the order of three to six minutes of arc whereas one or two minutes of arc is required if targets are to be acquired at realistic distances. Such resolution can probably only be obtained by projecting target imagery onto a dome independently from the background imagery.

Area of Interest systems can of course be used with both CCTV and CGI visuals. Computer generated imagery and its use in an AOI system will be discussed at the end of this paper.

Model

Model detail should be regarded as an integral part of the system MTF. The modern model maker has perfected techniques for providing highly detailed models at a moderate cost. Trees which are required by the tens of thousands in an average model board are made from printed circuits and require a minimum of manual handling. Buildings and even bridges are made by similar techniques. Paints have been developed which have high reflectances but are nonspecular and have a long life under intense illumination. CAE's CH-47 model was made by John Piper of England. He spent several days in Iran photographing and studying the terrain. This enabled him to make a model which incorporated the details CAE wanted yet still managed to look natural. He also realized that not all camera systems are alike and made several sample models which were viewed by the camera to allow the correct selection of paints and texture to be made.

The scale of the model is obviously a critical parameter from several viewpoints. It should be as small as possible to allow a reasonably large operating area yet large enough to prevent depth of focus problems. The CH-47 has two adjoining areas with scales of 250:1 and 750:1. A scale of 500:1 is probably the smallest which would allow a sufficiently high quality picture for NOE operation. If the position of the pilot's eye were continually measured and the probe focused at his look point on the model, a scale of 1000:1 might be feasible. This concept has not been thoroughly investigated yet but looks promising. The use of mirrors at the model boundary and special effects can increase the effective model area even more by allowing the pilot to shoot his weapons at targets beyond the model boundary and even be fired at by threats beyond the model boundary. This technique is shown in Figure 8 and can be seen to increase a nominal operating area of 7 by 20 kilometers to 15 by 18 kilometers allowing for a missile range of 4 kilometers.

In order that the probe may fly safely at or below tree top level some type of probe safety system must be incorporated. Several types of proximity detectors were investigated for the CH-47 but none appeared to be suitable. A software safety system was eventually designed which required a detailed topographical knowledge of the model stored in the simulator computer. This was obtained by using the gantry to measure the surface height of the model every two inches over the entire model. The program allowed the probe to land anywhere on the model and to fly just above the surface providing its velocity was sufficiently low. In effect, the program looked ahead and determined whether or not the probe was about to crash. If it was, the probe would either be raised to a safe height or the entire system would be frozen. In almost two years of operation only three serious crashes have occurred requiring the replacement of the probe head assembly, and all of these crashes occurred under manual control. The software safety program has since been modified to provide protection even under manual control which should prevent any further crashes except for those caused by a critical component failure.

A model board designed for NOE flying would probably be measured on a much finer grid spacing. The topographical information would not only be used for probe safety but would also enable line of sight calculations to be made to determine if an enemy threat could see the helicopter either visually or with radar. A further use for this information would be to enable the probe to focus at the optimum distance knowing the look angle of the pilot's eye as mentioned previously.

Model Illumination

The model illumination is a sadly neglected area in visual system design. Lighting engineers are used extensively in broadcast television studios to obtain the desired effects. CAE consulted an eminent lighting specialist by the name of Salvatore Bonsignore who worked for the CBS Television Network and followed his advice with some success. Stated fairly simply his advice was to illuminate the model from the side as much as possible and avoid direct overhead lighting. The reason for this is quite obvious when one considers the ratio of illumination of horizontal surfaces to vertical surfaces is 3:1 with flat nondirectional lighting and can be as high as 10:1 if lamps having strong directional properties are aligned normal to the model. Due to the limited dynamic range of any television camera all vertical surfaces will have little or no detail when seen on the display giving a very poor quality picture. The ratio of horizontal to vertical illumination achieved on the CH-47 model was 1.5:1 which appears to be quite acceptable.

Gantry

The gantry is the structure which moves the camera system in the X, Y and Z directions over the surface of the model. The normal flying velocity of a helicopter varies from zero to about 200 knots requiring a very large dynamic range for the servo system. Various types of servo systems were considered but the one which looked most promising was made by Icon using Sigma digital motors. These motors could be controlled at rates of 40,000 steps per second allowing a dynamic range of well over 1000 to be obtained.

Digital servo systems have a unique set of problem areas which require a thorough understanding before a successful design can be implemented. It is unlikely however that any other type of servo system could provide the required performance. The CH-47 gantry was designed with air bearings on both X and Y axes. Problems were encountered on the Y axis due to the uneven loading imposed by the movement of the Z carriage which were only solved by the substitution of linear ball bearings. It would seem likely that this type of bearing could be used on both X and Y, eliminating the need for an air supply.

Stiffness rather than friction would appear to be the most significant parameter of the gantry. Servo systems can be designed with almost zero lag and with time constants of 50 ms or less. Flexing of the gantry structure or any part of the drive train can not only increase this time constant but can also cause instabilities. Lags caused by the simulator computer are usually more significant than lags inherent to the visual system, and it may be necessary to use higher iteration rates for helicopters having very fast responses.

Special Effects

In a CCTV system it is necessary to generate certain display features electronically rather than incorporate them in the model. Sky, fog, and dust are usually generated in this manner, rotor blade effects can be incorporated for visuals used on helicopters and various weapon effects can be incorporated for mission simulators. These effects can all be generated using a mixture of analog and digital techniques similar to those used in broadcast television. During the design of the circuit used to simulate the rotor blade an important discovery regarding color breakup was made. Color breakup in field sequential systems has often been put forward as a reason for not using this technique even though it did not appear to be a problem in operational systems.

Being aware of the possible problem of color breakup, the circuit was so designed that the motion of the rotor blades was suspended for each color sequence of red, green, and blue. This should have resulted in a white rotor blade, but as soon as it started to move, a distinct color fringe was observed on each side of the rotor blade. It was then noticed that when the circuit suspending the motion for the three color fields was inhibited, so that the red, green, and blue images were now separated, the fringes disappeared. The explanation then became obvious. When the eye looks at a moving object it tracks the object to keep the image on the center of the fovea. Therefore, although the red, green, and blue images were separated on the screen, they were together on the retina, resulting in a white image. The background will, conversely, have color breakup, but as the acuity of the eye drops off sharply away from the fovea, it is not seen.

CAE has demonstrated the CH-47 visual to many people, and no color breakup has been apparent under normal operating conditions.

The general reaction to the rotor blade simulation has been quite favorable by both pilots and spectators.

This concludes the description and possible improvements to the CAE CH-47 visual system. Before dealing with some of the other aspects of visual simulation, a short summary of a visual system suitable for NOE operation will be given. A diagram of a possible approach is shown in Figure 9.

A wide angle probe would provide three outputs for three field sequential color cameras operating at 925 lines and 150 fields per second. Three GE light valves operating in a field sequential mode would provide an 'Area of Interest' display slaved to the pilot's head position either on a dome screen or preferably on a helmet display. The instantaneous field of view would be 110° by 50° and the overall field of view would be 220° by 70° or even greater. The special effects unit would supply fog, smoke, dust trails, rotor blade simulation, various weapon effects and sky. The model would have a scale of between 500:1 and 1000:1 and be about 7 by 20 meters in actual size.

NIGHT OPERATIONS

Attacking forces have a distinct advantage at night particularly when the defending forces have been prevented from training after dark due to civil regulations. The importance of mission training under night conditions in the simulator is therefore quite high. The significant differences between day and night operations are loss of contrast, loss of color, loss of acuity and the complete loss of vision in the fovea. These latter two effects can only occur at the very low light levels associated with night, i.e., 10^{-3} to 10^{-5} foot Lamberts (fL).

H. Ozkaptan at the 1975 NTEC conference proposed the use of a simulator to investigate the problems of NOE flight under low illumination levels and suggested that neutral density (ND) filters could be used to reduce the brightness of the display to the required level. This technique is necessary to preserve the signal-to-noise ratio and the contrast of the displayed image. As the CH-47 visual used an Eidophor projector, it was a relatively simple matter to insert ND filters in the optical path to reduce the image brightness to about 10^{-3}fL. A remarkably realistic simulation was obtained. The pilot had to wait for several minutes before becoming dark adapted and all the normal effects of night vision were noticed. The display resolution was no longer a limiting factor and the noise was imperceptible due to the longer integration time of the eye. An unsuccessful attempt was made to procure a pair of AN/PVS-5 night vision goggles but there would appear to be no reason why these could not be used in a simulator using the above approach for night simulation. A visual system designed for night operations only would be considerably cheaper than a full daylight visual system as only one tenth of the full lighting would be required, monochrome cameras could be used and small CRT projectors would provide adequate image brightness.

TARGET ACQUISITION SIMULATION

The prime task of an attack helicopter is to acquire and destroy enemy armor using 'stand-off' missiles such as HOT or HELLFIRE. It is virtually impossible to obtain adequate training for this task in the real world and mission simulators must be used. Present technology, however, prevents realistic targets being seen at the required distances in the visual scene. Fortunately for the simulator manufacturer the unaided eye has the same problem in the real world. Several experiments conducted by John Barnes at the U.S. Army Human Engineering Laboratory have shown just how difficult this task is. To solve this problem in the real world sophisticated Target Acquisition and Designation Systems (TADS) have been developed. These incorporate direct optics, television and Forward Looking Infrared (FLIR) imagery with various magnifications. It is expected that these systems will be superior to the unaided eye for acquiring targets at ranges of 2000 to 5000 meters.

It is reasonable to theorize therefore that the gunner will only gaze out of the window to look for targets on exceptionally clear days and only then if he expects to see moving tanks which throw up a considerable amount of dust and other debris. The simulation of the acquisition task would be quite adequate if the dust clouds were simulated by special effects in the 'out-of-the-window' display and the targets were only shown in the TADS. Missile trails and explosions would be shown in both displays.

The sensor characteristics and the various magnifications can only be simulated adequately by the use of CGI techniques. A suitable CGI system is discussed in the next section. A certain amount of risk is associated with making a CGI data base similar to a particular model board. Obviously it cannot be identical however it should be possible to model the significant features sufficiently accurately.

COMPUTER GENERATED IMAGE SYSTEMS

Computer generated imagery has almost completely ousted model board techniques from the visual scene. Calligraphic visuals offer a night landing image practically indistinguishable from the real world and have become almost universally accepted by the commercial aviation industry. The full color day/night CGI visuals using normal raster television techniques have become completely accepted by the U.S.A.F. for full mission simulation for fixed wing aircraft. They have no alternative of course, for although a model board visual could undoubtedly provide the highly detailed imagery for close air support missions it could never hope to offer an adequate playing area.

It is only in the field of full mission simulation for advanced attack helicopters and advanced scout helicopters that model board visuals can offer adequate training. Even here of course computer generated imagery has many advantages and as stated earlier the TADS must be simulated using CGI techniques. The U.S. Army will shortly be testing the UTTAS simulator which has two cockpits, one with a model board visual and the other with a CGI visual. It will be very interesting to see how the two systems compare.

Until a year ago CAE and probably most of the U.S. Army personnel involved in simulator procurement believed that computer generated imagery was not far enough advanced to provide imagery suitable for NOE flying. At this time CAE became aware of a new CGI system being developed by Marconi Radar Systems. Although a fully dynamic system is not working yet and probably will not be until the end of this year the static scenes were sufficiently impressive to modify CAE's views. The system is called TEPIGEN for Television Picture Generator. It uses the latest technology and consequently has many advantages over other systems; however, the one attribute which makes it quite remarkable is its ability to produce fully textured surfaces. This texture can be applied to any face and undergoes the same perspective transformations as the face, hence it remains coherent with the face at all times providing the correct texture gradient cues so important for low altitude flight. Many different types of texture are available to create clouds, trees, grass, bricks, sand and even town lighting for night scenes. The main effect of this texture is to produce highly complex scenes with relatively few faces. It has been estimated that the texture enhances the face capacity by a factor of between ten and one hundred. Before comparing the CGI with CCTV a short technical description of TEPIGEN will be given.

The TEPIGEN System

The TEPIGEN System as shown in Figure 10 consists of three processors which can be individually configured in various combinations, capacities and standards to meet a wide range of CGI requirements. The three processors: the scenario processor, the picture processor and the display processor provide the following functions:

Scenario Processor

All control data for the processing and display of the CGI is routed to the scenario processor. The interface with the host simulator computer and/or the operational controls of the simulated vehicle provides the scenario processor with both initializing exercise data and the on-line motion data of the vehicle. Using the library of terrain and model data (data base) the scenario processor is able to select the working model data for display. The working model data, which contains all faces including those which are only potentially viewable (i.e., occulted by other faces), is limited by the working capacity of the picture processor. The scenario processor, however, monitors the picture loading and controls the level of detail not only to avoid overloads, but to provide optimum picture detail at all times. The selected data is then transferred to the picture processors.

Picture Processor

Using processing instructions from the scenario processor, the picture processor orientates and translates the models to assemble the scene before mathematically projecting the three dimensional imagery into the necessary two dimensional screen imagery. The models at this stage are represented by the boundaries of colored areas which are overlaid or joined to form the picture. If texture and/or shading facilities are available the mathematical projection is extended to the texture and/or shading functions to ensure that the surface detail appears coherent with the surface of the model. The data output which represents only the viewable faces in the picture is now passed to the display processor for conversion to the display format.

Display Processor

The conversion of the two dimensional screen data into the TV raster line interlaced video data is the main role of the display processor. The processor also performs the color processing and edge smoothing functions as well as special effects generation for optional features such as sea state, graticules, tracer, etc. If the TEPIGEN system has been configured to provide more than one output display channel the display processor will assign the picture to the appropriate channels which may be either adjacent for a 'continuous picture' or independently sighted to show different views. The display processor can provide RGB video for 625/875 line standards at either 50 or 60 Hz Field Rate.

CGI or Model Board

Many reasons are given in favor of CGI or model board visuals but they can all be divided into two groups, those that affect cost and those that affect the displayed picture. Individual parameters such as the large size of model boards and the enormous quantities of power they consume are quite irrelevant once a price has been assigned to the parameter and included in the total life cycle cost. In a recent study which CAE did for the U.S. Army to determine the most suitable simulation techniques for advanced attack helicopters, the costs for a CGI visual and a model board visual were very similar. Cost therefore is not likely to be the determining factor. The only parameter which should be considered is whether or not the picture out of the cockpit window will provide sufficient cues to allow the mission to be flown in a very similar if not identical manner as it would in the real aircraft.

Many papers have been written lately on the subject of CGI realism and training. Most, however, seem to justify what is currently available rather than analyzing what is required. The visual cues required for the simulation of the full NOE mission almost defy analysis. Good texture and parallax cues are a minimum requirement for the pilot but the navigator requires a complex set of topographic, hydrographic and botanical cues. CGI and model board techniques can provide adequate cues for the pilot. However, a recent study by the U.S. Army to determine if computer generated imagery could provide adequate cues for NOE navigation was a complete failure. The cues required for NOE navigation would even tax the skills of the most ingenious model maker. Even if we assume that an adequate set of cues can be provided for both pilot and navigator in CGI and model board visuals the question of realism and crew acceptance of the visual scene must be resolved.

Mission simulators will be used mainly for developing, refining and maintaining the skills required to destroy enemy armor in a hostile environment. The only practice that experienced crew members will have in flying fully interactive missions will be in the simulator and then only for about four hours a month. The probability that they will have difficulty in accepting the unreal qualities of a CGI scene resulting in wasted simulator time is by no means negligible.

Scenes produced by a CGI system, such as the ones previously described which are based mainly upon texture than faces, will undoubtedly be more acceptable to experienced crew members than other types of computer generated scenes. Each tree can be either solid pyramids, dodecahedrons, etc. or open structures with branch-like members. Each face would have a texture resembling foliage enabling excellent depth perception cues to be given. They will not, however, be as realistic as the trees used on a model board. The model board approach has its limitations, but can certainly provide highly realistic environments.

The actual role of realism in full mission training is difficult to establish but should not be disregarded. It seems to be true, for instance, that many tasks are performed differently when the mind is in a highly emotional state. Greater reliance is placed upon learned and instinctive motor skills than upon the slower but perhaps more rational thought processes. The pilot's state of mind when flying a real world NOE mission is probably different from when he is flying a simulator, whether it has a CGI or model board visual. However, if a full mission simulator is to be something more than a flight and weapons trainer, this difference must be minimized.

REFERENCES

Barnes, J. A., Human Engineering Laboratory helicopter acquisition test. Technical Memorandum 20-74, U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD, September 1974.

Barnes, J. A., Use of the tank main gun for defense against helicopter attack. Technical Memorandum 14-76, U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD, April 1976.

Barnes, J. A., & Doss, N. W., Human Engineering Laboratory camouflage applications test. Technical Memorandum 32-76, U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD, November 1976.

Barnes, J. A., Human Engineering Laboratory identifications friend or foe test. Technical Memorandum 30-77, U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, MD, October 1977.

Ozkaptan, H., Critical Visual Requirements for Nap of the Earth (NOE). Flight Research 8th NTEC/Industry Conference, November 1975.

Acknowledgements

The author wishes to acknowledge Marconi Radar Systems Ltd. for the description of TEPIGEN.

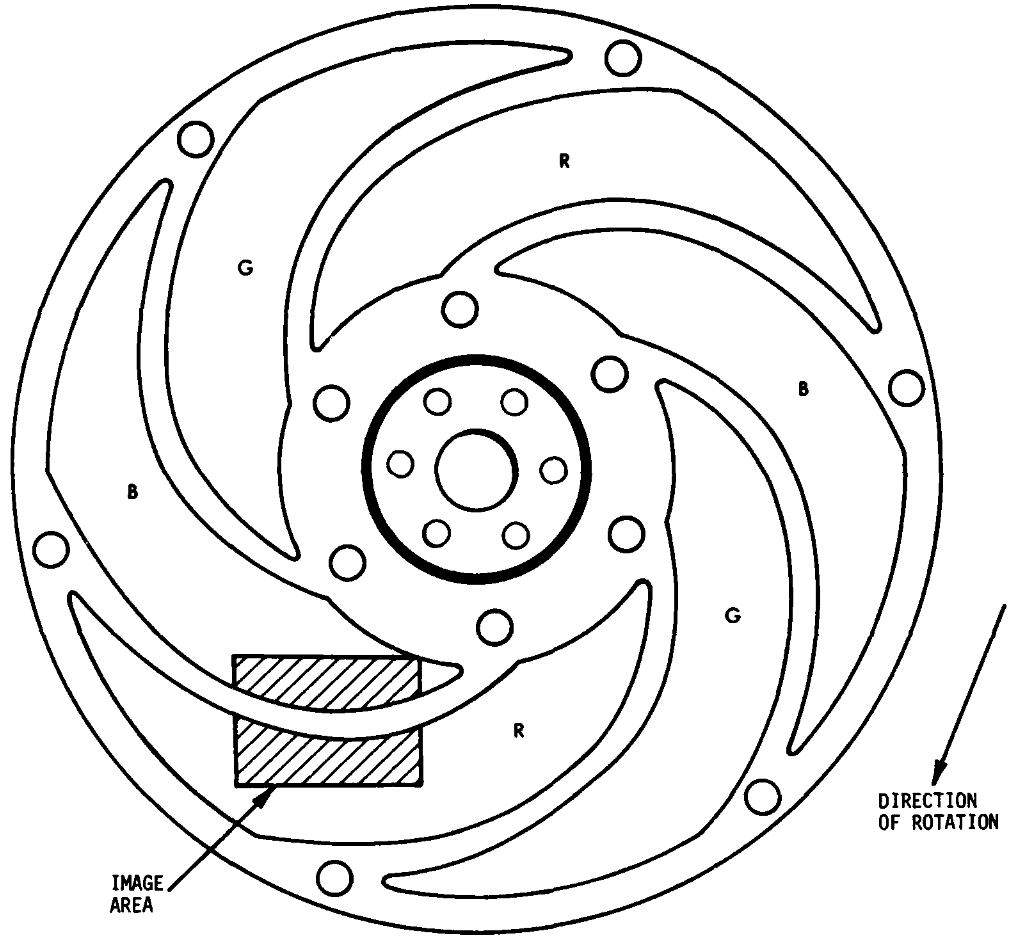


Figure 1 Color Wheel

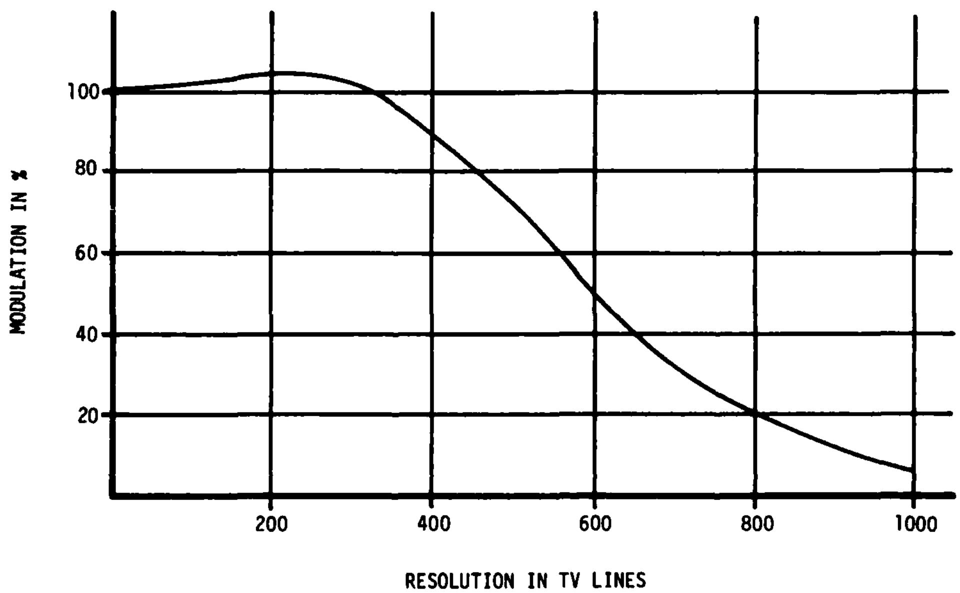


Figure 2 Modulation Transfer Function of CAE Camera and Farrand Probe

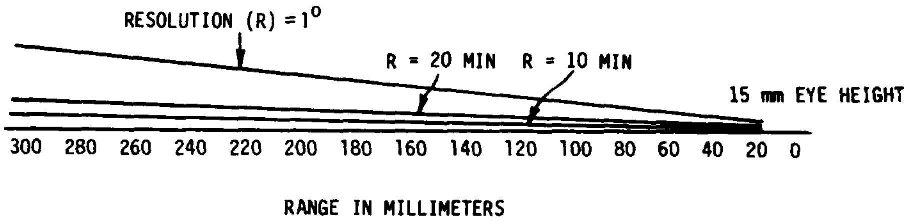


Figure 3 Resolution of Tilt Corrected Probe with 1 mm Pupil at 15 mm Eye Height

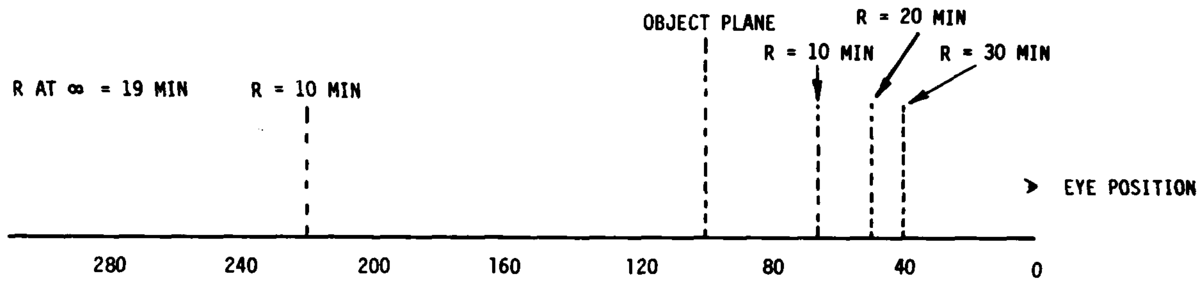


Figure 4 Resolution of Nontilt Corrected Probe with 0.7mm Pupil and Focused at 100mm

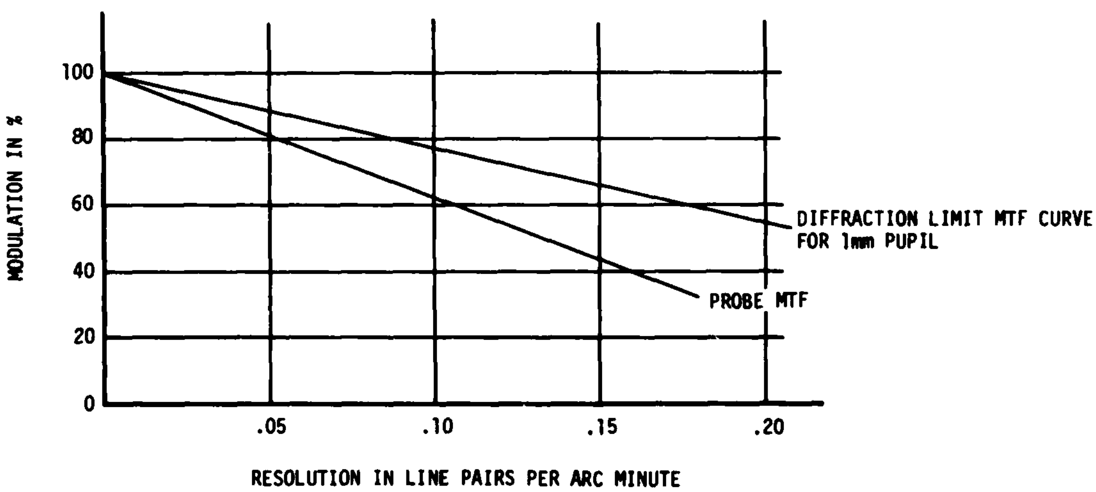


Figure 5 Modulation Transfer Function of Farrand Probe

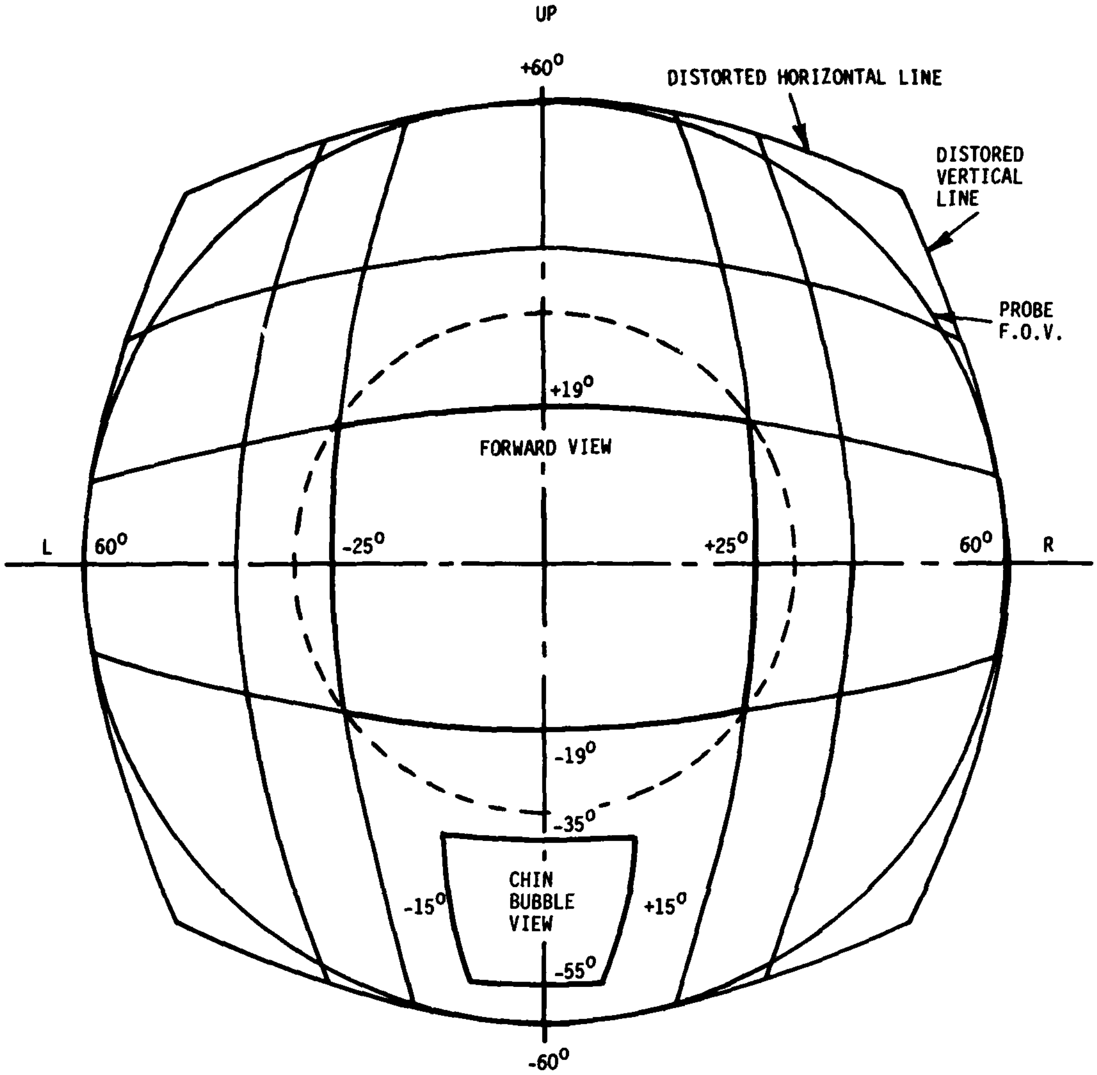


Figure 6 Field of View of CH-47 Probe

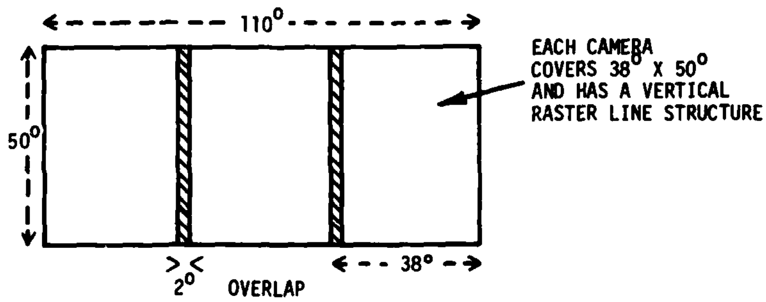


Figure 7 Multiple Output Probe Field of View

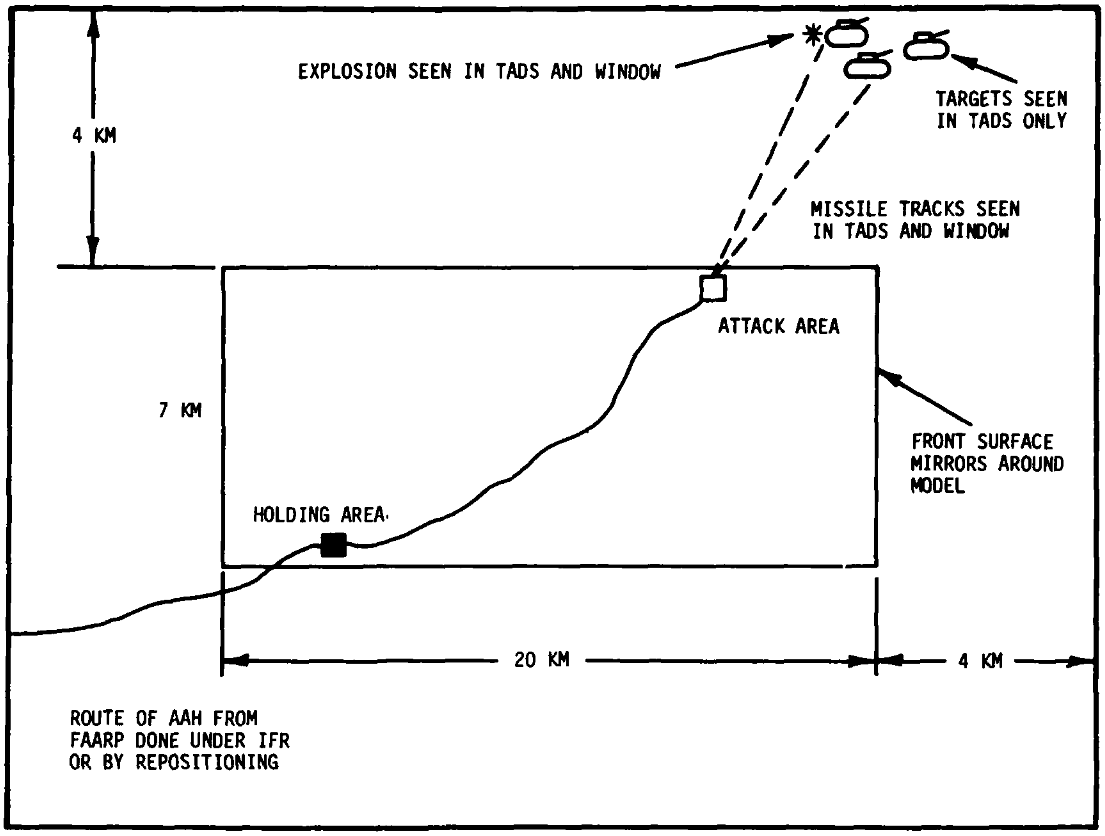


Figure 8 Use of Mirrors, Special Effects and TADS to Extend Tactical Area

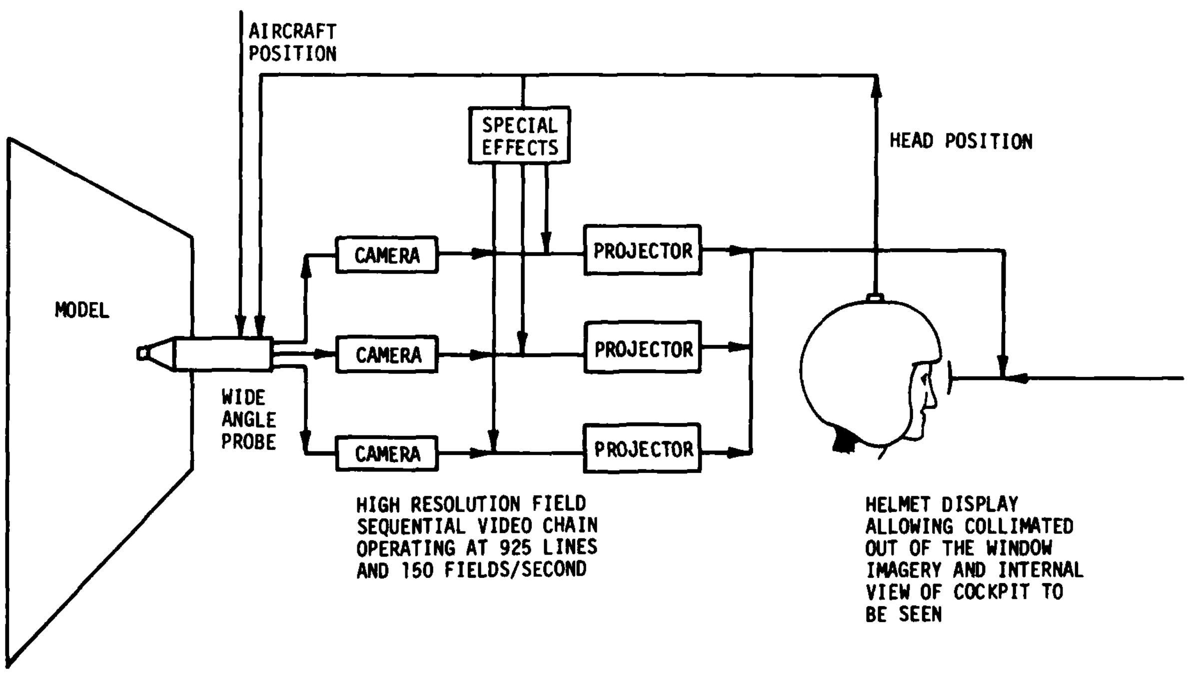


Figure 9 Visual System Suitable for NOE Operation

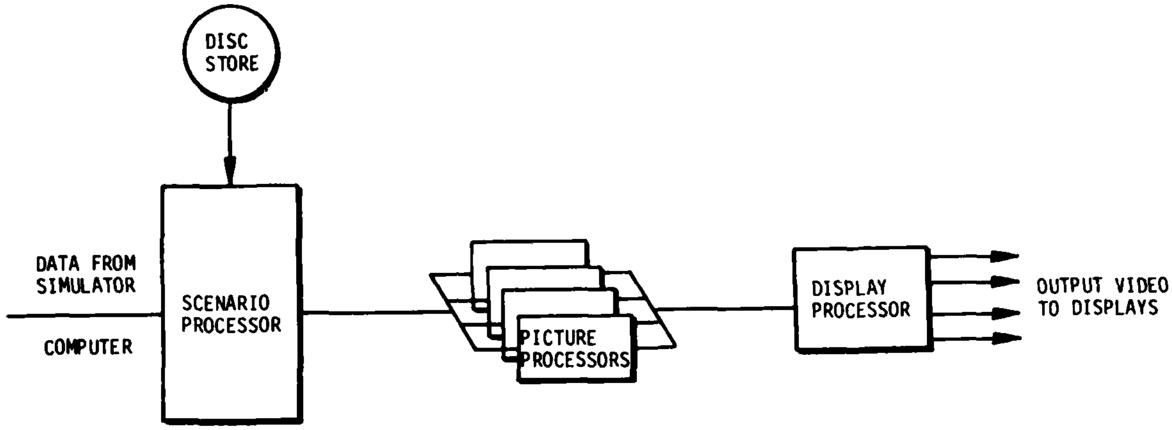


Figure 10 TEPIGEN CGI System

A HIGH RESOLUTION VISUAL SYSTEM FOR THE SIMULATION OF IN-FLIGHT REFUELLING

by

Martin J.P. Bolton
Research Engineer

Redifon Simulation Ltd.,
Gatwick Road,
Crawley,
West Sussex RH10 2RL,
England

SUMMARY

This paper describes a unique visual system, developed for the simulation of the in-flight refuelling task; it incorporates both wide bandwidth and computer generated image (CGI) techniques. After a brief review of the in-flight refuelling task and the simulation requirements, Redifon's previous experience in this field is outlined and the overall design of the latest visual system is described.

Particular attention is paid to the problem of providing the essential visual information within the constraints of cost and available technology. An important part of this visual system is the "special effects unit", which provides all video processing and image generation functions under the control of an autonomous computer.

INTRODUCTION

The task of training pilots in the skills of in-flight refuelling is still mainly performed in the air. However, with advances in the technology of visual simulation, in the areas of both television and computer generated images, effective ground-based training devices are now being developed. This paper will outline the efforts of Redifon in this field and describe our most recently developed in-flight refuelling visual simulation system.

In-flight refuelling procedures include rendezvous with the tanker aircraft, coupling, fuel transfer, disconnect and emergency breakaway. In all of these, the receiver aircraft pilot relies strongly on external visual information. This includes the tanker itself, with its various lighting patterns, the refuelling boom or drogue and below this, terrain or a cloud layer. Refuelling procedures must also be performed at night and in conditions of poor visibility.

A simulation display for in-flight refuelling is of the area-of-interest type; a highly detailed tanker image is required, while the background terrain/cloud image may be of low resolution. The first such visual system built by Redifon was built as part of a complete flight simulator in 1975. This simulator is used for training in all phases of flight, including in-flight refuelling. The simulator visual system is based on the Redifon 625-line colour closed-circuit television and modelboard system. A 144:1 scale model of the tanker aircraft was added on an 8 ft (2.5 m) x 15 ft (4.5 m) blue area at one end of the main 2000:1 landing and takeoff model. This arrangement met the requirement to provide a view of the tanker from a maximum range of about a mile and a maximum relative height of 1200 ft down to contact of the tanker's boom with the receiver's receptacle. Director and fuselage lights were provided and the boom is manoeuvrable and under the control of the simulator instructor. Figure 1 shows the arrangement of the model in this system.

The maximum height of the optical probe above the modelboard surface corresponds to only 288 ft, far less than the 1200 ft required. This limitation was overcome by arranging to move the probe away from the tanker model in the direction of the main axis of the terrain model to obtain the increased separation required and at the same time pitching the tanker model to maintain the correct aspect corresponding to a height change. There is also a problem with the use of models of this type in that at the greater ranges unwanted image details, such as parts of the terrain model, enter the field of view. This was overcome by electronically masking such details by providing a programmable "window" around the tanker image. That part of the image outside of this window was replaced with an electronically generated "sky" which matched the colour of the model background. On this was superimposed a white featureless cloud cover providing a horizon line. Figure 2 shows some pictures obtained from this system.

The system produces very acceptable in-flight refuelling images, but further improvements are possible without placing excessive demands on current technology. Improved smoothness of operation of the tanker boom would result if the mechanical drives were situated inside the model, which is not possible with the 144:1 scale. Secondly, a higher resolution television system would allow a better tanker image to be produced, especially at extreme ranges, and finally, a patterned cloud layer would present attitude and speed cues not present with featureless cloud. These improvements have been included in Redifon's latest in-flight refuelling training simulator.

The layout of the simulator complex is shown in Figure 3, while Figure 4 illustrates the visual system. The tanker is a 50:1 scale model equipped with a servo-controlled moveable refuelling boom, correctly scaled navigation lights, underbody floodlighting, director lights and rotating beacon. Refuelling boom movement is controllable from the simulator operator's station or by the main simulator computer. The model is viewed by an optical probe and television camera attached to a carriage which travels vertically along a tower structure. Simulated range variation is effected by a combination of vertical probe movement and a servo-driven zoom lens in the probe. The nose of the tanker model, which points towards the ground, is mounted on gimbals which permit movement of the model in the yaw and pitch axes. These motions, in combination with servo-controlled optical elements in the probe allow the full range of useful tanker/receiver relative positions to be simulated. A fixed lighting system, located on three sides of the model enclosure provides illumination for the tanker, which is variable for the simulation of day, dusk and night conditions. The television system operates on the 1023-line/60 Hz standard and is monochrome. The image of the tanker aircraft derived from the camera/probe is inset into a computer-generated cloud and sky background produced in the so-called special effects unit (SEU). The output from the SEU is fed to the display, a light valve television projector and Redifon Duoview 60° field of view collimating optical system. A block diagram showing the interconnections of the elements of the visual system is given in Figure 5.

THE MODEL/PROBE SYSTEM

The major design constraints on the model image generation system were that a 50:1 scale model was to be used and that the tower height was not to exceed a stated maximum. To overcome the latter problem a special optical probe with a continuously variable focal length was developed.

Figure 6 shows the tanker model in schematic form. The 50:1 scale enables very fine detail to be accurately represented; details included in the model are UHF antenna, main landing gear doors, and the refuelling boom and probe. The boom is articulated to permit servo control of pitch (+12.5 to -40 degrees) and azimuth (± 15 degrees), and can be extended 5 inches (13 cm) or fully retracted to the stowed position. The model is attached to a servo-driven gimbal assembly by an extension of the model nose. (See Figure 6)

Three sets of aircraft floodlights are simulated - the underwing, underbody and nacelle lighting. Glass fibre optics are used, illuminated by tungsten-halogen lamps housed in the tanker services assembly, located in the gimbal counterbalance weight. The fibre optics are routed from the lamps through the hollow tanker support tube and ducts in the model fuselage and wings. Navigation lights, rotating beacon and boom lights are also simulated by fibre optics illuminated by tungsten-halogen lamps in the tanker services assembly. The director lights are simulated by lamps and fibre optics contained in the model fuselage, and are individually controllable.

Illumination of the tanker model is provided by three vertical banks of fluorescent lamps, each containing 36 8 ft (2.5 m), 125 w lamps. Two levels of lighting are used, one for simulated day, and one for dusk and night.

Due to the tower height limitation, extreme tanker/receiver separation distances are simulated by reducing the focal length of the optical probe. Since it is not possible to integrate commercially available zoom lenses with the currently used probe optics, a specially designed zoom lens is used. This is because available zoom lenses generally have internal entrance pupils, whereas a complete probe lens system usually has an external entrance pupil, defining the viewpoint of the camera system, at which a pitch prism may be located. Figure 7 shows the layout of the probe optics. These optics enable the tanker image to be rotated in three axes, corresponding to pitch, roll and heading of the receiver and the roll of the tanker.

Pitching of the receiver relative to the tanker is simulated by rotation of the pitch prism about an axis through its reflecting surface, pitching of the tanker is simulated by rotation of the model about its nose. Combined movements of tanker and receiver are used to simulate relative altitude displacement between the two aircraft, as shown in Figure 8. Heading angle variation of the receiver relative to the tanker is simulated by rotation of the pitch prism about the optical axis of the front lens; the associated image rotation is removed by the roll/derotation prism. Yawing of the tanker is simulated by rotation of the model about its nose while combined heading and yaw rotations simulate a relative lateral displacement of the aircraft. When the receiver is on the same flight path as the tanker, relative roll is accomplished by the roll/derotation prism. With lateral and/or vertical displacement present, an additional positional correction must be made by use of pitch and heading rotation.

The probe platform can be raised a distance of 20 ft (6 m) above the tail tip of the model corresponding to a real-life separation of 1,000 ft. Within this range of physical separation, the zoom lens is set for maximum focal length. When the platform is at its highest position, the zoom lens focal length is adjusted through its range to its minimum to simulate further tanker-to-receiver separation throughout the range of 1,000 ft to 1.25 nautical miles. The perspective errors resulting from the change in focal length are considered acceptable as at far ranges the tanker image occupies only a small part of the display field of view.

CLOUD/SKY IMAGE GENERATION AND THE SPECIAL EFFECTS UNIT

The video signal representing the image of the tanker is sent to the Special Effects Unit (SEU) where it undergoes modification for simulation of variable atmospheric lighting and visibility effects and is combined with a synthetic cloud/sky background image. The SEU also has the task of controlling an electronic shift of the tanker image over the display, the purpose of which will be outlined later. The SEU is an integrated system under the complete control of a dedicated computer. Data required by the SEU for its video processing and image generation is passed from the main simulation computer (an Interdata 8/32) to the SEU computer. A block diagram of the SEU is given in Figure 9.

The SEU dedicated computer is a Redifon Computing Element (CE) which has been developed for use in simulator subsystems such as the SEU. The most important design criteria for the CE were small physical size (no more than one circuit board for a minimum system) and high arithmetic power (a 24 bit addition takes 350 ns). The CE is programmed in its assembly language which is converted into CE machine code by a FORTRAN cross-assembler program. This assembler can be run on the main simulation computer to produce a CE program, which can be transferred across the 8/32-CE interface. The SEU program (which runs in the CE) synchronises its operation to the television fields so that changes in set points of the SEU video and image generation units can occur during vertical fly-back periods, thus causing no disturbance to the picture. Data transfers to the SEU (defining receiver position and meteorological conditions) occur at the aircraft simulation program maximum rate of 20 Hz.

The image shifting facility is required to overcome a limitation of the probe optical system. When the zoom lens is set to its minimum focal length, the exit pupil of the probe objective and collimator will be smaller than the field of view of the zoom lens, so limiting the extent of pitch and heading simulation possible by movement of pitch prism. This limitation is overcome by introducing horizontal and vertical displacement of the camera tube image with respect to the displayed image. The Timing Unit section of the SEU performs this task. The master video system synchronising pulse generator is situated here, together with a variable delay synchronising pulse generator. The fixed synchronising pulses are routed to the displays, while the variable pulses are sent to the camera. The amount of time displacement of the camera synchronising pulses is determined by the CE, which in turn receives the data representing the displacement required from the main simulator computer. A maximum rate of change of image displacement must be imposed to prevent loss of camera synchronism.

The form of cloud chosen as the background image was dictated by cost and complexity constraints on the image generator. A simplified version of the strato-cumulus cloud tops illustrated in the photograph, Figure 10, was selected for its one-dimensional character - brightness only varies across the "streets", not along them. The simulated clouds are modelled as shadows on a plane surface, as can be seen in Figure 11, photographs of typical images generated by the Cloud Generator. Visible in this photograph is the smooth transition from cloud to sky, giving a realistic impression of the horizon.

A problem in image generation for high resolution television is the high signal bandwidth necessary to fully utilise the capability of the display. For example, in the 1023-line/60 Hz system used in the present simulator, a video bandwidth of at least 25 MHz is required.

This implies that a digital image generator would have to operate with a switching rate in its final stages of 50 MHz; such a speed can only be met with expensive high-speed circuit technology. However, due to the nature of the in-flight refuelling image, only the tanker needs to be portrayed with full resolution. An image generator output bandwidth of 7.5 MHz was felt to be adequate for the task - the presentation of attitude and velocity cues to the receiver pilot.

The principle of operation of the cloud image generator is an extension of a well known method, but based on modern digital circuit technology (Schottky TTL integrated circuits). The basic cloud pattern is stored in a memory accessed by a scanning ray which is the projection of an imaginary ray from the eye point to the cloud top surface through the display plane scanning spot. Figure 12 shows the form of the mapping of the display plane raster onto a surface; the shape and extent of this mapped raster is a function of the aircraft altitude and attitude. The rate at which successive samples of this mapped raster can be computed defines the resolution of the displayed pattern; in the present application, a 15 MHz computing rate is adopted - a new sample must therefore be computed each 66.7 ns.

The geometry of the surface scanning is shown in Figure 13. The surface lies in the (X,Y) plane of the (X,Y,Z) System and the observer (the receiver aeroplane) co-ordinate system is (u,v,w). The raster defining vector $\bar{P}$ is extended until it intersects the surface. The co-ordinates of the intersection are given by:

$$X = \frac{HP_x}{P_z} \qquad 1.$$

$$Y = \frac{HP_y}{P_z} \qquad 2.$$

Where P_x, P_y and P_z are the X,Y and Z components of the vector $\bar{P}$, and H is the height of the observer's eye point above the surface. Equations 1 and 2 are given by similar triangles and are in fact a statement of perspective division. P_x, P_y and P_z are functions of the position of the display raster scanning spot and therefore vary at the rate at which new elements of information are sent to the display, i.e 15 MHz. The altitude, H, is considered to be constant for the duration of a displayed field, 1/60 sec. P_x, P_y and P_z have a particularly simple form - they are linear functions of the horizontal and vertical positions of the display spot:

$$P = P_o + P_1 m + P_2 n \qquad 3.$$

where P represents HP_x, HP_y, or P_z

P_o, P_1, P_2 are constant for a television field,

m is the display spot horizontal co-ordinate,

and n is the display spot vertical co-ordinate

In computing X and Y as functions of receiver attitude and scanning spot position,only one of the equations 1 and 2 needs to be evaluated, say X, as the pattern utilised only varies along one surface co-ordinate axis.

The generation of a cloud display can be divided into the following tasks: (see figure 14)

a) Evaluation of the transformation (equation 1) in real time (i e 15 MHz)

b) Use of the intersection calculated (X) to address a memory holding the pattern, and

c) Modification of the image produced to correspond to lighting and visibility conditions

The functional units of the transformation processor are two linear function generators to generate values of HP_x and P_z, and a divider to calculate the intersection X. The transformation processor must produce a new output, X, every 66.7 ns for the duration of a television field. The inputs to the processor are the values P_o, P_1, and P_2 for both HP_x and P_z, and timing pulses to allow accumulation of values of m and n (see equation 3). The result of the division may be interpreted as having an integral and a fractional part - if H is expressed in units of cloud street width, then the integral part of X represents the number of full cloud cycles and the additional fractional part the fraction of a cloud cycle the intersection is distant from the surface origin. Since the pattern is infinitely repetitive the integral part may be discarded, simplifying the division circuit.

The complexity of the calculation and the high computation rate required demand specialised digital techniques. The transformation processor is implemented as a "pipeline", a method of parallel computing particularly suited to this task, where a high throughput is essential, but a time delay of several microseconds between input and output can be tolerated.

The output, X, of the perspective calculation is then added to a displacement term, X_o, constant over a field, representing the distance along the surface of the receiver aeroplane from a ground origin. Variation of X_o produces the correct movement of the cloud image to correspond to receiver heading and speed. The cloud memory itself is very compact, needing only to represent a one-dimensional and repeating pattern.

The cloud pattern generated is only correct for those regions in which aliasing does not occur, i e those nearer to the viewing point in the real world. The phenomenon of aliasing is one of the main problems in discrete image generation and much effort is devoted to its alleviation in all modern image generator designs. In the case of the cloud generator, aliasing starts to occur when the spacing of successive sampling vectors, X, becomes too large in comparison with the pattern dimension. Aliasing manifests itself as Moiré patterning in parts of the image approaching the horizon. The problem is solved in the cloud generator by fading image details in the display plane towards the horizon. This fading signal must roll and pitch with the horizon and vary with altitude, since at higher altitudes aliasing starts to occur at a lower point on the display. The fading function can be shown to be of the form given in equation 3, and is generated by a function generator identical to those used for HP_x and P_z. (This fading method is identical in function to the "wedge" used in the analog "fog box" in terrain model visual simulators).

Due to the symmetrical nature of the perspective transformation an inverted cloud image is also produced, filling the "sky" portion of the display. This is removed by switching to a sky image generator for those parts of the display representing sky. Study of Figure 13 reveals that the vector P_z represents the distance of the display scanning spot from the eye in a vertical direction - it is zero on the locus of spot positions corresponding to the horizon. A simple sign test on values of P_z can be used to operate the cloud sky switch, (shown in Figure 9).

The sky is modelled entirely in the display plane; it consists of a constant brightness section and a region of variable brightness at the horizon. The variable brightness profile is stored in a memory accessed by a vector computed in a function generator identical to that used in the cloud fader. It is possible to simulate scenes in which there is a brightness discontinuity at the horizon, for example at night only a "glow-band" may be visible. In these cases the "stairstep" effect at the boundary must be eliminated. This is achieved by blending the two brightness levels along raster lines over a length dependent on the roll angle in the horizon shader (see Figure 9), a well-known technique in computer image generation. No brightness discontinuity is present in the photograph (Figure 10), and therefore no blending is required here.

All four function generators (HP_x, P_z, cloud fader, and sky) are connected to the CE via its data bus. The set-up conditions are computed by the CE as functions of the data sent from the simulator computer and are sent to the function generators during field blanking periods. Each function generator requires an initial condition (P_o of equation 3) and slopes P_1 and P_2. Various constants defining the displacement, brightnesses and horizon shader set-up data are also output during the same blanking period. The final composite cloud/sky image is converted from digital to analogue form in a high-speed digital to analog converter and passed to the Video Processor for combining with the tanker image.

It is interesting to contrast the form of image generation adopted in the cloud generator with conventional computer image generation. In the latter, individual items are selected from the modelled world, perspective transformed into display co-ordinates which are then scanned to form a television picture. In the cloud generator, the perspective computation is continuous and independent of the complexity of the modelled environment; a surface in the "real world" is sampled along scan lines rather than objects being transformed piece-by-piece into the display plane.

The purpose of the Video Processor is to inset the tanker image into the cloud/sky image. Insetting is a well-known television technique nowadays when applied to coloured images ("chroma-keying"). However, the visual system is monochrome which rules out the use of this insetting method. The technique adopted uses the luminance level of the tanker video signal to switch between the two scenes. The tanker model mounting assembly and light-box floor are painted black to provide a contrasting luminance level to the brightly lit tanker. Insetting can then take place at the edges of the tanker image where the camera luminance signal passes through a unique level. A problem with normal insetting methods is that the switching between the two signal sources is rapid, giving a stepped boundary which can be very distracting on near-horizontal edges in a closely-viewed display. This is overcome by blending the signals over a transition region of the camera video signal, and is thus dependant on the rise and fall times of the tanker signal. Figure 15 illustrates the principle of this technique. The actual insetting aperture and threshold are functions of lighting conditions and are set up by the CE for optimum operation at all times. At far camera ranges and low zoom lens focal lengths, extraneous image details from the mechanical structure appear in the image. To prevent these being inset into the cloud/sky image, an inhibiting signal is generated by the window generator (see Figure 9) which sends a signal to the video processor preventing insetting outside of a rectangular area surrounding the tanker image. The location and extent of this area is computed in the simulator computer and sent to the window generator via the CE.

The output from the video processor represents the composite image which is sent to the pilots' display and operator's monitor. The Duoview display is mounted to give an elevated field of view more suitable for the refuelling operation - the horizon appears 12.5° lower than it would in a conventionally mounted display. At close ranges it is impossible to display a correct perspective view of the tanker from both pilot positions due to the different viewpoints. The operator thus has the facility to select which seat obtains the correct view. Figure 16 shows the appearance of the final image as it appears to the simulator crew.

REFERENCES

For a description of Redifon visual simulation technology in 1975, see:

A.M. Spooner

"Improvements in Visual Flight Simulation", 8th NTEC/Industry Conference Proceedings, Orlando, Florida, 18-20th November, 1975

The zoom optical system is the subject of the patent application:

D.R. Lobb and I.T. Whyte

British Patent Application 44657/76

The cloud/sky generator is the subject of the patent application:

M.J.P. Bolton

British Patent Application 15998/78

ACKNOWLEDGEMENTS

The design and development of the visual system described in this paper was the work of many members of the Redifon Simulation Development Department. In particular, Ian Whyte was responsible for the Zoom Probe concept, Paul Ewer for the Video Processor design and Jim Morris for the Timing Unit design.

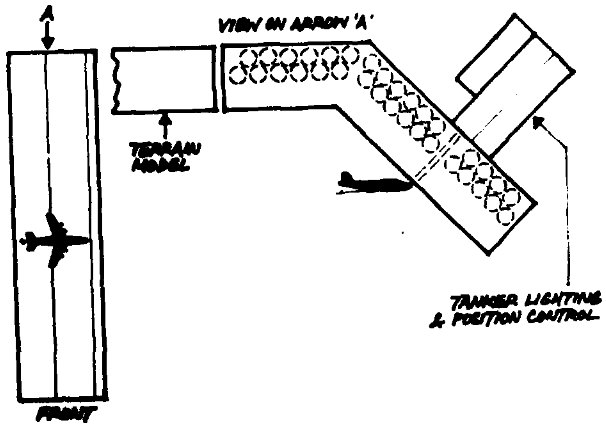


Fig.1 Combined terrain and tanker model

(a)

(b)

Fig.2 In-flight refuelling images with 144:1 scale model and 625-line television system

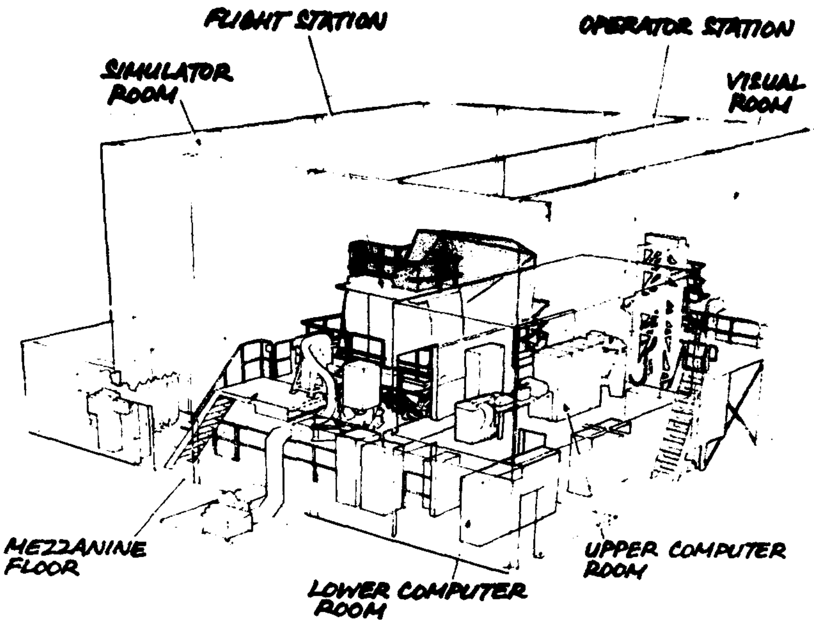


Fig.3 In-flight refuelling simulator complex

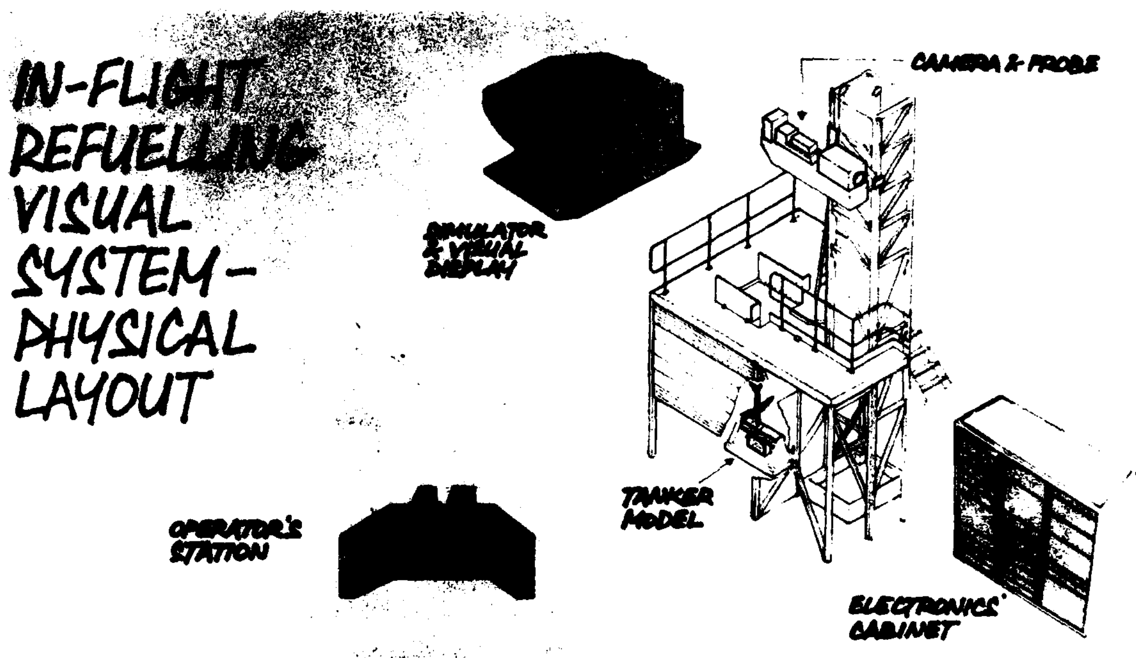


Fig.4 In-flight refuelling visual system physical layout

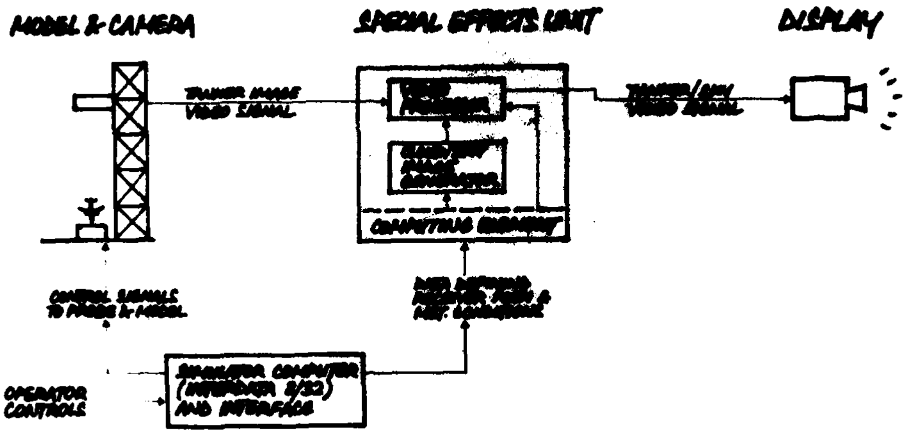


Fig.5 In-flight refuelling visual system block diagram

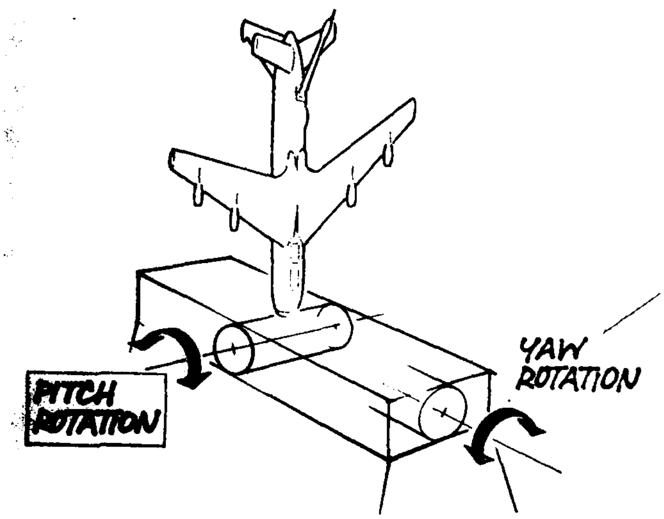


Fig.6 Tanker model

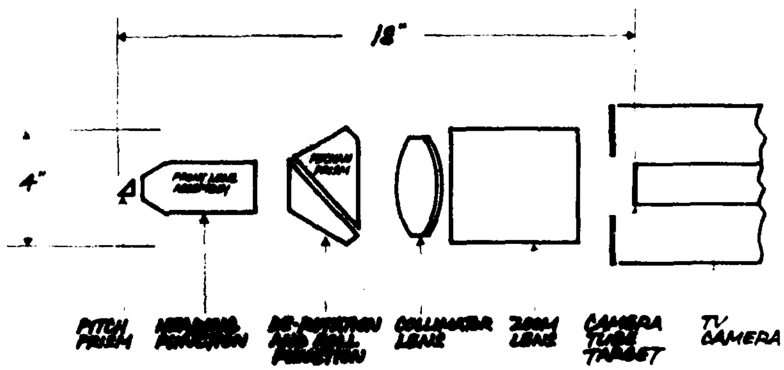


Fig.7 Probe optics schematic diagram

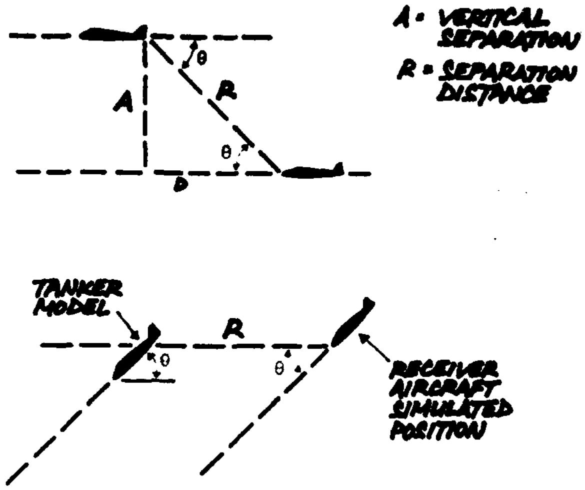


Fig.8 Simulation of vertical displacement

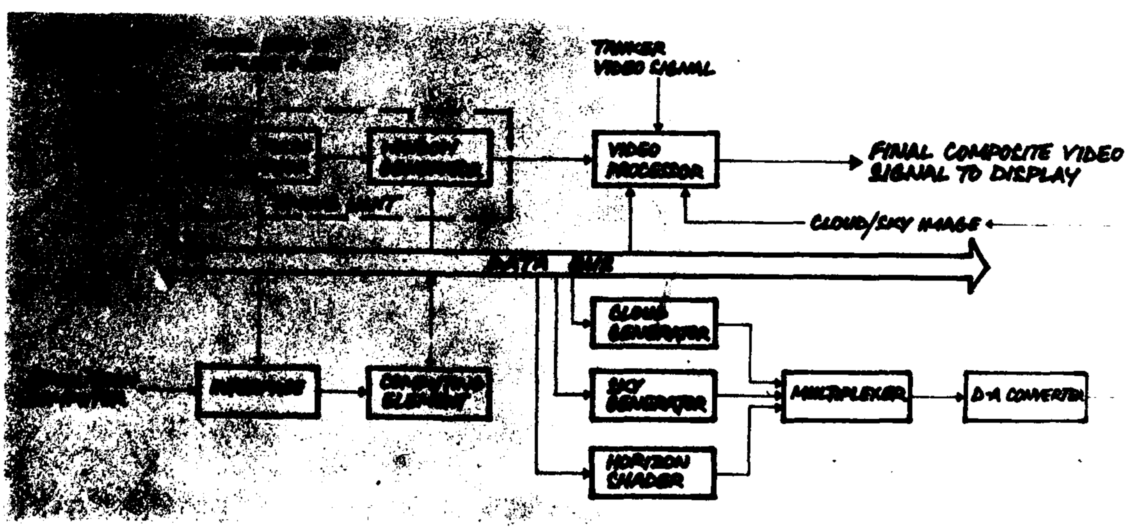
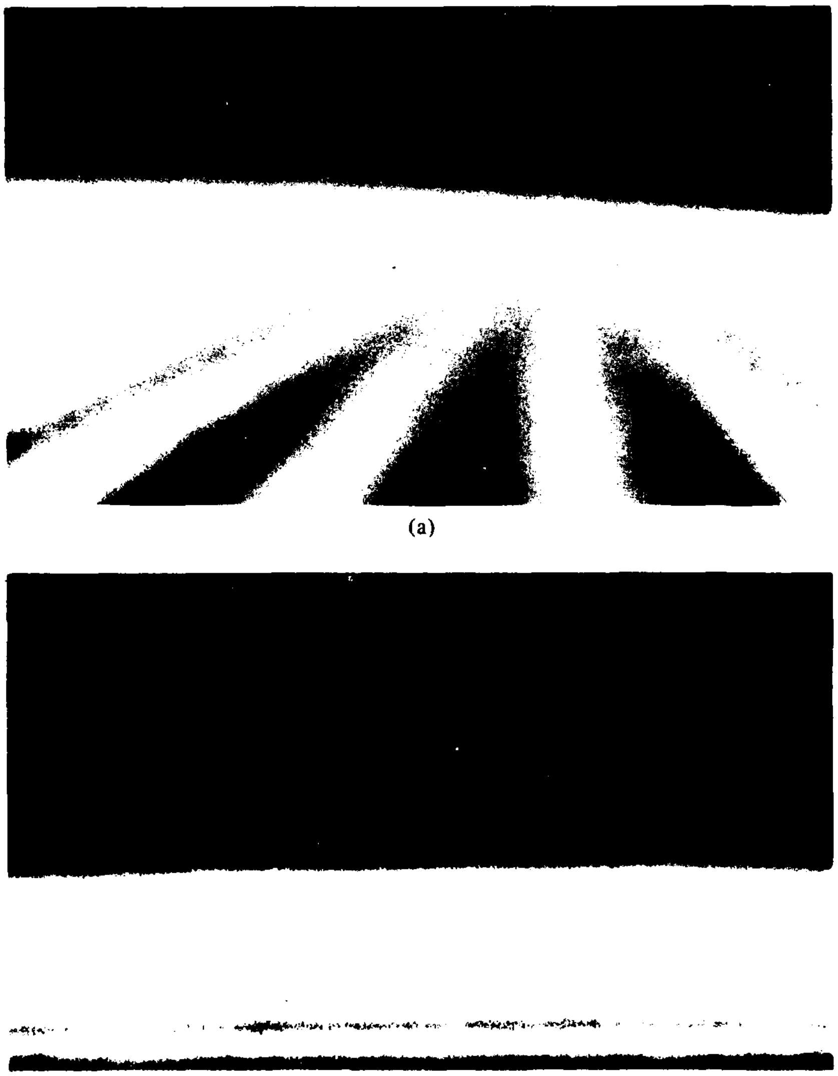


Fig.9 Special effects unit block diagram

Fig.10 Actual clouds



(a)

(b)

Fig.11 Synthetic clouds

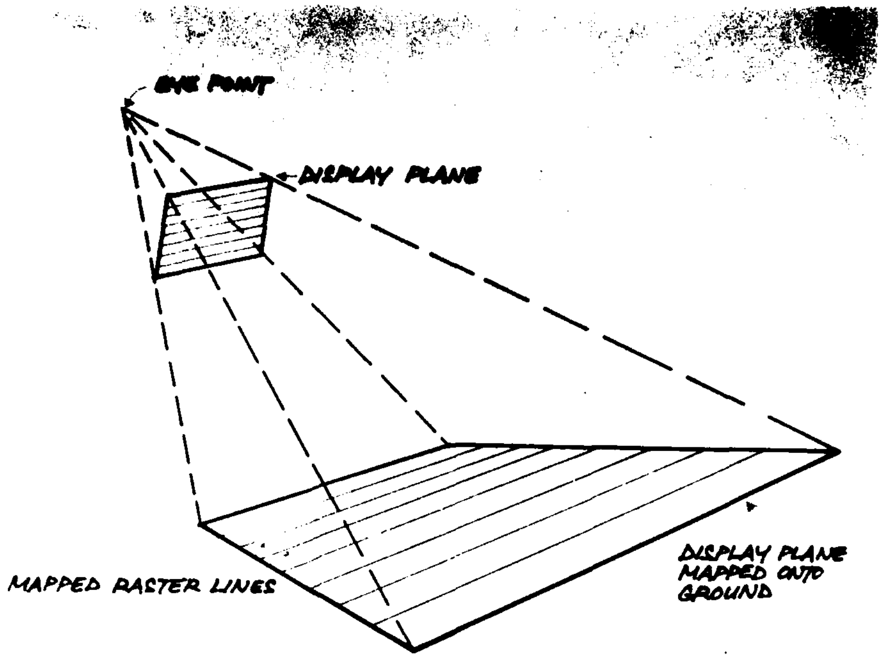


Fig.12 Raster line mapping

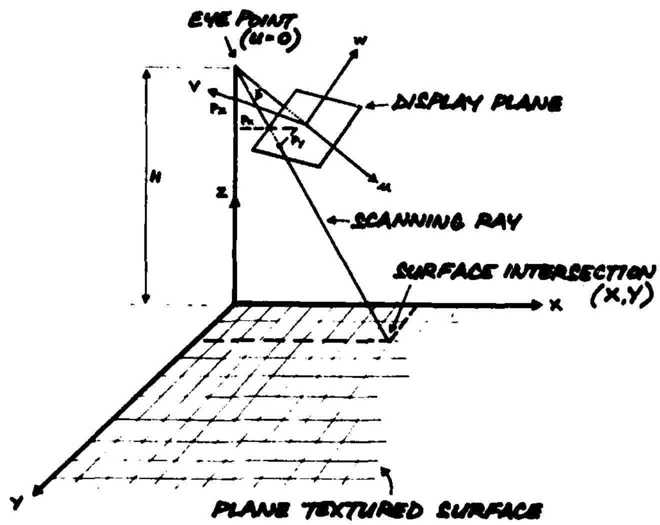


Fig.13 Surface generation geometry

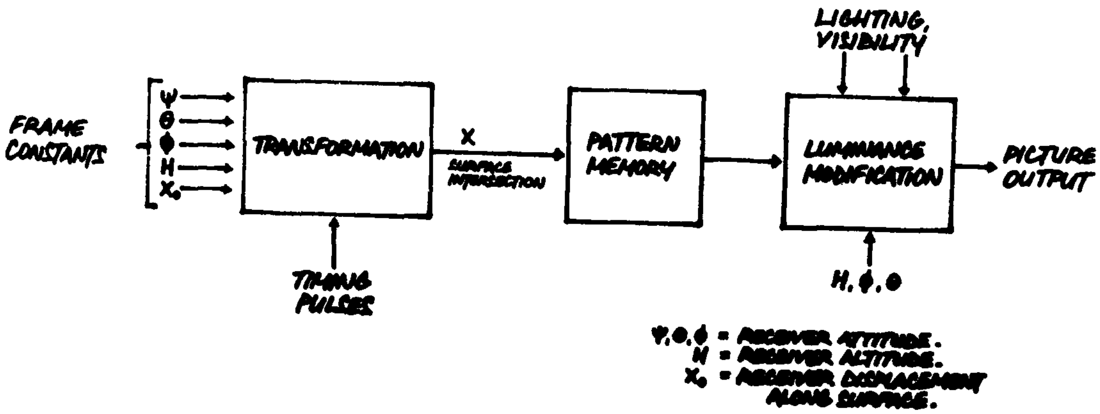


Fig.14 Cloud generator block diagram

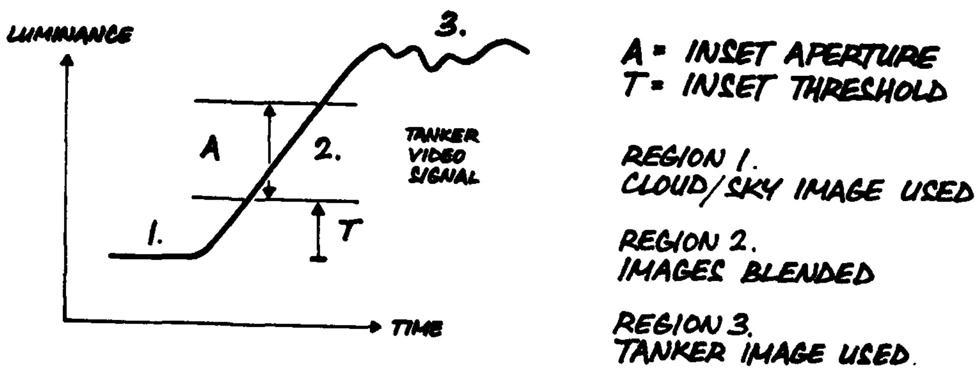


Fig.15 Insetting operation

Fig.16 In-flight refuelling image with 50:1 scale model and 1023-line television system

WIDE ANGLE VISUAL SYSTEM DEVELOPMENTS

by
Carl R. Driskell
Project Director
US Army Office of Project Manager for Training Devices
Naval Training Equipment Center
Orlando, Florida 32813

SUMMARY

The US Army Project Manager for Training Devices has two competing development programs designed to provide high resolution tactical scenes over a wide field of view for pilot training. In the first system, a laser beam scans the portion of a terrain model board to be presented to the pilot. A matrix of light sensors collects the light reflected from the model board. A composite video signal from the light sensors modulates a laser beam in the display scanner which scans the scene onto a spherical viewing screen. In the second system, an optical probe picks up a 360-degree annular image of a terrain model board. The annular image is scanned onto a radial array of charge coupled devices which converts the annular image into video signals. The video signals modulate laser beams in an annular laser projector which scans the scene through an annular projection lens onto a spherical viewing screen. Both visual systems provide continuous seamless visual scenes without the color matching, edge matching or brightness matching problems that arise in multiple window display systems.

INTRODUCTION

Two technical approaches are being experimentally investigated to determine the feasibility of using scanned lasers to display real world scenes for military training applications. The technical objective of each approach is to provide high resolution tactical scenes over a continuous wide field of view. The two competing approaches are being pursued to enable selection of the best approach to meet this important military need.

The first approach is a scanned laser visual system in which scanned laser beams are used to generate and display a 175-degree tactical scene. A breadboard model of this system is being developed on contract. The prime contractor is American Airlines Incorporated. Redifon Flight Simulation, Limited, a subcontractor, is conducting a main body of the work in England, and the Sira Institute of England is providing expertise on optical and electronic systems. Support for this program is being provided by the US Army and Navy.

The breadboard models of each visual system are scheduled to be completed in the third quarter of 1978.

SCANNED LASER VISUAL SYSTEM

System Description

The basic components of the scanned laser system are illustrated in Figure 1. In the image generator, the laser scanner scans that portion of the model board to be presented to the pilot. The laser light reflected from the model board is collected by light sensors, such as photomultiplier tubes, mounted parallel to the model board. The light sensors convert the light to video signals that are summed into a processor which provides blanking, gamma correction, aperture correction and special effects such as clouds, fog and haze. The processor feeds a composite video signal to a laser beam modulator in the display laser scanner which scans the visual scene onto a spherical projection screen. The timing generator provides line and frame scan synchronization to the image generation and display laser scanners.

Image Generation

The basic principle of the image generation system will be described with comparison to a conventional television system. The basic components of a conventional television system are illustrated on the left side of Figure 2. The object to be televised is illuminated by a lamp and the reflected light, over a field of view set by the lens, is picked up by a television (TV) camera. The TV camera generates a video signal which is fed to a TV monitor for viewing. The signal is generated as the electron beam in the television camera tube scans the target image in a raster format.

On the right side of Figure 2, the same object is scanned in raster format by a laser beam. The laser scanner scans the object over the same angle as the conventional camera lens. The video signal is generated by a light sensor or photocell placed where the lamp was placed in the conventional television system.

There are several important points that should be noted in this comparison. Perhaps the most important point is that exactly the same image appears on both television monitors. This is true as long as the generating and display scanning processes are synronized and the field scanned by the laser beam is the same as the field of view of the conventional television camera.

Secondly, the point of perspective or viewpoint with the laser system is the point from which the scanned laser beam leaves the laser camera and not the photocell. Movement of the laser scanner produces normal perspective views just as if it were a normal television camera.

Thirdly, lighting effects can be achieved with appropriate placement of photocells. Just as in a conventional model board visual system, where multiple lamps are used to evenly illuminate a terrain model, so in a scanned laser visual system multiple photocells can be used to produce a scene that appears to be evenly illuminated. A concentration of photocells can be used to generate directional lighting effects and fiber optics, with photocells behind the model, can be used to generate cultural lights.

Now that the principle of image generation has been established, the laser scanner system will be described. The principle of the scanning probe is illustrated in Figure 3.

The basic principle of the complete wide angle scanning system involves passing the laser beam through a line scanner which uses a rotating mirror drum to deflect the beam in a sawtooth deflection approximately 132,000 times per second. The deflected beam is then passed through a pechan prism which provides derotation and a wide angle lens which expands the verticle angle to 60 degrees. Finally, the beam is deflected by the rotating frame scan prism to emerge as a raster of 5280 verticle scan lines. The derotation prism runs at one half the speed of the final prism to keep the scanned line vertical as the final prism rotates. Using a single frame scan prism would produce a 360 degree frame scan, but a nominal 180-degree scan is obtained by using two prisms. To allow for a small percentage of dead time during which the black level of the video signals is established, the actual horizontal field of view will be 175 degrees.

At the end of each 180-degree rotation of the prisms, the line-scanned beam is switched rapidly by a galvanometer mirror between the two frame scan prisms to keep the emerging beam always in the forward direction. This process of changing the beam from one prism to the next inverts the line scan so that the beam deflected by the galvanometer must be taken through an additional prism for correction.

Scene Display

The optical layout of the display laser scanner is similar to that of the model board laser scanner as far as the line and frame processes are concerned. However, some provision is needed in the display to prevent geometric distortions in the scene that result from a projection point that is offset from the pilot's head. As illustrated in Figure 4, the laser beam emerging from the scanner is reflected first from a spherical mirror and then to the screen to give overall correct display geometry in the wide angle scene.

Attitude Control

The next aspect of the system to be considered is the simulation of changes in roll, pitch and heading. In a conventional camera model visual system, the optical probe has servo-controlled optical elements to change pitch and roll, and the complete lower part of the probe structure is usually rotated about an axis normal to the model surface to provide heading changes. With the laser probe, the prisms from which the beam emerges, are already rotating continuously. By altering the phase of this rotation at the probe in relation to the corresponding rotation at the display, heading changes can be simulated.

In order to allow close approach to the model surface and easy passage between obstacles, simulation of roll and pitch at the display is preferred. At the display there is plenty of room for the mechanisms necessary to achieve this, as shown in Figure 4.

There are several advantages of simulating roll and pitch at the display. First, objects that appear within the vertical field of view continue to be displayed during pitch maneuvers since the entire display format is pitched. Secondly, targets are not lost off the top or bottom of the screen during roll maneuvers since the entire display format is rolled. Thirdly, it is not necessary to waste television scanning lines in reproducing blank sky. The sky can be simulated with an auxiliary optical projector attached to the main projector.

The primary disadvantage of simulating pitch and roll at the display is that an area of terrain beneath the aircraft cannot be viewed at any attitude and parts of this dead area appear under extreme conditions of roll or pitch.

Focus

The next aspect of the scanned laser system to be considered is that of focussing the beam on the terrain model. Focussing of the beam on the display screen is constant and presents no problem.

Depth of field is a very important consideration in conventional camera model visual systems. The optical probe attached to a conventional television camera has an entrance pupil whose size determines the depth of field in which objects will appear to be in sharp focus. The larger the aperture the worse the depth of field, but the smaller the aperture the more the resolution is limited by diffraction.

With the laser system, in which the scanned laser beam leaves an exit pupil to strike the model, the same basic tradeoff exists. The laser system has the advantage, however, that the laser beam can be put through any chosen aperture. This is unlike the conventional camera model system which needs a minimum aperture to get enough light through for a noise-free picture. Another significant advantage of the laser system is that only one spot on the model is illuminated at a time. Therefore, changes of focus and aperture can be accomplished during scanning to give optimum results. By contrast, within a conventional camera model system, the whole field of view is continuously imaged and techniques to improve the depth of field must operate on the whole field at once.

Two main types of focus correction may be used in the scanned laser visual system; the choice depends on the visual mission. For missions where the model board may be considered to be flat for focussing purposes, the tilt lens techniques used for conventional television optical probes may be adopted. An analysis shows that good results will be obtained by using a high aperture tilt lens in the optical system such that the beam is focussed at a short distance when it scans the near part of the model and at a greater distance when it scans the far parts. The absence of roll and pitch motions in the probe makes the design easier.

For missions where the model board cannot be considered to be flat, the instantaneous focus may be changed dynamically to give optium focus for each object struck by the scanning beam. The technique for dynamic focussing is to use electro-optic cells to vary the width and convergence of the laser beam before scanning. At the exit pupil of the laser probe, the emerging beam is rapidly focussed on the object being scanned and the width of the beam is varied to change the depth of focus. Figure 5 shows the laser beam passing through an electro-optic cell. The control signal is applied to the cell which can switch the polarization of the emerging beam through 90 degrees. The beam is passed through a calcite lens which has different refractive indices for the two polarizations. Therefore, two different degrees of convergence of the beam can be obtained. By using up to three such cells, eight different focus conditions are provided to give smooth change of focus with distance. By careful design of this focussing system, the increased convergence of the beam needed to focus on near objects can be linked with a decrease in pupil size to give a better overall result.

Resolution

The 175-degree by 60-degree field of view, selected for the experimental breadboard model, was based upon current military training requirements and reasonable development goals. With this field of view and a 100-Megahertz video bandwidth, a resolution of five arc minutes should be achieved. Various tradeoffs are possible between field of view and resolution, the higher the field of view the lower the resolution and vice versa.

Color

The system described so far is a monochrome system which will be used to demonstrate feasibility. A full color scene can be provided with additional lasers, light sensors and video channels. In a full color system, the lasers must produce the three primary colors. An argon laser will provide green and blue primary colors while a krypton gas laser will provide the red primary color. In the image generator, the three color laser beams are combined and scanned as a single beam onto the model board. The light sensors are arranged in groups of three or triads with each light sensor sensitive to one of the primary colors. All of the red signals from the red light sensors are summed as are the blue and green, to produce red, blue and green video signals. The video signals are processed with blanking, gamma correction, and aperture correction, etc., and fed to the display. At the display, the three primary color beams are modulated by the respective color video signals. Then the modulated color laser beams are combined and scanned as a composite modulated beam onto the projection screen to produce the desired color scene.

360-DEGREE ANNULAR VISUAL SYSTEM

System Description

The 360-degree annular visual system is based upon recent developments in annular optics and charge coupled devices (CCD's). The basic components of the annular visual system are illustrated in Figure 6. In the image generator, the annular camera views a terrain model board through a 360 degree annular lens probe. The annular image is illustrated in Figure 7. Radial lines in the annular image cover the vertical field of view while concentric circles in the annular image cover the horizontal field of view. The full 360-degree horizon falls on an intermediate concentric circle.

The annular image from the optical probe is scanned onto a radial array of 12 CCD's which convert the annular image into 12 video signals. Twelve channels were selected to reduce the scan rates and video bandwidth requirements of each channel. The 12 video signals are fed to a processor that provides gamma correction, aperture correction and special effects in a manner similar to the scanned laser visual system. The processed video signals then modulate laser beams in the annular projector which scans the scene onto a spherical viewing screen.

Image Generation

In the annular visual system, the image is generated with an annular optical probe illustrated in Figure 8. This probe has three unique characteristics. First, the probe derives a full 360-degree horizontal by 60-degree vertical field of view from a single optical channel. With conventional image generation techniques, several optical channels would be required to provide coverage of a 360-degree field of view. Secondly, the probe converts the single annular image into 12 parallel channels of video information. The multiple channels are required for a high resolution display because of the information transmission constraints imposed by state-of-the-art video components. Thirdly, each channel covers the entire 360-degree visual scene. This is unlike conventional multichannel systems which provide adjacent scenes derived from separate channels.

To convert the annular image into video signals, the annular probe rotates the first annular image through a pechan prism into a second image plane. From the second image plane, the rotating annular image is reflected from a pyramidal arrangement of 12 mirrors onto a cylindrical arrangement of 12 linear CCD's. This layout was used because of space requirements for the CCD's. Conceptually, the CCD's could have been arranged in a radial array in the plane of the rotating annular image.

The image transfer system of Figure 9 illustrates the manner in which the annular probe image is scanned onto the CCD array, and then reconstructed into an identical annular image for the projection lens to display. The readout of each linear CCD is the equivalent to one vertical scan line in the probe field of view. As mentioned earlier, the horizontal scan of the probe field of view is accomplished with a pechan prism which rotates the annular image about its center. As the annular image is rotated, each CCD is exposed to the entire image. The 12 video signals derived from the CCD array are used to modulate laser beams in the annular projector. In the projector, the modulated laser beams are scanned in a radial pattern corresponding to the CCD array. Rotation of the image in the probe and derotation of the projector are accomplished by the identical, synchronized, rotating pechan prisms.

Interlace of the multiple channels is accomplished by slightly staggering adjacent CCD's and laser scan lines by three arc minutes. The pechan prisms are rotated at a rate such that the annular image rotates six arc minutes for every vertical scan time. At this rate, alternate scan lines will interlace.

The system scan rates are derived as follows. Since the line spacing over the 360-degree display is three arc minutes, a total of 7200 scan lines are required for each frame. The 12 laser channels scanned by a 24-facet mirror provides 288 scan lines for each rotation of the mirror. Hence, for a 30 Hertz frame refresh rate, a mirror rotating rate of 45,000 revolutions per minute is required. This rate of rotation automatically produces a two-to-one interlace at 60 fields per second.

Scene Display

The optical layout and light path of the annular projector are illustrated in Figure 10. To simplify the diagram, only two of the 12 lasers and modulators, which are arranged radially around the mirror scanner, are shown. The optics, between the mirror scanner and the first image plane, convert the tangential laser scan pattern into a radial scan pattern.

The scan conversion process is illustrated in more detail in Figure 11. Each of the 12 incident laser beams is scanned by the rotating 24-facet mirror onto three, 45-degree mirrors and a pyramidal mirror which results in a radial scan. Emerging from the pyramidal mirror are 12 laser beams scanned in a stationary radial pattern. This radial array of modulated scanned laser beams is then fed through the derotation pechan prism to the final annular projection lens.

The details of the annular projection lens are shown in Figure 12. This lens consists of two hyperbolic reflectors and a series of conventional lens groups. The reflectors are designed to eliminate astigmatism, while the conventional lens groups are designed to eliminate the other abberations.

Attitude Control

In the annular visual system, roll and pitch changes will be simulated by rotating the optical probe in roll and pitch about the entrance pupil. Heading changes will be simulated by varying the phase of the probe pechan prism with respect to the display pechan prism.

Focus

Focus of the probe annular image will be varied as a function of altitude. As the probe approaches the terrain model board, only a ring of best focus will be achievable. It is anticipated that, for most applications, the ring of best focus will be maintained about the horizon or may be changed dynamically for varying requirements.

Focus at the display is no problem since the distance from the projection lens to the spherical display screen remains constant.

Resolution

Based upon a video bandwidth of nine Megahertz and the scan rates cited earlier, the nominal resolution of the system breadboard model is computed to be approximately nine arc minutes. However, the vertical resolution will be degraded for angles of depression below the horizon due to the nonlinear mapping of vertical lines in the probe and display annular optics. The inner portion of the annular image, which corresponds to the bottom of the scene, will be compressed. When this compressed portion of the image is scanned onto the linear array of CCD's, there will be fewer sensors of the CCD's per degree of image. Similar distortions in the projector lens and the Kell factor associated with the spacing of 1024 elements on each CCD array will further degrade the verticle resolution. In Figure 13, the overall system resolution is plotted as a function of verticle field angle. Similar resolution curves are plotted for the optical probe, the projection lens and the CCD array. The system resolution, R_S, was computed using the equation shown in the figure where R_P is the projection lens resolution, R_P is the probe resolution and R_{CCD} is the CCD resolution.

Color

The system described so far will use 12 argon lasers to demonstrate feasibility of the system with a monochrome display. A full color, field sequential system may be constructed by replacing four of the argon lasers with krypton lasers, and placing appropriate color filters over the CCD's. The krypton lasers will provide red while the argon lasers will provide blue and green. Alternate channels will cover a 30-degree sector on the screen before the next channel covers the same sector. To eliminate color flicker, the rotational rate of the two pechan prisms must be increased and to provide the same resolution as that of the monochrome system, the bandwidth of the 12 video channels and the line scan rates must be increased. Since the spectral band of the CCD's is from 500 to 1000 nanometers, a false color on the model board will probably be necessary for a full color display.

CONCLUSION

Two alternative approaches to a high resolution, wide angle visual system for military flight simulation have been described. The basic feasibility of each system has been established through studies and subsystem demonstrations but the practical realization of each total system design remains to be proven. Satisfactory completion of either approach will meet an important military need and will provide a substantial advance in visual simulation.

ACKNOWLEDGEMENTS

Dr. A. M. Spooner, Chief Scientist of Redifon Flight Simulation, Limited, and Mr. F. J. Oharek, Project Engineer of the Naval Training Equipment Center, primarily are responsible for the conception of the Scanned Laser Visual System and the 360 degree Annular Visual System respectively. The author wishes to thank Dr. Spooner and Mr. Oharek for their generous contribution of illustrations, graphs and technical details in support of this paper.

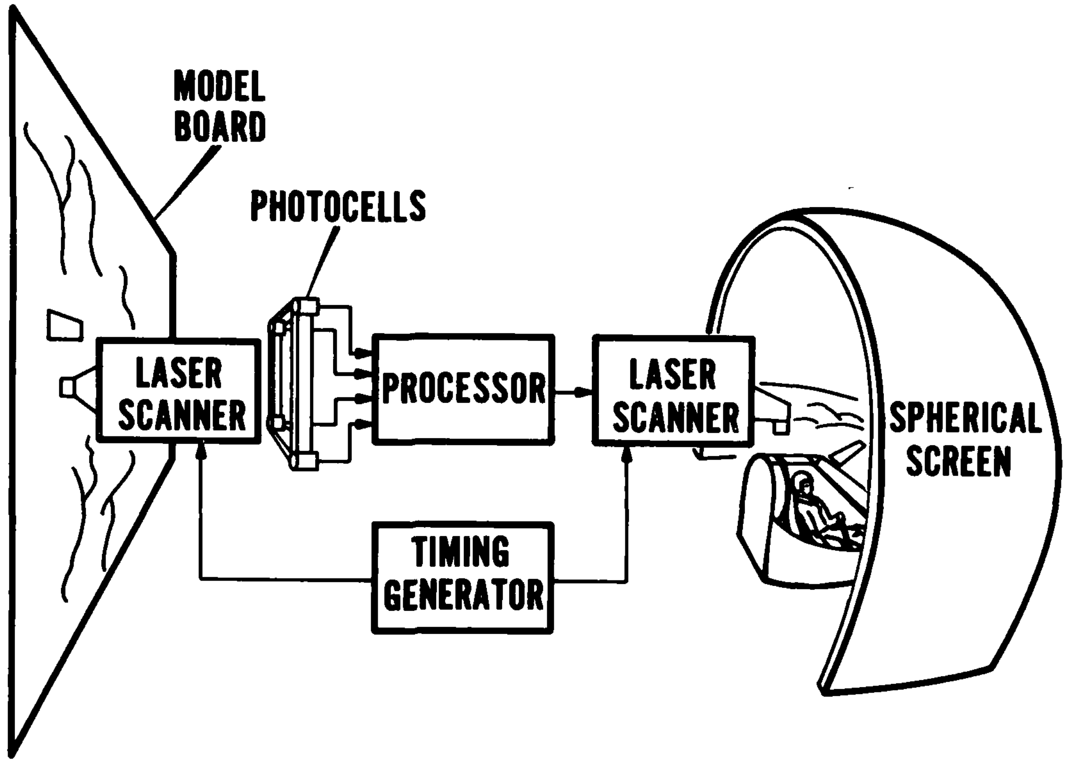


Figure 1. Scanned Laser Visual System.

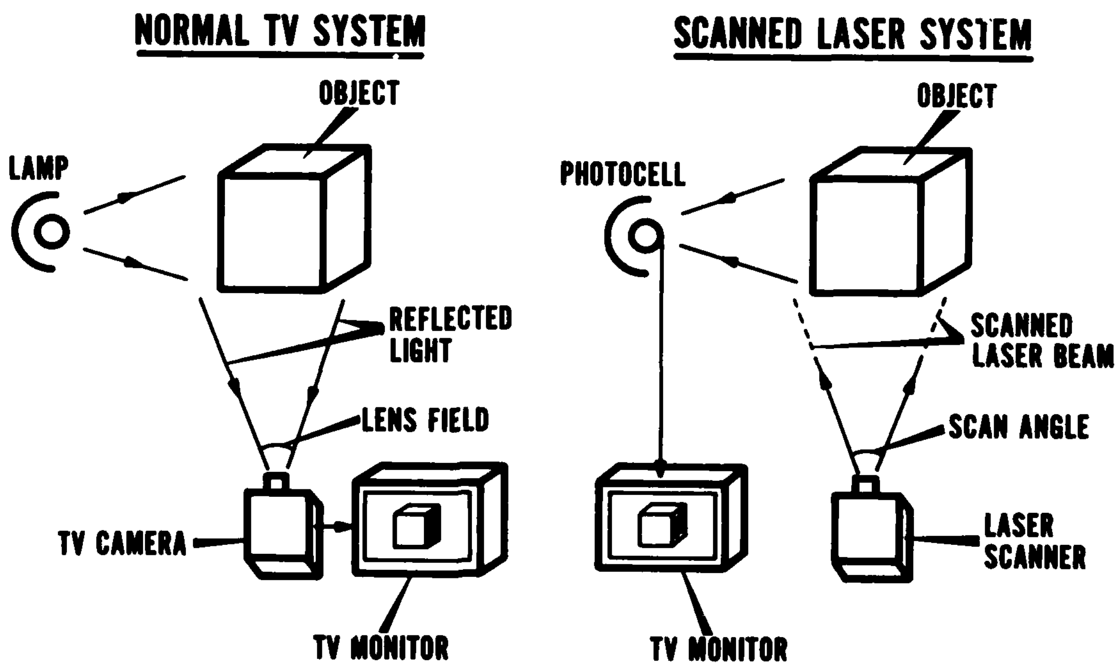


Figure 2. Comparison of Systems.

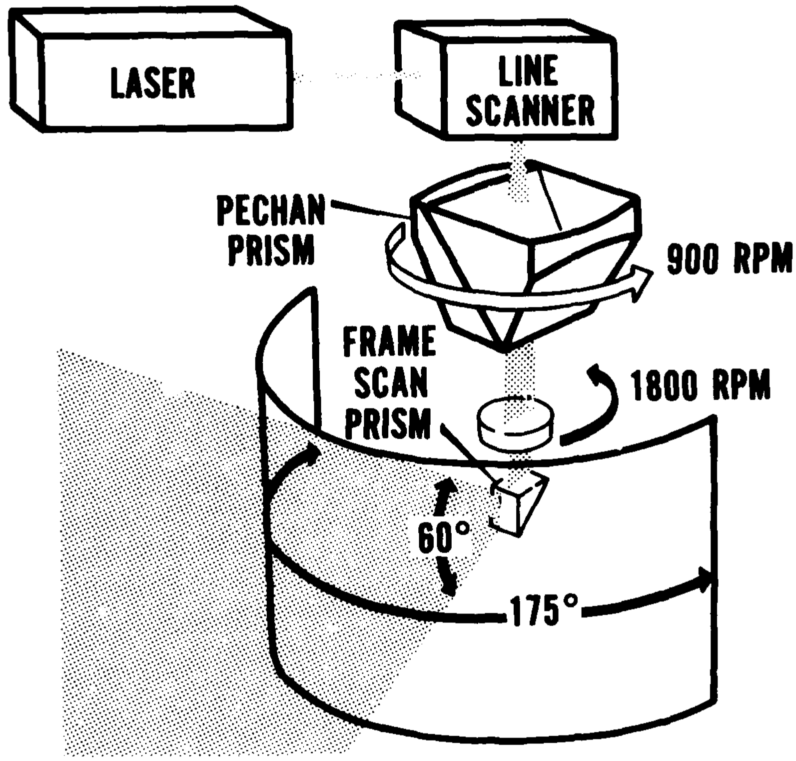


Figure 3. Laser Scanner System.

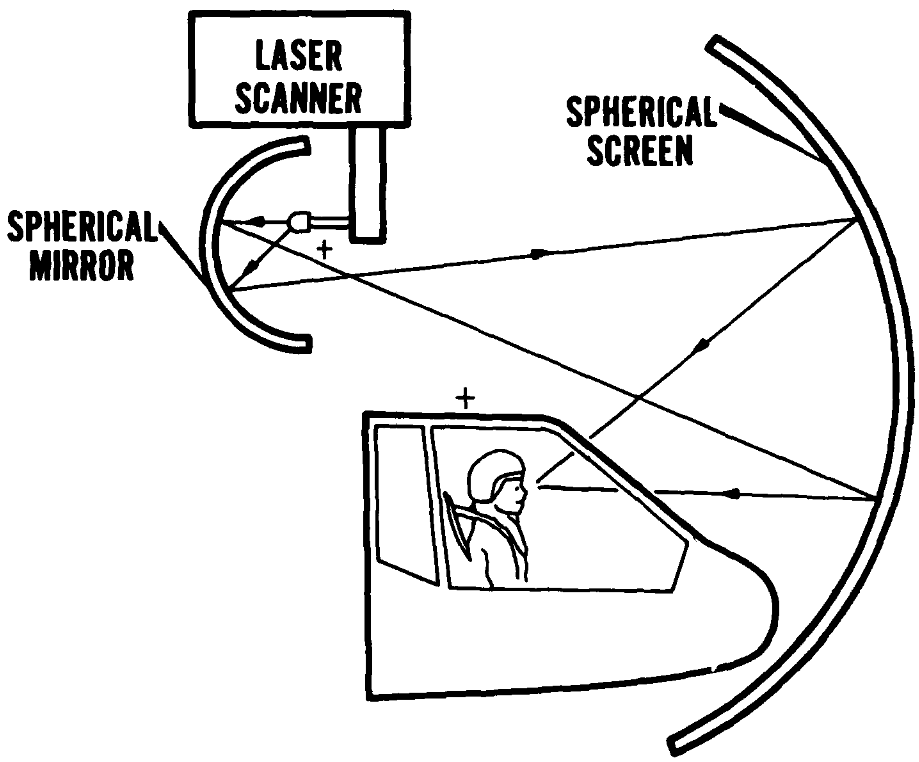


Figure 4. Scanned Laser Display.

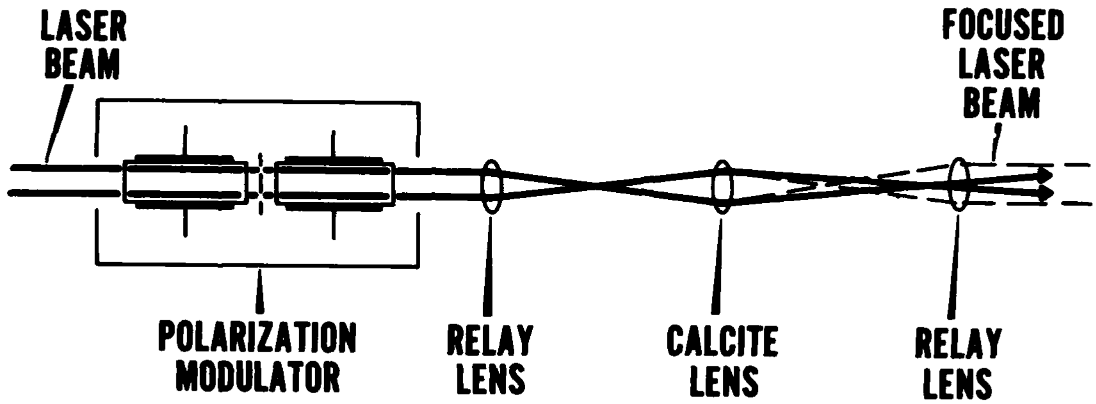


Figure 5. Electro-Optical Focus System.

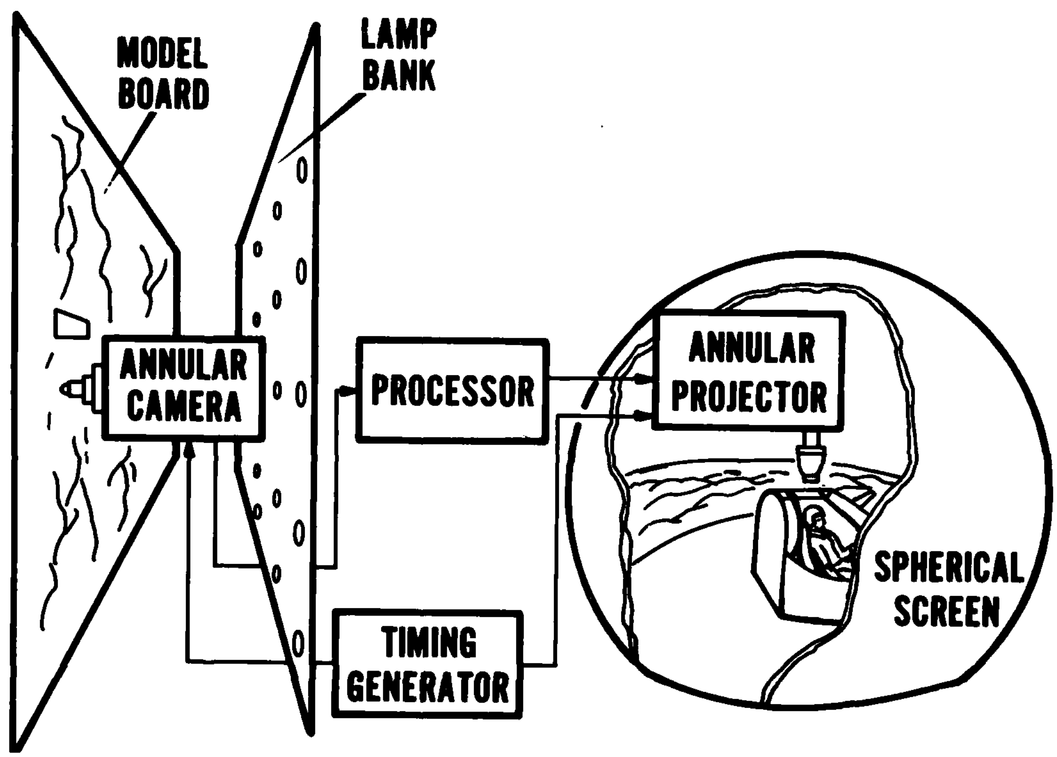


Figure 6. 360° Annular Visual System.

Figure 7. 360° Annular Image.

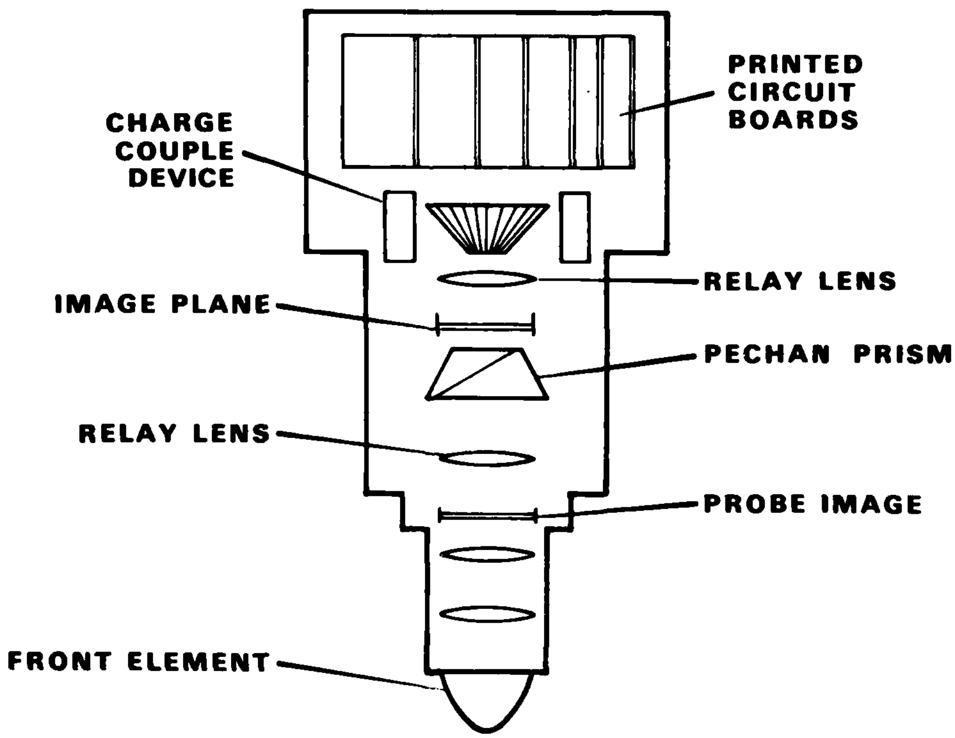


Figure 8. Annular Optical Probe.

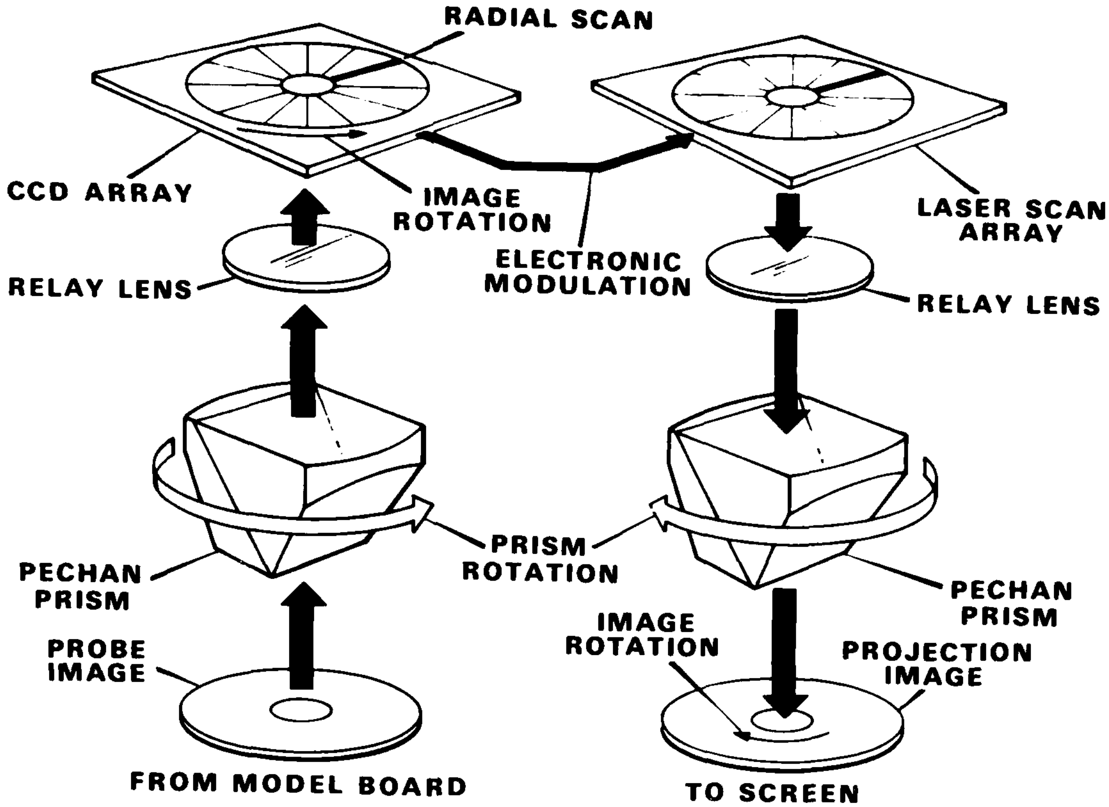


Figure 9. Image Transfer System.

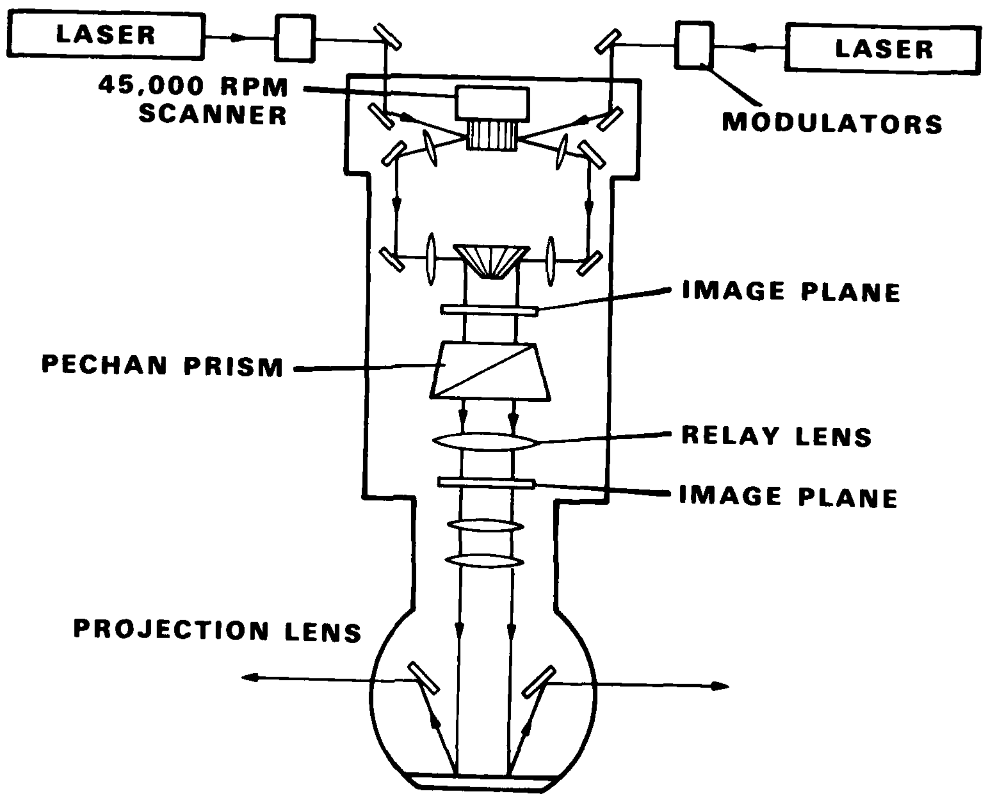


Figure 10. Projector Arrangement.

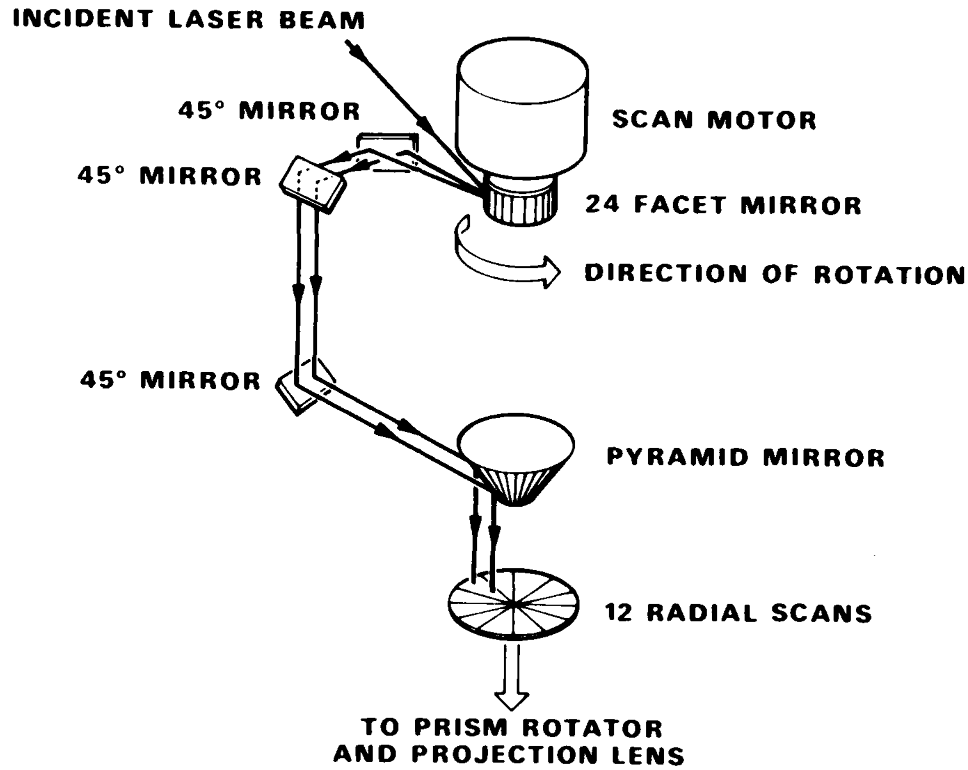


Figure 11. Scan Conversion System.

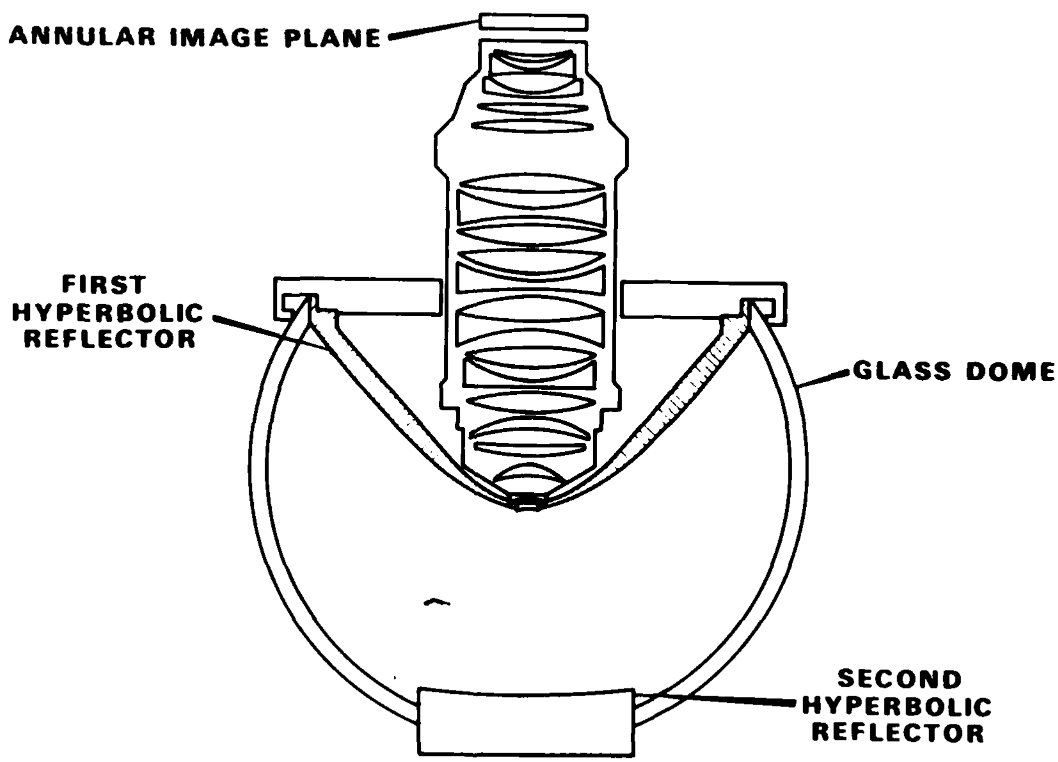
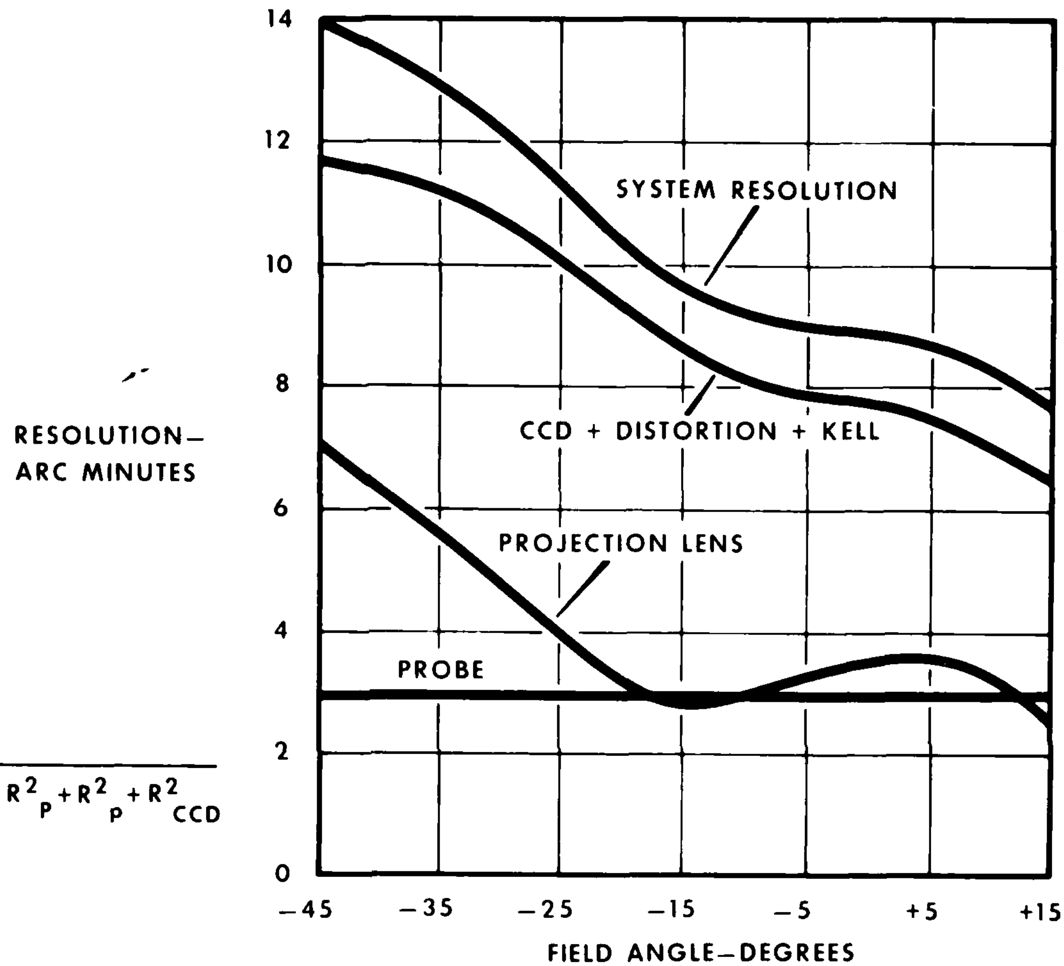


Figure 12. Annular Projection Lens.



$$R_S = \sqrt{R^2_P + R^2_P + R^2_{CCD}}$$

Figure 13. Limiting Vertical Resolution Factors.

VISUALLY INDUCED MOTION IN FLIGHT SIMULATION

by
Laurence R. Young
Man Vehicle Laboratory
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge, MA, USA
02139

Summary

Much of the attention to visual displays for flight simulation in recent years has been devoted toward precision wide field presentations. The significant advances in multiscreen computer image generation and point light source displays has quite literally widened our horizons for presentation of "out-the-window" information. Most attention has been devoted to the precise static display considerations including perspective, grain and contrast. Relatively less attention has been devoted to the dynamic properties of the visual scene and in particular the role of the moving wide field presentation in sustaining a pilot's motion sense. This paper addresses the experimental data accumulating on the subject of visually induced motion for all linear and angular degrees of freedom. In particular, we discuss visually induced yaw (circularvection) resulting from a moving wide field presentation, and its interaction with vestibular yaw cues generated by base motion. A model is presented for the interaction between visual and motion cues in yaw which rationalizes the high frequency utilization of vestibular cues and the low frequency use of visual cues to support sustained angular velocity. The implications for fixed and moving base flight simulator design are discussed. Similar considerations apply to visually induced linear velocity (linearvection) and interesting asymmetries in the fore-aft direction are noted. Finally, visually induced pitch and roll are discussed and modelled in terms of conflict between the visually induced motion and the information regarding attitude based upon graviceptor signals.

Introduction

It is useful to distinguish between two classes of visual cues for flight simulation: high acuity, high information density, central field cues which must be "read" to be interpreted, and which we will term "foveal" cues, and wide field, lower acuity and contrast, rapidly moving cues which generate non-cognitive motion perception, and which we refer to as "peripheral" cues. The selection of names for these two categories which correspond to the high static acuity, primarily cone filled, fovea and the lower static acuity, high dynamic sensitivity, primarily rod filled, periphery is deliberate. The former category includes, of course, all of the inside the cockpit instrument displays. With an out-the-window or VFR display, it also includes elements of the picture whose internal structure must be examined in order to gain the desired information, such as runway, VASI lights, or another aircraft being pursued, evaded, or accompanied in a formation flight. In the latter category are wide field scenes, usually showing homogeneous motion, in which the scenic content or structure is normally irrelevant except for the presence of a horizon. These wide field scenes give rise to the perception of continued linear or angular velocity and are widely applicable to use in flight simulation for reducing the platform motion requirements. In this paper, we review some of the principal characteristics of visually induced motion sensation associated with these peripheral cues, point out those practical aspects relating to their use in flight simulation, and explore the relationship between visual cues and true vestibular stimulation in flight simulators which contain both wide field displays and platform motion. Finally, two current models for visual vestibular interaction, potentially applicable to flight simulation, are introduced.

Characteristics of Visually Induced Motion

The phenomenon of visually induced motion is a common one easily observed when staring at a flowing river from a bridge or having an adjacent train in a railroad station move slowly. Just over 100 years ago, Ernst Mach[1] experimented with an apparatus in which subjects were rotated and also surrounded by an independently movable wood and paper drum, by means of which he induced alternating sensations of drum motion and self rotation about a vertical axis. This phenomenon, which came to be known as circularvection in later years, cannot be explained entirely on the basis of the slow phase of nystagmic eye movement, since it was present and even enhanced when eye movements were minimized by use of a fixation point. The physiological properties involved in the generation of self motion and optokinetic nystagmus, and the interaction with stimulation of the vestibular system through true body rotation is a subject of active current investigation, but beyond the scope of this paper, where we will restrict our attention to the perceptual phenomena.

When a full visual field suddenly begins to rotate about a vertical axis, the response is rather startling, although repeatable. At first, when the surround begins to move suddenly, the veridical motion is sensed: The surround appears to be moving and the subject feels himself stationary. However, if the peripheral moving field is large enough and the experimental situation is one such that the subject's mental set would permit self rotation, a change from field motion to self motion occurs beginning after a typical latency of 2 to 5 seconds, at which time the visual field appears to slow, often to a stop, and the subject perceives himself as rotating in the opposite direction. The postural reaction to this illusory movement can cause some observers to fall over (to prevent this, most 360° movie exhibits, like the one in Disneyland, provide a support to hang onto). This sensation of rotation builds to a maximum over a period of 3 to 10 seconds, rising approximately as an exponential. The exact relationship between the final sensation of self rotation and the field velocity depends to a great extent on the details of the experimental situation. In order to achieve "saturation" of the effect, in which the visual field is perceived to be entirely stationary, it is useful to have a wide rich field of view in the periphery, moving at uniform velocities less than 50°/sec. When the visual field is accelerated slowly and smoothly, expecially when its acceleration does not exceed the acceleration thresholds of the semicircular canals (of the order of $0.2°/sec^2$), then the self motion phenomena is more likely to develop continuously and without noticeable latency.

Visually induced self motion has been explored for rotations about the earth horizontal axis as well as for rotations about the vertical axis. Visually induced motion is also easily observable along the three linear axes. The general characteristics of visually induced motion in the absence of concomitant vestibular cues are summarized briefly below.

1. The peripheral, rather than the central, visual field must be stimulated. Blanking of the central visual field up to 60° has barely any effect on the development of self motion[2], emphasizing the importance of side window displays for its utilization in flight simulation. As first pointed out by Fischer and Kornmuller[3], a central moving field which generates nystagmus in the direction opposite to that associated with the peripheral field, does not interfere with the peripheral field induction of self motion. Similar dependence of the self motion effect on visual field content has been found for visually induced motion about the roll axis[4].

2. Background stimulation dominates over foreground stimulation[5]. Fixed objects in the foreground, such as a window frame or elements of the instrument panel, do little to inhibit visually induced motion based upon a moving background field, especially if the latter is at optical infinity. On the other hand, fixed objects in the background, such as blemishes on a projection screen, can inhibit visually induced motion.

3. The spatial frequency of the scene rather than its content or color determines its effectiveness for the generation of self motion. Held et al[4] quantified the visual border placement and velocity required to achieve a given visually induced roll. In experiments involving rotation about all three axes in the "Dual Maneuvering Spheres" at NASA Langley Research Center, we observed no significant differences between the effects of using a wide moving field containing randomly spaced and oriented black rectangles (each subtending 2 to 3° of visual angle) and using projected scenes corresponding to realistic earth-sky backgrounds[6]. Of course, for simulation purposes, the peripheral field display must have a sufficient number of borders in the way of stars, clouds, or ground features to induce the perceived motion effect.

4. The visual field velocity determines the magnitude of the self motion up to a saturation velocity, which probably corresponds to the blurring of the field associated with increased dynamic visual acuity. The vection is termed "saturated" when the field appears stationary in space and all motion is egocentric. Saturation is easily achieved for yaw rotation up to 60°/sec and linear forward velocity up to 1 m/sec. As field velocities further increase, the self velocity saturates and finally drops to zero. For visually induced pitch and roll, the saturation velocities are of the order of 40 to 60°/sec, inducing visually induced static tilt from 15 to 60°[6]. Thresholds for the development of linearvection have been reported in the range of 1 to 3 cm/sec[7].

5. The onset delay of visually induced motion is highly variable among individuals and for any one subject. Repeated exposure reduces the delay in vection, as does the development of the appropriate mental set, which allows for the possibility of self motion. Delays of the order of 30 seconds are not at all uncommon on initial exposure. Delays in onset are reduced as the acceleration of the visual field becomes smaller, to the point where the latencies are barely noticeable when the visual field acceleration is of the order of the thresholds of the semicircular canals (approximately $0.2°/sec^2$) and of the otoliths (approximately 0.005 g's). The delay in onset of visually induced motion is critical for its use in flight simulation. These delays can be minimized by the appropriate use of limited true motions as will be discussed below under visual vestibular interaction. It will be shown how brief vestibular cues in the appropriate direction hasten the onset of self motion and those in the conflicting direction delay its onset.

6. Adaptation is seen in vection, such that long duration constant velocity stimulation can result in a gradual decrease in subjective velocity. Adaptation to forward linearvection was reported as high as a factor of 2 with a time constant of 30 to 50 seconds, and corresponds qualitatively at least to the well known phenomenon of underestimating vehicle speed after a long constant velocity exposure[7].

7. Occasional losses of vection may occur suddenly and without warning during the constant velocity stimulation. The reacquisition of vection following these losses is similar to that seen at the initial stimulation, namely a delay of a few seconds followed by a sudden rise to the saturated level. These losses may be correlated with eye movements[8].

8. The quality of the induced motion is in most respects identical to that produced by vestibular stimulation, with the exception that no sensation of acceleration and deceleration is felt to accompany the perceived changes in self velocity. Visually induced motion sensations can develop into a form of motion sickness known as "simulator sickness"[9]. Tilting of the head during visually induced yaw results in a "pseudo Coriolis effect" resembling the sensation of rotating about an orthogonal axis and the accompanying malaise associated with actual cross-coupled accelerations[10].

9. The frequency response of visually induced motion effects depends upon the predictability of the signal; it is wider for predictable then for random motions. The approximate frequency response for linear random motion and for yaw circularvection is approximately flat from static inputs up to 0.1 Hz, beyond which it falls off at least as rapidly as a first order filter. In the presence of vestibular cues, however, as will be discussed below, this visually induced motion frequency response must be modified.

10. There are several important asymmetries in visually induced motion. The zero velocity state is preferred, so that buildup of vection away from the stationary condition is slower than is the return to zero. For the case of vertical linearvection, this has been modelled as the addition of a non-linearity producing a third harmonic in the sinusoid response[11]. For fore and aft linearvection, there is a much greater sensitivity and a shorter latency for backward linearvection (field moving forward) than for the reverse. For visually induced pitch, subjects appear to experience a much stronger sensation of pitching down than of pitching up for symmetric visual stimuli[6]. Individual asymmetries in visually induced roll are the rule, but as yet no attempts to explain these asymmetries on the basis of handedness, visual dominance, or ocular countertorsion asymmetries have been successful.[12,13]

Visual-Vestibular Interaction, Interpretation of Visual Cues with Concurrent Platform Motion

The principal characteristics of visually induced motion described above pertain to the case of fixed base simulation. When the simulator platform is permitted some additional platform motion, visual vestibular interaction effects must be considered. Although, the detailed interactions are quite complex, the general patterns can be summarized as follows:

Visual cues dominate in the perception of velocity and orientation in the steady state and at low frequencies, well below 0.1 Hz. At higher frequencies, vestibular cues tend to dominate and are of special importance in the development of "onset cueing". When visual and vestibular cues conflict, especially regarding the sign of motion, vestibular cues dominate initially. Two models which appear tenable for describing most forms of visual-vestibular interactions are discussed in the next section. The material below summarizes some of the predominant findings on interaction between platform motion which stimulates the vestibular apparatus and movement of wide field visual scenes.

1. Graviceptor cues limit the extent of visually induced pitch and roll. Rotation of the visual field about the roll or pitch axis produces, after a delay of 5 up to 30 or more seconds, a paradoxical sensation of continuous roll rate and a limited roll angle, both in the direction opposite to the field motion[14]. The magnitude of the visually induced roll or pitch angle is presumably limited by the conflict between visual cues which indicate continuous rotation, and graviceptor (primarily otolith) cues indicating no chage in body orientation relative to the vertical[15]. When the same visual stimulus is applied about a vertical axis, with the subject lying on his back, continuous roll rate is observed with no limitation on perceived roll angle. Furthermore, when the head is placed in orientations known to permit less effective utilization of otolith signals (head on side or inverted), then the magnitude of visually induced tilt associated with rotation about a horizontal axis is markedly increased[6]. Finally, the rapidity of visually induced tilt is increased when the body is given a small initial displacement in the direction opposite to the field motion.

2. Visual cues can bias the perceived angular velocity in the presence of platform motion[16]. A closed loop yaw tracking task based solely on vestibular senses will inevitably result in a drift characteristic of each subject[17]. The presence of veridical visual field motion (field fixed in space) will null this drift and permit a pilot to exercise higher gain in his low frequency stabilization tracking. When the visual field is moved at a constant velocity relative to the simulator, a significant bias is introduced in the sensation of angular velocity, which may be useful for inducing constant velocity sensation with a limited motion trainer.

3. Circularvection masks opposite direction accelerations. In the presence of a steady visually induced motion, small platform accelerations opposite to the circularvection require a longer time for their detection and imply a shift in threshold for their detection[16]. With the use of visually induced motion cues, therefore, flight simulators with limited motion may be programmed for faster return washout circuits without risk of generating unacceptable false motion cues.

4. Confirming vestibular cues decrease the latency for attainment of visually induced motion. Limited amplitude accelerations in the appropriate direction, coincident with the onset of visual field motion, can lead to a rapid onset of the visually induced motion which is sustained by vision after the vestibular cues have been washed out. Although, considerable work remains to be done on quantification of this characteristic

it is certainly important for the consideration of limited, but adequate, motion cues for use in conjunction with wide visual field flight simulators, to prevent unwarranted delays in the onset of motion cues.

5. Visual and vestibular cues evidence frequency separation and non-linear interaction when applied simultaneously. Simultaneous presentation of independent random disturbances to a wide visual field and yaw disturbance force the operator of a closed loop control system to base his yaw stabilization commands on his perceived angular velocity. As indicated in Figure 1, the operator of a closed loop yaw stabilization task is forced

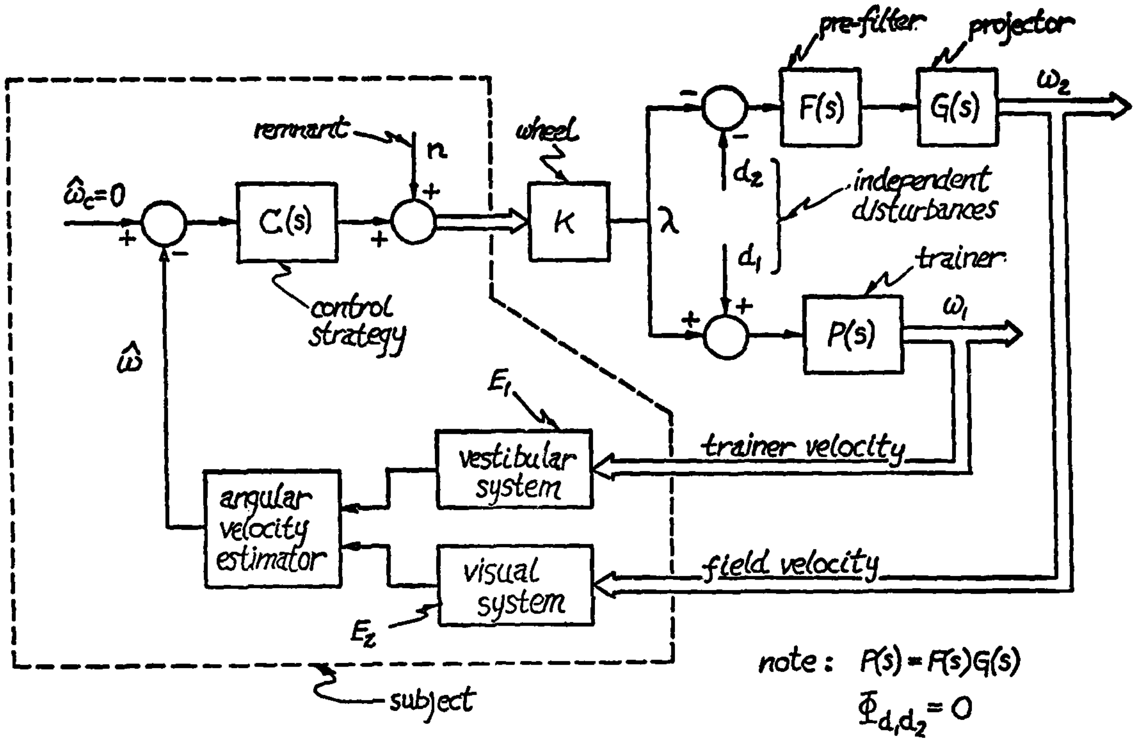


Figure 1: Closed Loop Velocity Nulling Task (Dual Disturbance Input)[17]

to base his manual control on a choice between independent random disturbances applied to a wide visual field and to yaw platform motion in his manual control. Application of dual input describing function methods, taking into account the operator's manual control characteristics, yielded the average frequency responses for his effective use of the visual and vestibular cues shown in Figure 2. Although the frequency responses show the separation into low frequency visual and high frequency vestibular dominance discussed above, non-linear interactions between the two account for the yaw motion time constant being much shorter than that associated with the semicircular canals, and for the relative increase in the utilization of visual cues at higher frequencies.

Models for Visual-Vestibular Interaction

We have been pursuing two parallel modelling efforts directed at the quantification of visual-vestibular interaction and its eventual application to flight simulator problems. Both of these will be summarized briefly.

The cue conflict model, developed by Zacharias[18] based on our earlier hierarchical switching notion[19], is illustrated in Figure 3. The model is a quantitative statement of the characteristics discussed in the previous section: when the visual and vestibular cues yield consistent orientation estimates, a weighted sum of the two is used to generate the perception of angular velocity in yaw. When there is a conflict between the estimates based upon the two senses, however, and when this conflict is sufficiently great, weighting on the visual signal is reduced and that on the vestibular signal is increased until the conflict is once again reduced. An essential element in this model is the notion of an "internal model of the semicircular canals". The visual scene angular velocity is passed through this "internal model", whose output is compared with the current output of the semicircular canals to generate the magnitude of any conflict which may exist. Thus, the current vestibular signal is compared with an estimate of what the vestibular signal would have been if the visual input represented true motion about the vertical axis, and were sensed by the vestibular apparatus. When this difference between the actual and expected vestibular signals increases in magnitude, a somewhat arbitrary weighting function, based on vestibular thresholds, reduces the gain K used to weight the visual component. The actual magnitude of the gain K may be adjusted according to the training of the subject and/or the compelling nature of the visual display system. This

Figure 2: Dual-Input Describing Functions: Vestibular and Visual Channels

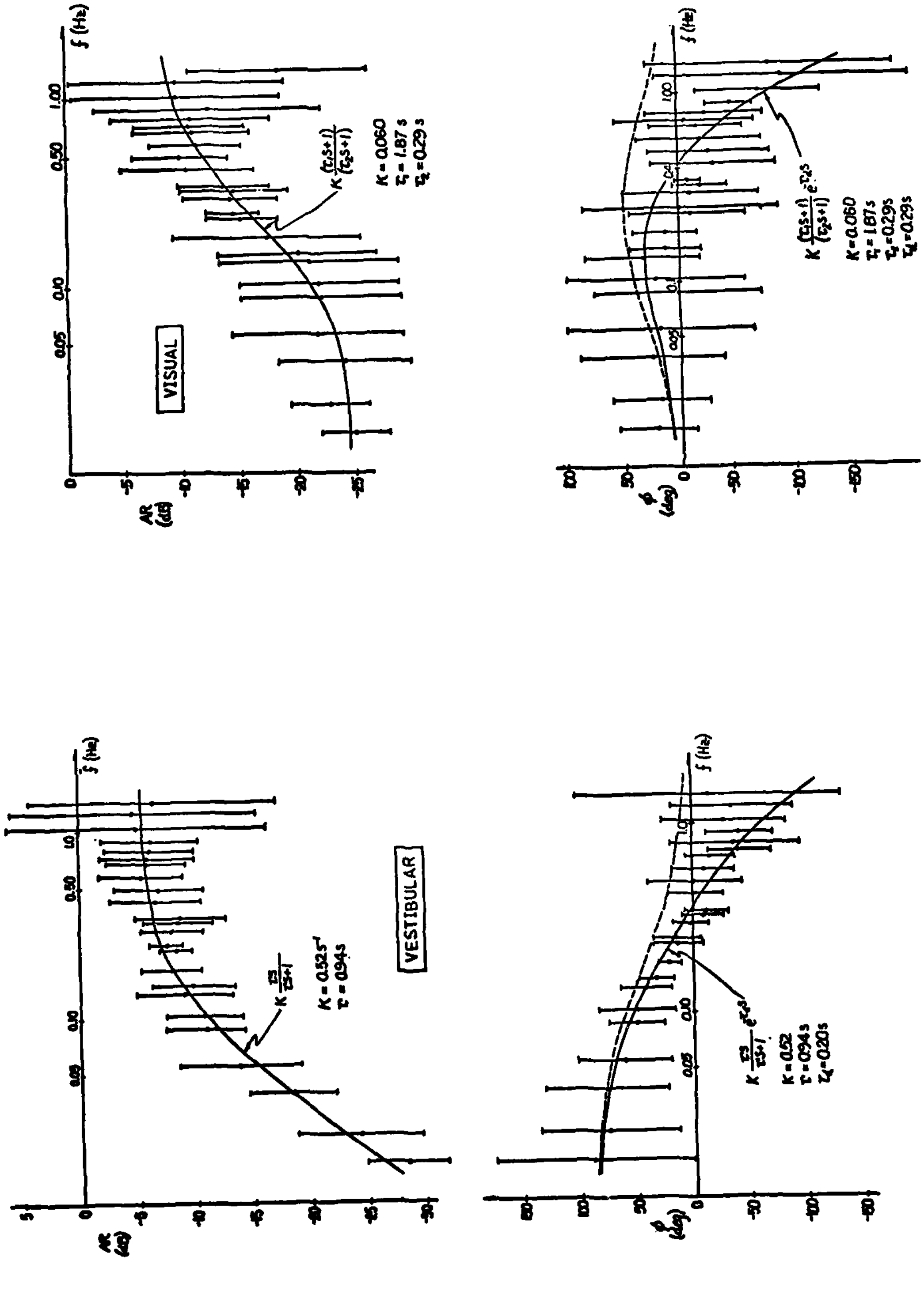


Figure 3A: Dual Input Conflict Model[17]

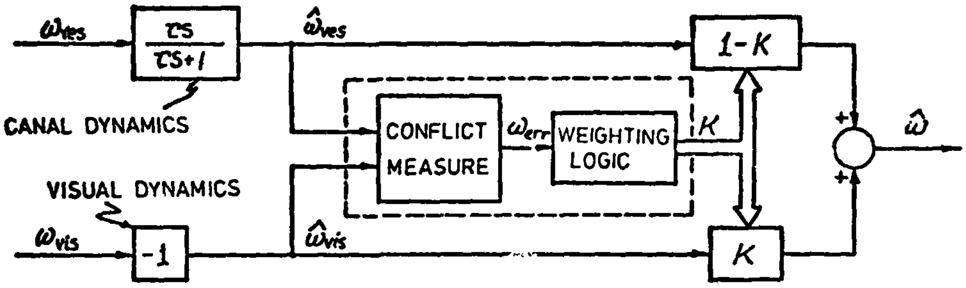
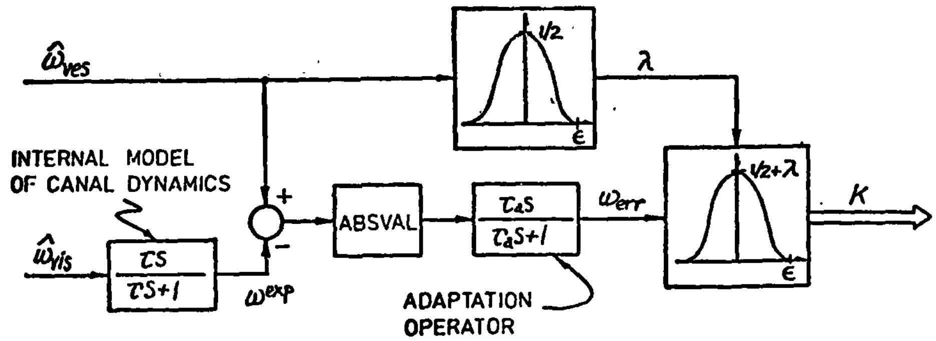


Figure 3B: Conflict Measure and Weighting Function[17]



model has been successful in matching the dual input describing function results in Figure 2 as well as in predicting the results of transient input experiments consisting of step angular accelerations with the visual field either fixed, counterrotating, or rotating at constant angular velocity relative to the cab. Current effort is continuing in extending this model to include otolith effects for consideration of roll and pitch as well as linear accelerations.

The second approach to visual-vestibular interaction we are pursuing, which is extended to the use of proprioceptive and tactile cues as well, is based upon the optimal estimation concept and involves the assumption of a steady state Kalman filter as a representation for the central nervous system processing of sensory inputs[20]. As indicated in Figure 4, the estimation process is modelled as a steady state filter which minimizes the RMS error in the estimate of the state. Calculation of the gains of this linear filter requires knowledge of the following factors: statistical characteristics of the input, descriptions of the dynamic response of the sensors, and estimates of the "additive noise" spectra associated with each sensor modality. Once these assumptions are made and the filter gains set, deterministic stimuli can be applied through the sensor models, which may include such non-linearities as are deemed essential. The overall structure of the modelling effort is illustrated in Figure 5. To date, the interactions between semicircular canal and otolith signals as related to perceptions of linear and angular accelerations have been tested and preliminary encouraging results using yaw circularvection and linearvection have been included in the model.

It is our intention to extend this modelling effort so that we will be able to answer the following questions in a few years. To what extent are platform motion requirements changed, for training or research simulators, by the presence of wide field visual display capabilities? We believe that the use of quantitative models of visual vestibular interaction will in the long run enable us to participate in the design of simulators which produce greater fidelity at lower costs in terms of platform motion.

Figure 4: Basic Structure of Unified Motion and Orientation Perception Model[20]

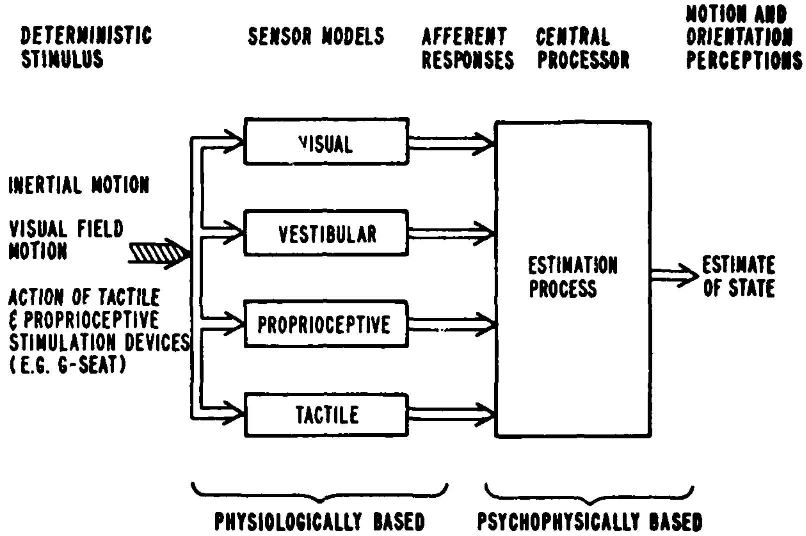
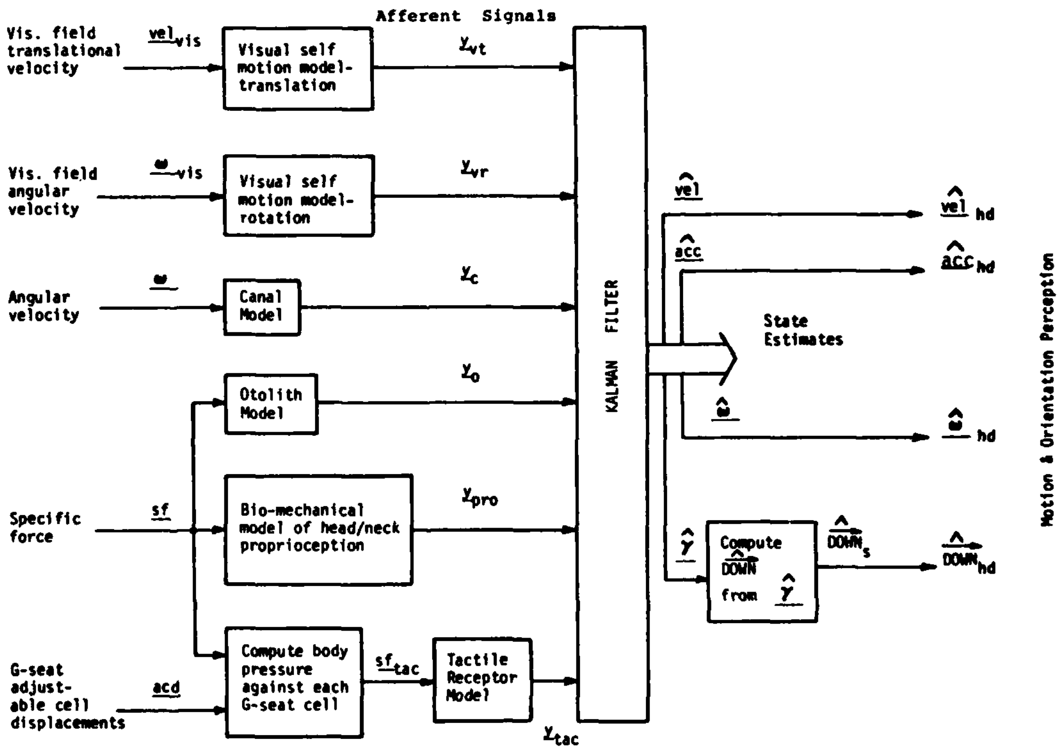


Figure 5: Optimal Estimator Model for Motion Perception[20]



References

1. Mach, E.: Grundlinien der Lehre von den Bewegungsempfinden. Engelmann, Leipzig, 1875; Bonset, Amsterdam, 1967.
2. Brandt, Th., Dichgans, J. and Koenig, E., "Differential Effects of central versus peripheral vision on egocentric and exocentric motion perception", Exp Brain Res 16 (1973) 476-491.
3. Fischer, M.H. and Kornmuller, A.E., "Optokinetisch ausgeloste Bewegungwahrnehmungen und optokinetischer Nystagmus", J Psychol Neurol (Lpz) 41 (1930) 273-308.
4. Held, R., Dichgans, J.M. and Bauer, J., "Characteristics of moving visual scenes influencing spatial orientation", Vision Res 14 (1974) 1-9.
5. Brandt, Th., Wist, E.R. and Dichgans, J.M., "Foreground and background in dynamic spatial orientation", Perception and Psychophysics 17 (1975) 497-503.
6. Young, L.R., Oman, C.M. and Dichgans, J.M., "Influence of head orientation on visually induced pitch and roll sensation", Aviat Space Environ Med 46 (1975) 264-268.
7. Berthoz, A., Pavard, B. and Young, L.R., "Perception of linear horizontal motion induced by peripheral vision (linearvection)", Exp Brain Res 23 (1975) 471-489.
8. Brandt, Th., Dichgans, J.M. and Buchele, W., "Motion habituation: inverted self-motion perception and optokinetic after-nystagmus", Exp Brain Res 21 (1974) 337-352.
9. Miller, J.W. and Goodson, J.E., "Motion sickness in a helicopter simulation", Aerospace Med 31 (1960) 204-212.
10. Dichgans, J. and Brandt, Th., "Optokinetic motion sickness and pseudo-Coriolis effects induced by moving visual stimuli", Acta Otolaryng 76 (1973) 339-348.
11. Chu, W., Dynamic Response of Human Linearvection, S.M. Thesis, Department of Aeronautics and Astronautics, MIT, January 1976. Young, L.R. and Chu, W., "Human vertical linearvection", in preparation.
12. Tang, J., Held, R. and Young, L.R., "Interaction of visually induced and labyrinthine sensed postural tilt", presented at the Psychonomic Society, Boston, MA, November 1974.
13. Dolezal, H. and Held, R., "Two components of visually-induced tilt during rotary field motion", abstract of paper presented at E.P.A. Meeting, New York, NY, April 1975.
14. Dichgans, J., Held, R., Young, L.R. and Brandt, Th., "Moving visual scenes also influence the apparent direction of gravity", Science 178 (1972) 1217-1219.
15. Young, L.R. "Developments in modelling visual-vestibular interactions", AMRL TR 71-14, 1971.
16. Young, L.R., Dichgans, J.M., Murphy, R. and Brandt, Th., "Interaction of optokinetic and vestibular stimuli in motion perception", Acta Otolaryng 76 (1973) 24-31.
17. Zacharias, G.L. and Young, L.R., "Manual control of yaw motion with combined visual and vestibular cues", presented at the 13th Annual Conference on Manual Control, MIT, June 1977.
18. Zacharias, G.L., Motion Sensation Dependence on Visual and Vestibular Cues, Ph.D. Thesis, Department of Aeronautics and Astronautics, MIT, September 1977.
19. Young, L.R. "On visual vestibular interactions", Fifth NASA Symposium on the Role of the Vestibular Organs in Space Exploration, NASA SP-314, 1970.
20. Borah, J., Young, L.R. and Curry, R.E., Sensory Mechanism Modelling, AFHRL TR 77-70, 1970.

Acknowledgements

This work was supported by NASA Grant NSG 2230 and AF Contract F33615-76-C-0039.

MOTION VERSUS VISUAL CUES IN PILOTED FLIGHT SIMULATION

by

J. R. Hall

Flight Systems Department, Royal Aircraft Establishment,
Bedford, Bedfordshire, UK

SUMMARY

In the ground based simulation of piloted flight the provision of 'adequate' cues to the pilot is essential for both training and the successful evaluation of handling and ride qualities. Realistic motion cues are particularly difficult to provide and attempts to justify other techniques are frequently made in order to provide the pilot with, subjectively at least, a realistic handling task. This paper presents two examples to show that motion cues can be vital even when 'adequate' alternative visual cues are available. The first shows that practical, low gain, roll motion cues are better than nominally perfect peripheral vision cues for controlling a vehicle with an unstable dutch roll mode and the second that motion can be vital even for developing items such as head-up displays for which it might not at first sight seem necessary.

The paper concludes that for the prediction and evaluation of handling qualities using a piloted flight simulator it is not always sufficient for the pilot to achieve a similar performance in the simulator as in flight: it is also necessary that he should adopt the same control strategy. To achieve this it is often essential to provide the pilot with motion cues as no substitute in these circumstances has yet been found.

1. INTRODUCTION

Ideally when simulating a piloted flight vehicle the pilot should be provided with all the cues available and used by him to control the aircraft in real life. In practice in a simulator many of the cues are degraded compared to their real life equivalent, and this applies particularly to motion cues which are often difficult or impossible to reproduce.

Fortunately pilots are very adaptable at synthesising, from the limited or imperfect information available to them, what is required for control of the vehicle and severe degradation or omission of cues can often occur before a loss of performance is noticeable. Whilst advantage can, and should, be taken of this adaptability in simulation to obtain the fullest possible training or research benefits in as efficient and economical manner as possible, there exists a serious danger of either negative transfer of training or the incorrect prediction and evaluation of handling qualities.

Unfortunately little is known about the factor limiting a pilot's performance or the manner in which he synthesises the information required for controlling the aircraft, and in particular what criteria he uses for selecting, rejecting or weighting the sensations impinging on him[1]. As a result it is not known how much motion is required in what circumstances and for what tasks. In the training field it is sufficient to show that the overall cost of training is reduced by the use of simulators even though, in some respects, the pilot adopts an unrealistic control strategy which has to be corrected by flight training. In the research field, however, any change in control strategy due to imperfect cues must be shown not to affect the pilot's assessment of the vehicle, and this is very difficult to do if the vehicle has no real life equivalent. Since motion cues are invariably degraded in the simulator, the successful interpretation of simulation results inevitably relies heavily on past experience in similar circumstances.

This paper attempts to add to this experience by presenting two examples where, despite the provision of 'alternative' visual cues, degraded or missing motion cues have resulted in either an unrepresentative handling task or, more seriously, a failure to predict the handling characteristics of the vehicle. The first example compares the relative importance of roll motion and peripheral vision cues for the lateral control of a V/STOL aircraft with an unstable dutch roll mode. The results indicate that roll acceleration plays an important part in alerting the pilot to the imminent departure of the vehicle from the desired flight path.

The second example concerns the relative importance of motion cues and visual flight information displays on speed control of a V/STOL aircraft in partially jet-borne flight. Fore and aft acceleration cues, which are an important feedback to the pilot in flight, were absent from the simulation with the result that the pilot had to rely on indicated airspeed (IAS). This had little apparent effect on performance though control activity on the nozzle lever was greatly reduced. An apparently unrelated change in the format of the head-up display (HUD) presentation, however, modified the pilot's instrument scan sufficiently to cause large and unacceptable speed variations in the simulator which did not occur in flight. This illustrates the ease with which false handling predictions can arise when visual cues in the simulator totally replaced the motion cues the pilot would use in flight.

2. THE SIMULATOR

The results cited are all taken from simulations of a Harrier GR Mk 3 (Fig 1) at RAE Bedford using the single seat cockpit[2,3] (Fig 2). This cockpit has motion freedoms in roll, pitch and heave.

Roll motion was used to simulate both angular roll acceleration and, in combination with the gravity vector, low frequency lateral acceleration cues. Details of the roll motion drive laws and frequency response are given in the Appendix and Fig 16. Heave motion was used to simulate normal acceleration;

pitch motion was used for both angular pitch acceleration and, again in combination with the gravity vector, low frequency fore and aft acceleration (surge) cues (the low pass filter used here had a time constant of 4 s compared to 2 s in roll - see the Appendix). The high frequency surge cues of interest in the second example could not be simulated using pitch motion and the gravity vector since this would have given rise to false angular pitch acceleration cues.

Visual information was supplied by a head-up display (HUD), a collimated TV monitor, a skyscape shadowgraph projector and head-down instruments. The HUD presented all the flight information required with the exception of nozzle angle and rpm which were displayed head-down. The picture on the TV monitor, generated by a camera looking at a moving belt model, included an horizon but, for these trials, little or no ground detail. The skyscape projector generated a simple horizon line, on the inside of the 9m diameter dome which surrounds the cockpit. Flying on instruments (IF) was simulated by displaying cloud on the TV and by switching off the skyscape.

Fig 3 shows the field of view presented by the HUD, TV and skyscape as seen from the pilot's position. The skyscape provided an horizon over a full 360° but the pilot's field of view was limited to about ±100° by the cockpit structure. Because of the mounting of the collimating lens and the structure of the canopy there appeared to be a gap between the horizon displayed on the TV and that generated by the skyscape.

To give an impression of distance (and to hide features on the wall of the dome) the skyscape horizon was made to appear slightly hazy to the pilot by covering the cockpit hood with two layers of 'transparent' self adhesive film (compare Figs 2 and 3).

3. MOTION VERSUS VISUAL CUES FOR THE LATERAL CONTROL OF AN UNSTABLE VEHICLE

The first example is taken from a simulation of a Harrier GR Mk 3 without autostabilizers, the model being based on data supplied by Hawker Siddeley Aviation[4]. This example compares the relative importance of roll motion and peripheral vision cues for lateral control in partially jet-borne flight, where the model has an unstable dutch roll mode (having a natural frequency, ω_n , of 1.4 rad/s and a time to double amplitude of 2.2 s at 75 kn), and refers particularly to flight on instruments (IF). The task was to fly straight and level at 75 kn and 8° of incidence and whilst lateral and especially roll control predominated, considerable attention also had to be paid to speed and height control. All trials were flown in light turbulence of 0.3 m/s rms.

3.1 Effect of motion

In visual flight (using the HUD and TV but not the skyscape) roll motion had a significant effect on lateral control which is illustrated in Fig 4. With motion on, only a small residual oscillation with occasional larger excursions was in evidence and lateral control was acceptable. In contrast, with motion off the excursions in roll and sideslip were larger with only the occasional calm patch and lateral control was considered by the pilots to be unacceptable. This mixture, rather than a constant limit cycle oscillation, is typical of all the configurations considered. (Since variations in pilot performance can occur from trial to trial, all comparisons presented in this example are taken from consecutive runs within the same trial.)

On instruments (*ie* with cloud on the TV and using only the HUD) the effect of motion was similar but much more marked (Fig 5). With motion on, the residual oscillation was larger than in visual flight whilst with motion off the model was only just controllable. In the air pilots are not aware of any significant lateral oscillation whereas in the simulator there was always a residual dutch roll oscillation present, particularly on instruments. Thus whilst motion made the model much easier to fly and a much closer match to the aircraft, the simulator was still not a good representation of the aircraft without autostabilizers.

The residual dutch roll oscillation on instruments and with motion on was around ±5° in bank (Fig 5). The peak roll acceleration associated with this, one of the smallest limit cycle oscillations observed IF, is still at least one order of magnitude greater, even after allowing for the reduced gain of the roll motion, than the absolute threshold of perception which is around $0.5^o/s^2$ in roll[5]. However the latency time (*ie* the time taken for the pilot to become aware of the cue) associated with this peak roll acceleration[5,1] as perceived by the pilot (*ie* allowing for the reduced motion gain of around 0.23 - see the Appendix and Fig 16) is approaching that required for one quarter of an oscillation, *ie* 0.6 to 0.7 s. It may be, therefore, that this limit cycle oscillation is defined by the amount of lead which the pilot can generate using the available motion cues. Further, though the response of the roll motion as measured by its position was quite good, pilots noticed a distinct jerk as the motion reversed direction. In an investigation of a simple tracking task[6] quite a small dead space inserted into the bank or heading response of an aircraft caused a limit cycle oscillation to be generated. These and the marked effects of motion already observed suggest that motion deficiencies rather than modelling errors were largely responsible for the residual limit cycle oscillation. Before resorting to an artificially stable model in order to provide the pilot with, subjectively, a realistic task, the possibility of artificially supplementing the unsatisfactory motion cues with peripheral vision cues was investigated.

3.2 Motion versus skyscape

The effects of roll motion and skyscape cues on lateral control in straight and level flight on instruments are shown in Fig 6. Also shown are the pilot ratings given[7] for the task.

The pilots considered the addition of the skyscape, with motion on and under IF conditions, provided a very powerful peripheral rolling cue but it did little or nothing to ease their task of maintaining wings level. Either motion or skyscape alone provided the pilot with very useful cues, in addition to the HUD, for maintaining laterally level flight, the pilots having a marginal but definite preference for motion alone over skyscape alone. When very large lateral excursions occurred (motion cues would be further reduced under these circumstances - see the Appendix) it was extremely difficult to regain control using either cue.

Under visual flight conditions the TV picture provided very useful cues for maintaining level flight in *all* axes (Fig 7). Again the addition of the skyscape provided a powerful peripheral rolling cue which did little or nothing to ease the pilot's task. When used without motion the skyscape went some way to replacing the motion cue but the effect was small and not as marked as when flying on instruments.

3.2.1 Further skyscape effects

The skyscape provided no useful cues in pitch or yaw even when large clouds were included. The pilots considered the use of the skyscape when flying on instruments (*ie* when IF) was most unnatural and detracted considerably from the realism of the simulation, whilst its use with the TV picture was most natural and added noticeably to the realism.

3.3 Effect of haze

In an attempt to achieve the same level of improvement as provided by the TV visual cue, the haze was removed or the canopy opened to give a more compelling peripheral cue. (The canopy slides forward and when open the rear frame reduces the amount of peripheral information as well as removing the haze. It was not practical to remove or replace the haze on the canopy during a trial but only between trials.)

Removing the haze (or opening the canopy) resulted in a marked increase in the frequency of the roll response and lateral control activity (Fig 8) which could persist, motion on, to some extent if the skyscape was switched off whilst the pilot was still flying. This confirms previous results where identical contrast and clarity of far and near terrain[8], or simply a sharp horizon in the peripheral vision[9], gave the impression that distant objects were at much closer than true range. As a consequence the displacement of the horizon in the peripheral vision appeared more rapid than intended and this could lead to overcontrol in roll[9]. As is often the case in conditions prone to pilot induced oscillations, the pilots learnt with experience to avoid this degree of overcontrolling but still complained that the vehicle felt more oscillatory without the haze.

3.4 Spectral analysis

When a yaw autostabilizer was added the pilot was able to reduce the amplitude of the dutch roll oscillation, with both motion on and motion off, but the effect of motion remained essentially unchanged, *ie* a marked reduction in amplitude with little or no effect on the basic frequency (Fig 9). The standard deviations for stick activity and roll response are also shown on the Figures. The yaw autostabilizer increased both the frequency and damping of the dutch roll (to 1.55 rad/s and 4.5 s to double amplitude at 80 kn, compared to 1.4 rad/s and 2.2 s (at 75 kn) with the yaw autostabilizer off) but had no measurable effect on the yaw/roll ratio.

This data was analysed in the amplitude and frequency domains. The probability density function plots (Fig 10) illustrate the much larger amplitudes of both stick activity and roll response motion off. These plots have the characteristic central dip, particularly motion off, of sine wave plus random noise signals. (The autocorrelation functions of roll response, p and ϕ, with motion off are characteristic of sine wave plus random noise signals, whilst those for cases with motion on exhibit more of the characteristics of narrow band random noise signals.)

The power spectral density plots (Fig 11) show that with motion off the largest increase in both stick activity and roll response occurs at or just above the dutch roll natural frequency and that the pilot is 'working' up to significantly higher frequencies with little apparent effect on aircraft response, *ie* there is a significant increase in pilot remnant or noise.

The implication is that whilst pilots are quite capable of working at the dutch roll natural frequency and of controlling this unstable mode, they can only generate sufficient lead and reduce the amplitude of the oscillation to acceptable levels when roll motion is present.

4. SPEED CONTROL OF A V/STOL AIRCRAFT IN PARTIALLY JET-BORNE FLIGHT

This second example is taken from a simulation of a Harrier GR Mk 3 with all its autostabilizers on and concerns the effects on speed control, on the approach in partially jet-borne flight, of omitting the fore and aft (surge) acceleration cues available in flight. At the approach speeds considered the longitudinal short period oscillation (SPO) of the vehicle was stable and well damped.

4.1 The simulation

The simulator was set up initially to represent a Harrier GR Mk 3 aircraft (Fig 1) over the speed range 0 to 200 kn and had been extensively validated by 12 test pilots[2,3]. With autostabilizers on, the handling, particularly in respect of gentle IF manoeuvres using the HUD (V/STOL mode), was considered by all pilots to be a good representation and by one pilot to be "so like the Harrier in the same circumstances as to be remarkable". It was noted, however, that rather more attention to indicated airspeed (IAS) was needed when changing nozzle angle, especially when initiating deceleration and acceleration manoeuvres, and more attention to the rpm gauge was needed when lowering the nozzles and establishing partially jet-borne flight. This, it was suggested, was due to the absence of surge motion cues on the simulator. In the real aircraft the "seat of the pants" enables this "down with the nozzles and up with the power" stage to be achieved, retaining a balance between thrust and drag, with little or no cross reference to the instruments other than for the final accurate setting of the desired rev/min or nozzle angle.

In the air nozzle and throttle movements are accompanied by:

(a) trim changes;

(b) noise changes;

(c) changes in normal and longitudinal acceleration.

With the exception of noise changes due to nozzle deflection, these effects were all modelled but many of the resulting cues to the pilot were either less pronounced (*ie* pitch motion and engine noise) or non-existent (*ie* normal and longitudinal accelerations).

Heave motion was not always acceptable when rapid and frequent nozzle movements were made, which occurred whenever the nozzle lever was used as a primary control - see section 4.2, as it sometimes excited the structural modes of the simulator cockpit. This is because the build up of normal acceleration in response to nozzle lever movements is essentially instantaneous (depending only on nozzle rotation rate) whereas that due to longitudinal stick and throttle movements is comparatively slow (since it depends on the aircraft's pitch and engine response characteristics respectively). Since heave motion was of little benefit on the approach, and could be switched off in this flight regime without prejudicing the results, it was not used during most of the trials from which the data of this example is taken. (Heave motion was necessary in the hover for acceptable height control, especially when using only external visual cues.)

Overall the pilots considered these deficiencies to be minor ones and that, autostabilizers on, the simulation was a good representation of the Harrier. They had few reservations about using the simulation to study handling qualities of related configurations.

All the approaches presented in this example, both simulator and flight, were flown under instrument flight conditions (IF) using the HUD, with the final deceleration to the hover being carried out visually. In the simulator the skyscape was not used.

4.2 Piloting techniques

Before presenting this example it is helpful to digress to consider the two piloting techniques developed to simplify the pilot's control task in partially jet-borne flight. These are known as the 'fixed-nozzle' and 'fixed-throttle' techniques. In this flight regime there are now three controls available to the pilot for the control of flight path and airspeed/incidence - stick, throttle and nozzle lever. In effect incidence has become an independent variable since the proportions of the total lift carried by the wing and by the engine (by jet lift) can be varied independently of speed. In both techniques the pilot uses just two controls for short term longitudinal control, as with a conventional aircraft, the third being used in the longer term to set the desired airspeed/incidence relationship. In practice aerodynamic and power-to-weight ratio considerations impose limits on the range of incidence (and airspeed if a hover capability does not exist) that usefully can be used.

At the large nozzle angles of partially jet-borne flight (65 to 70° to the horizontal at 120 kn) the most immediate effect of throttle is on normal acceleration and thereby on rate of climb and incidence. In contrast the first, and immediate, effect of nozzle angle is on longitudinal acceleration and thereby on airspeed. In the fixed-nozzle technique, therefore, throttle and stick are used for the short term control of flight path and *incidence* (nozzle angle being used in the longer term to select the desired airspeed) whilst in the fixed-throttle technique the stick and nozzle lever are used for the short term control of flight path and *airspeed* (throttle being used in the longer term to select the desired incidence).

With the fixed-nozzle technique the pitch attitude for a given flight path and incidence is known and does not vary with aircraft weight or airspeed, *ie* it does not depend on the setting of the secondary control (nozzle). In contrast the pitch attitude for a given flight path and airspeed using the fixed-throttle technique obviously does depend on incidence, *ie* on both aircraft weight and the setting of the secondary control (throttle), and is only known approximately by the pilot from experience. As a result constant nozzle flight is largely at constant attitude whereas in constant throttle flight stick movements are coordinated with nozzle movements to control flight path, and larger and more frequent attitude changes are involved.

4.3 1:1 HUD pitch display

One change studied in the main investigation was the replacement of the standard 5:1 HUD used in the Harrier GR Mk 3 (V/STOL mode) with a similar display having 1:1 pitch bar gearing and an analogue altimeter display. Speed and flight path holding during approaches on instruments (HUD) in partially jet-borne flight using the 5:1 display had been quite satisfactory in the simulator (Fig 12), and not markedly different from flight, using either piloting technique. (The deceleration to approach speed and the start of the transition to the hover or overshoot is also shown on the Figures to indicate the time scale within which the pilot was working.)

The effects of piloting technique during IF approaches in the simulator using the 1:1 HUD are shown in Fig 13. Using the fixed nozzle technique, speed and flight path control was as good or better than on the 5:1 HUD (Fig 13a) since this is essentially a constant attitude task and small attitude changes were more easily noticed on the 1:1 display. Using the fixed throttle technique, however,(Fig 13b) control was unsatisfactory and unpredictable, speed control depending critically on the accuracy of the initial nozzle selection for the speed required. Subsequent nozzle corrections generally failed to stabilise the speed and dangerously large amplitude speed variations were often seen. Fig 13b shows a typical approach, much larger and smaller variations of speed being observed on other approaches.

Since the only significant change was to the pitch bar gearing this must have been responsible for the change in speed and flight path holding in the simulator. The more sensitive 1:1 pitch gearing enabled a given attitude to be held more accurately but the pilots disliked the rapidity of pitch bar movement even for small attitude changes, and attitude changes featured more in the fixed throttle than the fixed nozzle technique.

In flight, however, the pilot is known to rely heavily on surge motion cues when making nozzle selections and a direct read across to flight was not possible. Fortunately the opportunity to conduct a flight experiment occurred within a few weeks of the simulator trials and before the pilot concerned had gained further experience on 1:1 displays.

4.4 Comparison of flight and simulator, 1:1 HUD

In flight, using the identical display and HUD hardware in a T2 Harrier, speed and flight path control posed no problems on the 1:1 display using *either* piloting technique (Fig 14). Fig 15 presents a comparison between typical approaches in flight and on the simulator using the fixed throttle technique and reveals the reasons for the failure of the simulator to predict the correct handling in flight.

In flight, nozzle activity is fairly continuous and of comparatively large amplitude for a given speed correction (Fig 15a). This indicates a fairly tight, closed loop control of speed by the pilot with continuous feedback of nozzle effect, presumably via motion cues. In contrast, in the simulator, nozzle activity tends to be in discrete steps and with long intervals between changes (Fig 15b) which indicates a more open loop form of control strategy probably associated with the pilot's scan of IAS. The amplitude of nozzle increments in the simulator appears to depend on the size of the speed error on both the 1:1 and 5:1 HUDs and is markedly less than that used in flight for the same speed error. Table 1 compares the number of discrete nozzle movements made during typical IF approaches in flight and in the simulator. The frequency of nozzle activity in flight is about twice that in the simulator and is also marginally greater on the 5:1 than on the 1:1 HUD.

In flight the pilot has both surge motion cues and IAS, and is known to rely heavily on motion cues, whereas in the simulator only IAS is available. IAS provides a much less immediate feedback of information because it:

(a) needs to be scanned whereas motion is felt almost immediately;

(b) is velocity information whereas motion is acceleration information.

This means that the pilot can no longer rapidly zero the longitudinal acceleration in the absence of surge cues. This, it is surmised, leads to:

(a) a less immediate appreciation of non-zero longitudinal acceleration, and hence of speed changes, which results in lower frequency inputs and

(b) a less immediate feedback of the results of his control actions and hence more tentative inputs, *eg* small step inputs compared to large pulses.

Furthermore the 1:1 pitch display modifies the pilot's instrument scan on the HUD so that the IAS information available to replace the motion and noise cues he would normally use in flight, whilst adequate on the 5:1 HUD, is no longer adequate on the 1:1 HUD. Whether the pilot is deliberately making use of the greater sensitivity of the pitch display or whether the higher gearing is more compelling and therefore detracts from the scan of IAS is not clear.

5. DISCUSSION OF RESULTS

The first example has shown that even a practical motion system suffering from backlash, low gain (less than 25% of real life - see the Appendix) and hence reduced perception thresholds, and subject to washout, is as good or better (in terms of performance) than nominally perfect peripheral vision for controlling a vehicle with an unstable dutch roll. In addition motion adds to, whereas peripheral vision detracts from, the realism under IF conditions. If peripheral vision is accepted as being particularly acute at detecting velocity changes[1,10] then the implication is that a pilot achieves this better performance by using roll acceleration to warn him of the vehicle's imminent departure from its proper flight path.

The use of unrealistically powerful peripheral vision cues caused the pilots to overdrive the system and to increase the amplitude and frequency of the roll response. This confirms many previous results[8,9] but is at variance with some evidence[10] that very powerful visual cues in the periphery can give as good performance as motion cues in a moderately demanding roll tracking task. Pilots can readily adapt their control strategy to minimise or avoid many PIO situations (as observed in the first example presented here), or learn to fly a simulator using whatever cues are available often with little apparent loss in performance (as demonstrated in the second example presented). This may well explain this discrepancy.

The second example has shown that the importance of motion cues is not restricted to the evaluation of handling characteristics *per se*. It can also be vital for the development of items for which motion would not at first sight seem necessary, *eg* head-up displays. In this case in the absence of surge motion a change of *pitch* gearing on the HUD led to *speed* control problems in the simulator which did not exist with the same HUD presentation in flight. The example also emphasises both the dangers of allowing the pilot to adopt a different control strategy in the simulator compared to flight, even when performance is apparently not affected, and the difficulties of judging how much motion is required and for what task. A control strategy adopted or learnt in order to fly a simulator is a totally unsatisfactory basis for predicting the handling qualities of the total vehicle.

6 CONCLUSIONS

This paper has presented two examples to show that motion cues in piloted flight simulation can be important even when 'adequate' alternative visual cues are available and even for the study of head-up display presentations. In the first example a practical motion system suffering from backlash and reduced gain was better than nominally perfect peripheral vision cues for controlling a vehicle with an unstable dutch roll. Only with roll motion present could the pilot generate sufficient lead to reduce the amplitude of the motion to acceptable levels. In the second example the absence of surge motion in the simulator led to control activity on the nozzle being much reduced compared with flight and a change in HUD presentation led to speed control problems in the simulator which did not exist with the same HUD presentation in flight.

It is concluded that for the prediction and evaluation of handling qualities using a piloted flight simulator it is not always sufficient for the pilot to achieve a similar performance in the simulator as in flight: it is also necessary that he should adopt the same control strategy. To achieve this it is often essential to provide motion cues as no substitute in these circumstances has yet been found.

ACKNOWLEDGMENTS

The author is indebted to all the test pilots who took part in the simulations and flight trials referred to and particularly to Mr J. Farley, Deputy Chief Test Pilot, HSA, and Sqn Ldr J. Bolton, Flt Lt G. Ellis and Lt M. Hagen all of Flight Systems Squadron, RAE Bedford, whose work is cited in this paper. The author, however, takes full responsibility for the opinions expressed and conclusions drawn.

Appendix

ROLL MOTION LAW

The aim of a motion system is to reproduce the motions that the pilot uses for controlling the vehicle. Pilots make extensive use of their perception of motion, particularly when exercising tight control over the higher frequency modes and especially when the vehicle's stability is low[5,11]. The accurate representation of the higher frequency motions of the aircraft are therefore of primary importance and, if it is assumed that aircraft acceleration rather than velocity is the cue required, this is consistent with the use of ground based motion systems having limited travel. With roll motion care must be taken to minimise false motion cues, due to the inclination of the gravity vector, and preferably to reduce them to below the pilot's level of perception (compensation is only possible if sway motion is available) and this consideration effectively limits the gain and time constants that can be used. At the same time the gravity vector can be used to give lateral acceleration cues.

Drive law:

Available travel $\pm 10.5^{\circ}$

$$\phi_{cp} = \left[0.25 \frac{1.25\, s}{1 + 1.25\, s} \phi_{ac}\right]_{lim} - \frac{1}{1 + 2.0\, s} a_{yp} , \qquad \gamma = 0$$

where ϕ_{cp} and ϕ_{ac} are the bank angles of the cockpit and aircraft respectively in radians, a_{yp} is the lateral acceleration sensed by the pilot in g units and γ is the flight path angle. lim is a soft limit set at 7° above which the gain in ϕ_{cp} is halved.

Roll rate rather than bank angle is used to drive the roll motion in order to remove the restriction of level flight ($\gamma = 0$), without resorting to axis transformations, and to facilitate the use of lead to compensate to first order for the mechanical and hydraulic lags in the system. This lead had a time constant of 0.25 s and was applied to the first term only.

The first and more important term simulates the higher frequency rolling motions of the aircraft and is rapidly washed out to prevent the false lateral acceleration cues which would result if the cockpit was tilted significantly with respect to the gravity vector. 10° of tilt is usually considered to be the absolute maximum acceptable from this point of view. The second term simulates low frequency lateral acceleration cues, by making use of the gravity vector, high frequency cues being removed by the filter to prevent false angular cues.

The measured (*ie* measured and corrected from rate to position input) and theoretical (*ie* assuming the lead fully compensates for motion deficiencies) frequency responses of the roll motion, including drive law filters, are given in Fig 16. The response of the system is satisfactory up to around 1 Hz whereas the highest frequency of interest occurring in the first example presented was around 0.67 Hz with the haze removed - see Fig 8. Over the range of frequencies of interest in example one, *ie* 0.22 Hz (dutch roll natural frequency) to 0.67 Hz, the gain and phase of the motion cues varied from around 0.19 and 40° to 0.25 and 27° respectively.

Table 1

NUMBER OF DISCRETE NOZZLE MOVEMENTS MADE DURING TYPICAL IF APPROACHES

	HUD	
	5:1	1:1
Flight:	32 (2)	30 (1)
Simulator:	17 (1)	14 (1)

(1) Taken from data presented in Fig 15. (2) Data supplied by A & AEE, Boscombe Down - Pilot A.

REFERENCES

1 K.J. Staples, "Current problems of flight simulators for research", The Aeronautical Journal 82, 805, January 1978.

2 J.R. Hall, "A simulator study of approach profiles and recovery techniques for Sea Harrier in reduced visibility", unpublished RAE Technical Report.

3 J.R. Hall, "The development of a guidance display for the recovery of Sea Harrier in reduced visibility: a simulator study", unpublished RAE Technical Report.

4 D. Laidlaw, "GR3 Harrier mathematical model", to be published as HSA-HSL-R-HAR-01921.

5 J.L. Meiry, "The vestibular system and human dynamic space orientation", NASA CR-628 (1966).

6 A.G. Barnes, "The effect of visual threshold on aircraft control, with particular reference to approach and flare simulation", AIAA paper 70-357 (1970)

7 G.E. Cooper, R.P. Harper Jr, "The use of pilot rating in the evaluation of aircraft handling qualities", AGARD Report 567 (1969)

8 E.A. Stark, "Motion perception and terrain visual cues in air combat simulation", AIAA Visual and Motion Simulation Conference, Dayton, Ohio, 26-28 April 1976.

9 A. McPherson, "A piloted simulator study of a slender wing research aircraft (HP115)", RAE Technical Report 68068 (1968) ARC R & M 3614 (1970)

10 A.M. Junker, D. Price, "Comparison between a peripheral display and motion information on human tracking about the roll axis", AIAA Visual and Motion Simulation Conference, Dayton, Ohio, 26-28 April 1976.

11 D.H. Perry, A. McPherson, "A flight simulation study of handling characteristics of a slender wing supersonic transport aircraft at landing approach speeds", RAE Technical Report 66250 (1966) ARC R & M 3616 (1970)

Copyright © Controller HMSO, London, 1978

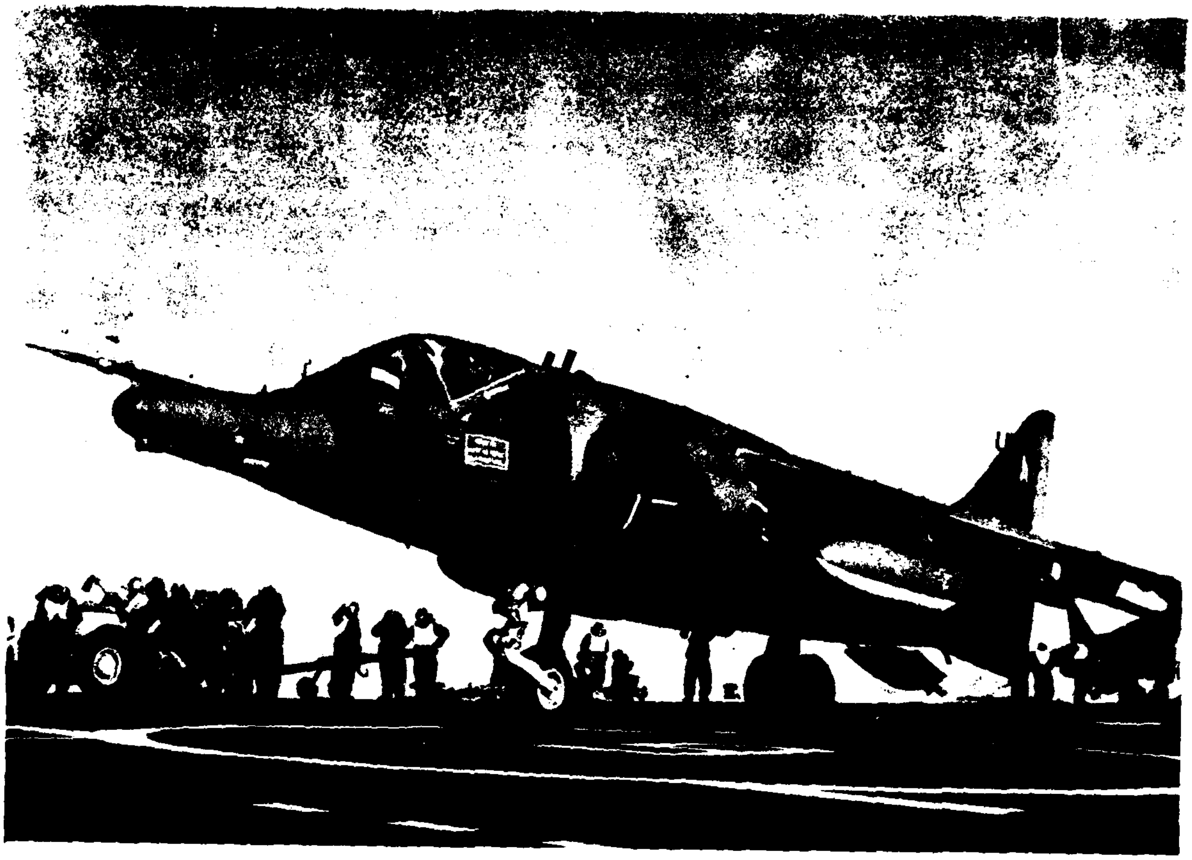


Fig 1   Harrier GR Mk 3 with laser nose

Fig 2 Cockpit and motion system showing skyscape

Notes: A seascape, and not a runway, was presented on the TV. The curved horizons and cockpit frames and misalignment of TV and skyscape horizons are distortions introduced by the Fisheye lens and camera.

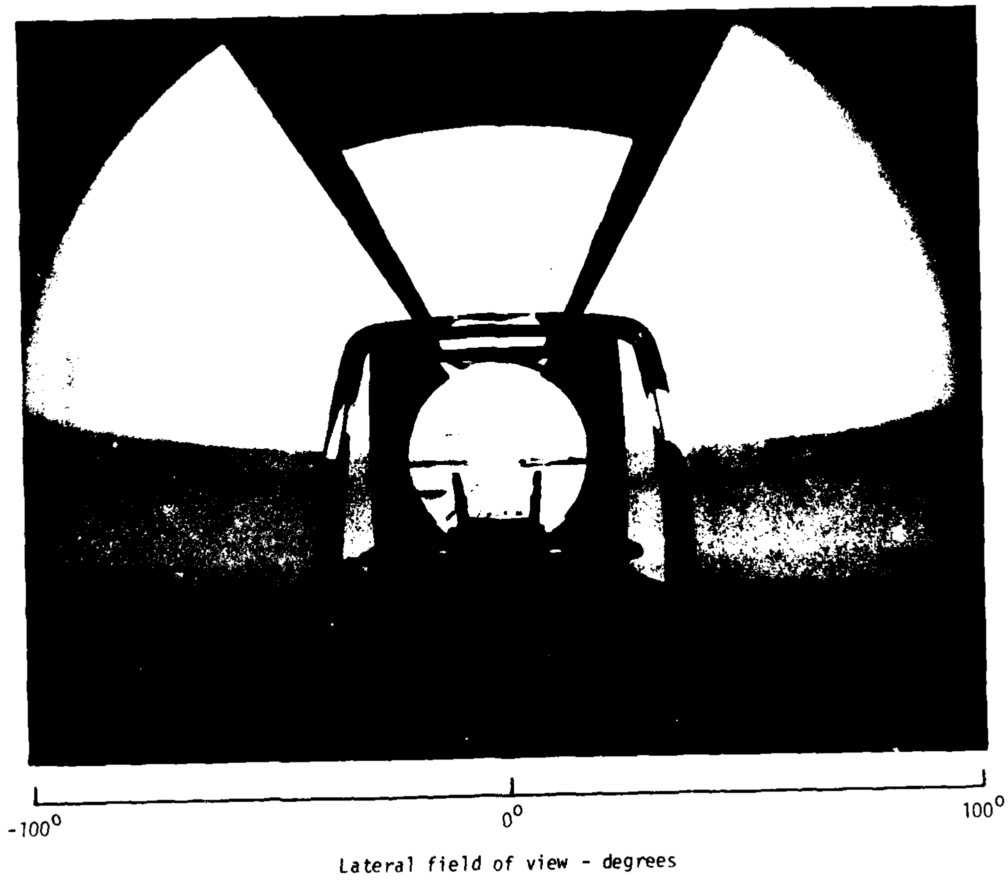
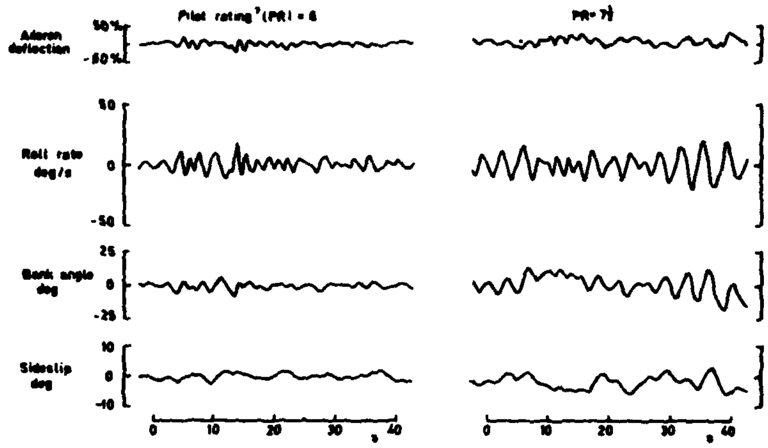
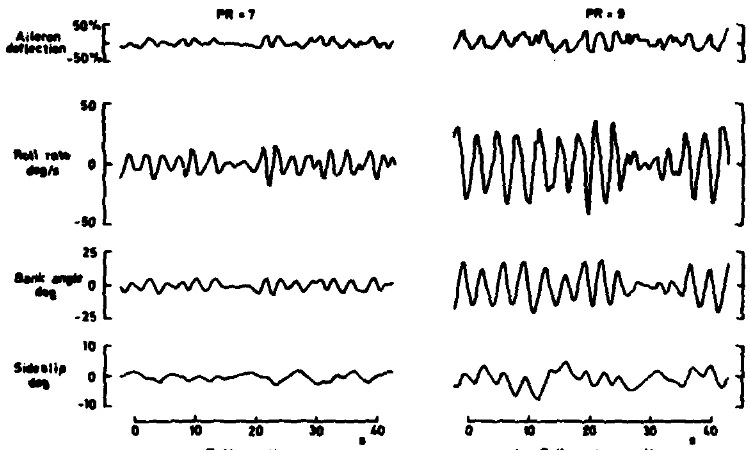


Fig 3 Pilot's field of view in simulator



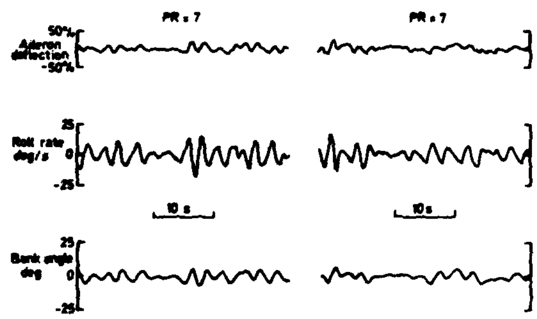
a Roll motion-on   b Roll motion-off

Fig 4 a&b Effect of roll motion on lateral control in visual flight: HUD on, TV on, skyscape off, V = 75Kn, pilot C

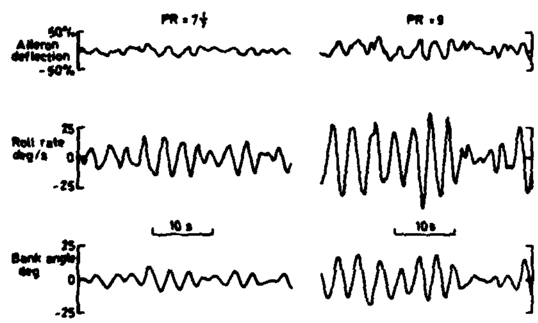


a Roll motion-on   b Roll motion-off

Fig 5 a&b Effect of roll motion on lateral control on instruments: HUD on, cloud on TV, skyscape off, V = 75Kn, pilot C



a Roll motion-on, skyscape-off   b Roll motion-on, skyscape-on



c Roll motion-off, skyscape-on   d Roll motion-off, skyscape-off

Fig 6 a-d Effect of roll motion and skyscape, on instruments: HUD on, cloud on TV, V = 75Kn, pilot C

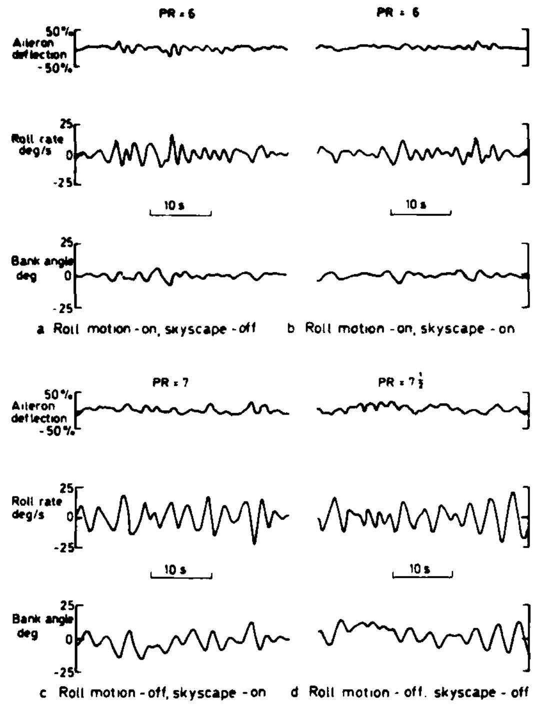


Fig 7 a-d Effect of roll motion and skyscape in visual flight: HUD on, TV on, V = 75 Kn, pilot C

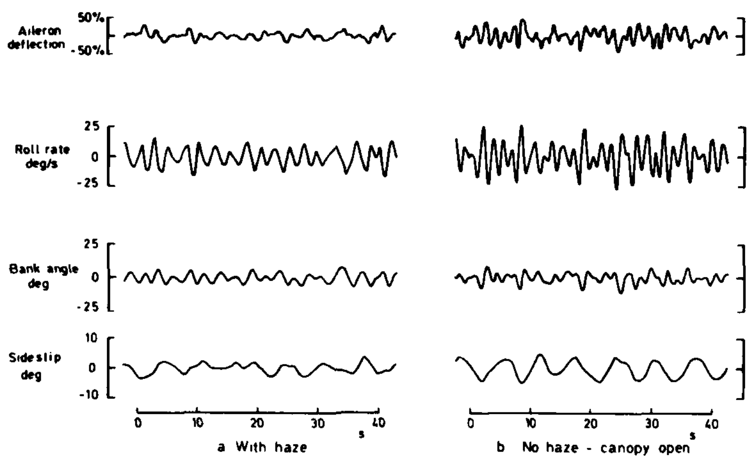


Fig 8 a & b Effect of haze on lateral control on instruments: HUD on, cloud on TV, roll motion on, skyscape on, V = 75 Kn, pilot C

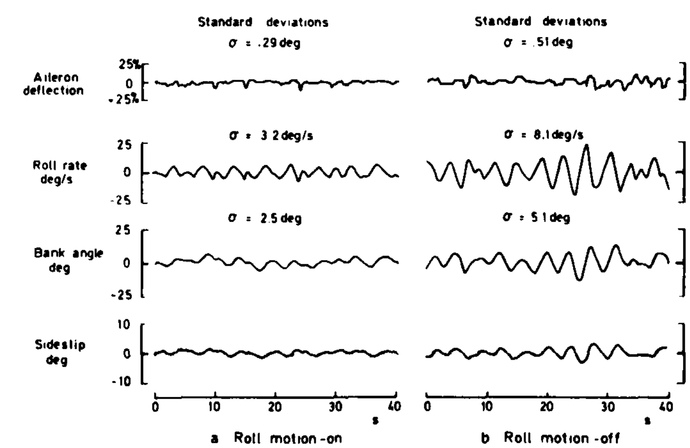


Fig 9 a & b Effect of roll motion on lateral control on instruments: Yaw autostabilizer on, HUD on, cloud on TV, skyscape off, V ≟ 80 Kn, pilot D

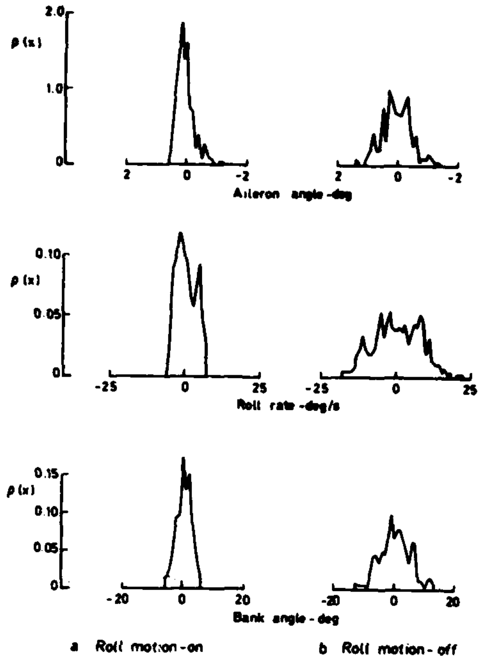


Fig 10 a & b Probability density functions for data of Fig 9

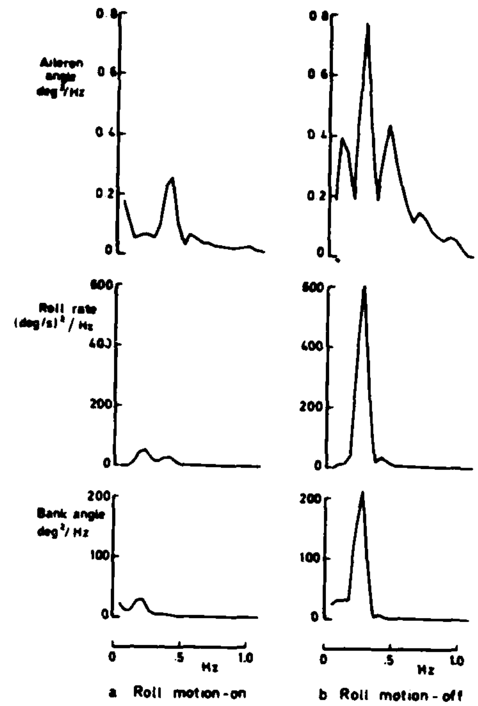


Fig 11 a & b Power spectral density functions for data of Fig 9

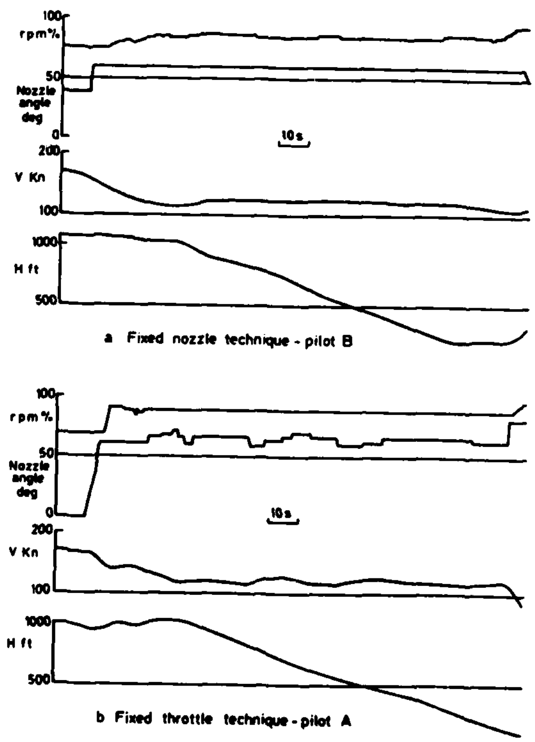


Fig 12 a & b Approaches in simulator using 5:1 HUD, IF

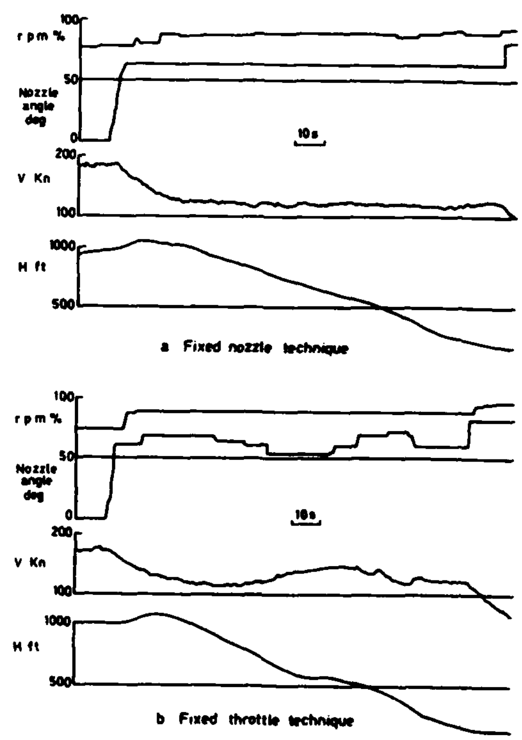
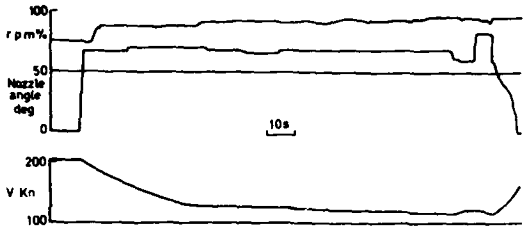
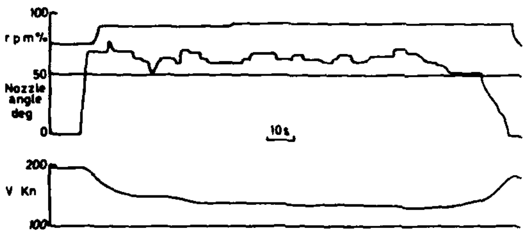


Fig 13 a & b Approaches in simulator using 1:1 HUD, IF, pilot A

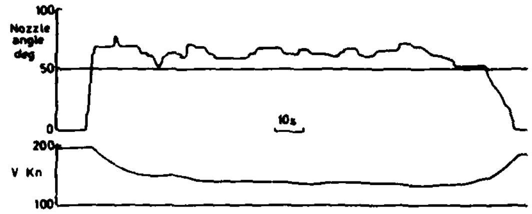


a Fixed nozzle technique



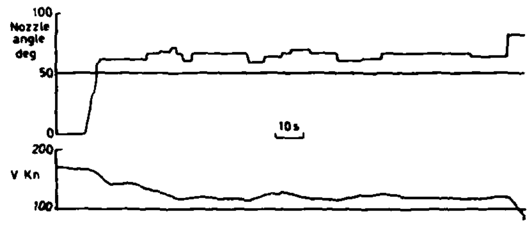
b Fixed throttle technique

Fig 14 a & b Approaches in flight using 1:1 HUD. IF, pilot A



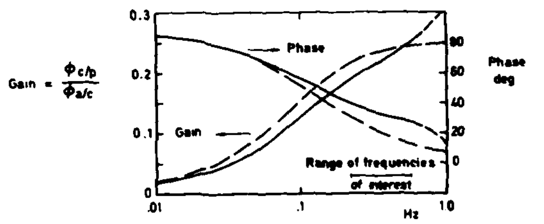
a Flight, 1:1 HUD, W = 18300 lb

b Simulator, 1:1 HUD, W = 16000 lb



c Simulator, 5:1 HUD, W = 15000 lb

Fig 15a-c Flight comparison using fixed throttle technique, IF, pilot A



——— Measured phase and gain corrected from rate to position input

– – – – Theoretical phase and gain assuming lead fully compensates for motion system lags

Fig 16 Frequency response of cockpit roll motion to bank angle

MOTION AND FORCE CUING REQUIREMENTS AND TECHNIQUES FOR ADVANCED TACTICAL AIRCRAFT SIMULATION

by

William B. Albery, Electronics Engineer and
Don R. Gum, Chief, Simulation Techniques Branch
Air Force Human Resources Laboratory
Advanced Systems Division
AFHRL/ASM
Wright-Patterson AFB, Ohio 45433
U.S.A.
and

Gerald J. Kron
Senior Staff Engineer
Link Division, Dept 495
Singer Company
Binghamton, New York 13901
U.S.A.

SUMMARY

The approach being pursued by the U.S. Air Force to advance motion and force cuing technology for tactical air flight simulators is twofold. The first part includes efforts directed towards building a data base on which to base motion and force cuing requirements. The second part includes efforts to improve the performance of existing devices that have been shown to be somewhat effective and to develop new devices and techniques as indicated by the data base efforts. The data base development involves looking at the pilot who receives motion and force cues and the aircraft and environment which impart the motion and force cues. Models of human motion and force sensory mechanisms (vestibular, tactile, visual, and nonvestibular proprioceptive) describing how motion is perceived have been developed and the motion and force environment for tactical aircraft performing various maneuvers is being characterized. The results of these efforts are being used to define motion and force cuing requirements and concepts for new devices to impart the necessary cues. Cuing device development efforts include the development of the next generation g-cuing (g-seat, g-suit, and buffet) system with improved response and onset cuing capability; techniques for myoelectric control of visual simulation system brightness and field-of-view as a function of the g-force environment and pilot physical action; and designs for systems such as arm, thigh, and head loading devices to provide for simulation of the extremely high-g flight environment.

In this paper, the following symbology is used:

g = denotes sustained acceleration $1g \cong 9.8 m/sec^2$
ms = milliseconds
Hz = cycles per second (Hertz)
ASUPT = Advanced Simulator for Undergraduate Pilot Training
SAAC = Simulator for Air-to-Air Combat
ALCOGS = Advanced Low-Cost g-Cuing System
F-4E18 = F-4E simulator, number 18
STARS = Simulation and Training Advanced Research System

1. DATA BASE DEVELOPMENT

In the motion and force simulation area, like most all technology areas, a fundamental knowledge base is required in order to be able to make intelligent decisions concerning the need or requirement for and the design of various cuing devices and techniques. Our current data base is inadequate in terms of knowing precisely what kind of motion cuing is required for various flying training tasks. Although our knowledge base, necessary for designing a device once a requirement has been established, has improved considerably over the past few years, additional data are required in several areas. Several efforts are under way to help fill these knowledge gaps by better describing the motion and force environment and better understanding how a pilot senses and utilizes motion and force information.

1.1 Motion Sensory Mechanism Modeling

In order to obtain a better understanding of how a pilot senses and utilizes motion and force information in flight, an effort was initiated in early 1976 to investigate and to develop and/or refine models of the more prominent motion sensory mechanisms. This work stimulated and sponsored by the U.S. Air Force Human Resources Laboratory (AFHRL) is being performed under the direction of Dr. Laurence Young of the Massachusetts Institute of Technology. This effort has resulted in the development of a unified, or composite, model for motion and orientation perception which integrates four sensory modalities including: vestibular, visual, nonvestibular proprioceptive, and tactile (Figure 1). The individual models are in various states of refinement and validation, with the vestibular model (semicircular canals and otolith) being the most understood and refined, the visual model next most developed, and the tactile and proprioceptive models being initial first cut models. Although there are still gaps in our knowledge of the various sensory modes and considerable experimental data collection and model validation remaining to be done, it was felt that there was currently enough information available to put together a first attempt unified perception model (Ref. 1).

The individual component models are largely physiologically based, and in order to produce a composite perception model, the physiological had to be related to the psychological. The biological control processor, which integrates information from the various sensors, is considered to function in a manner similar to an optimal estimator. A natural choice for the psychophysical function part of the model was a Kalman blending filter.

The model development effort, in addition to producing a first attempt unified model, has identified a number of deficiencies in the motion and force psychophysical data. The National Aeronautics and Space Administration (NASA) Ames Man-Carrying Rotational Device (MCRD) is currently being used to gather data on the threshold of rotational motion. The advanced g-cuing system described later in the paper as well as an in-flight simulator will be used to obtain additional human tactile and pressure receptor data. Also experiments have been designed to provide data on the relation and interaction of visually and proprioceptively induced motion using a wide field-of-view visual system in concert with a platform motion system.

1.2 Motion and Force Environment Characterization

Another important part of the effort to develop an adequate data base has been to obtain data on the motion and force environment to which the pilot is subjected and data on the aircraft/pilot interaction. Efforts are underway to obtain motion and force characterization data at the pilot station on fighter/attack aircraft for various flight maneuvers using ground based engineering simulations. In addition, data are to be collected on aircraft/pilot interaction, such as body contact pressure and loading and body movement within the cockpit through the use of an instrumented in-flight simulator. Special pressure sensitive seat overlays will be developed and cameras are to be installed to record the aircraft/pilot interaction. Various maneuvers will be flown in the aircraft while these data, as well as data on subject's perceived orientation, are being recorded.

1.3 Visual/Motion Time Delay Experiments

Visual/motion cue correlation problems have been encountered in the development of advanced Air Force training simulators for the T-37B and F-4E aircraft (Ref. 2). These problems have been traced to excessive time delays inherent in motion and force cuing devices such as the first generation six degree-of-freedom synergistic platform motion system and the first generation pneumatic g-seat. Approximately 10-50% of the total cue correlation problem was also attributable to low computational iteration rates. Total simulator delays, as measured from initial control input to observed acceleration output on the motion device, ranged from 200-400 milliseconds (ms). In some cases this resulted in the motion cuing lagging the visual cuing by as much as 100-200 ms. The low iteration rate delays can be easily cut in half by additional computer power, but the cuing system delays caused by excessive cue build-up time in the software drive algorithm and the device hardware itself presented more formidable problems. Obviously to provide effective visual/motion correlated cuing the response of these systems had to be improved and efforts including the development of a new, more responsive g-seat were undertaken in late 1975.

While it was obvious that the response time of g-cuing devices had to be improved, little data were available on the amount of visual/motion mismatch that could be tolerated and how much improvement was necessary. To gain more insight into and to help quantify this important design parameter, a series of experiments using some unique laboratory equipment has been designed. The experiments are intended to determine the effect of various amounts of motion-following-visual cuing delay on roll-axis tracking performance. The device being used is a single axis roll motion system with a narrow field-of-view visual display. The plant dynamics of the system are similar to the roll dynamics of a high performance fighter aircraft. The motion/visual asynchronization range being used in the experiments is from zero to 300 ms with delay conditions of zero, 80 ms, 200 ms, and 300 ms. Also a static or no motion condition is being used. From preliminary data, a delay of approximately 200 ms appears to produce tracking performance equivalent to the no motion condition. A delay beyond 200 ms appears to produce performance degraded over the no motion conditions. Best performance occurred as expected with zero delay. From these early results it appears that the motion-following-visual cuing tolerance should be in the range of 50 to 100 ms. More details of the experiments and the results should be documented and available during mid-1978.

1.4 Applications of Technology Base Data

The unified motion and force sensory model is being used to give researchers insight into which sensory mechanisms are being stimulated and to what degree under various flight conditions. The results of this effort are being applied to the development of new motion cuing hardware and drive techniques such as the advanced g-seat described later in the paper. Figure 2 shows the sensory model in a flight condition being stimulated by simulated aircraft forces and moments at the top of the diagram and stimulated by forces and moments from a simulation through various cuing devices at the bottom of the diagram. Use of the model as shown in this example permits a comparison of the perceived motions and forces as created by an aircraft simulation directly and by various cuing hardware and drive concepts driven by a simulation. Through such a process involving selective experimentation with existing or proposed simulator hardware/software, an optimum match of perceived orientation in the aircraft and simulator can be achieved.

Just because certain motions and forces are present and perceived in flight does not necessarily mean that they are important in performing or learning certain flying tasks. The motion and force characterization effort in addition to providing information for cuing system design is essential for performing task analyses to identify cuing requirements. The motion and force profiles that are being generated for various aircraft on a maneuver by maneuver basis are to be used as an aid in performing task analyses. These data profiles will allow the analysis to be conducted on a more objective basis helping the pilot/analyst reconstruct or recollect the cue environment.

2.0 MOTION AND FORCE CUING DEVICE DEVELOPMENT AND REFINEMENT

The first generation six degree-of-freedom synergistic platform motion systems were used with transport aircraft simulators in their first training simulator field application. Their low response characteristics when coupled with the dynamics of these transport aircraft simulators did not create a significant cue correlation problem. The first generation g-seat was designed for the fighter and trainer type of simulator, but primarily as a sustained cuing device. Its response delays were similar to those of the synergistic motion system (Ref. 2). It was felt however, from the early sensory mechanism modeling work, that the g-seat could be an effective onset cuing device. Since the g-seat interfaces with the most responsive sensory mechanisms, the tactile and pressure receptors, it can be argued that it should be the most responsive of the g-cuing devices. Improved platform motion systems and an improved g-seat capable of onset cuing were felt to be essential developments necessary to satisfy the motion and force cuing requirements of high performance fighter/attack aircraft. In addition, other high-g augmentation devices appeared to offer benefit for providing the complete motion and force environment necessary for tactical flight training.

2.1 The g-Seat

The first generation g-seat pictured in Figure 3 was developed for AFHRL by the Singer Company during the development of the Advanced Simulator for Undergraduate Pilot Training (ASUPT) (Ref. 3 & 4). It was developed for sustained cuing during basic airwork and aerobatic flight in the T-37B training aircraft simulator. The cuing philosophy was to provide onset acceleration cues with a six degree-of-freedom platform motion system and then to blend in the g-seat cues to sustain the acceleration effect. The seat was designed with research flexibility in order to investigate the simulation of tactile, pressure, and skeletal posture associated cuing resulting from flight-induced body g-loading.

The approach selected involved the use of seat cushions composed of mosaics of pneumatically activated elements in which the elevation of each is individually controlled by the drive philosophy programmed into the simulator's computational system. It is therefore possible to change cushion attitude, elevation, and contour with the same mechanical system. The g-seat also employs a variable-tension lap belt to apply pressure in the abdominal area of the pilot during negative g and/or braking conditions. The g-seat drive philosophy primarily addresses the localized flesh pressure changes and tactile perceived area-of-flesh/seat contact changes, skeletal attitude shifts and their impact on eyepoint perspective, and flesh scrubbing associated with sustained g conditions. Experimentation with this seat indicated that not only were the sustained g stimuli presented by the seat employed positively by pilots in the control of the simulated aircraft, but in moving from one acceleration magnitude to another, a form of acceleration onset information was provided to the pilot. Two g-seats were built for the ASUPT which were the first of 29 similar "First Generation" g-seats built or currently under construction for use by the U.S. Air Force and Navy and the Swedish Air Force.

2.2 The g-Suit

The g-suit cue represents an excellent example of apparent pilot g-level assessment by way of association. The g-suit is employed in tactical aircraft to counter blood pooling in the lower extremities during high-g conditions. A predominant early perception experienced by the pilot, well before any blood restricting effects materialize, is a tactile perception associated with the pressure induced by the g-suit. The pilot appears to associate this perception with increased g loading. Providing a similar experience within the simulation by inflating operationally issued g-suits according to the simulated flight g loading produces a very strong g loading cue for pilot utilization. Equally important is the fact that this cue is made available by a device which is present in the actual task, and, therefore, visual environmental fidelity is maintained within the simulation.

2.3 Limitations and Ranges of g-cuing Devices

The successful introduction of the g-seat within the training and tactical aircraft simulation environment was an extremely significant milestone in terms of mid-range g-level cuing. However, just as the motion system has its limitations, so does the g-seat. As previously mentioned, the g-seat confines its physiological stimuli production to the pilot/seat inertial coupling area. It makes no demands upon the pilot other than to sit in the seat and buckle the strapping used in the seat and in the actual aircraft, thereby maintaining visual environmental fidelity. As a consequence of this approach, pressure buildup in the back/buttocks area is limited to that obtainable from the 1-g weight of the subject himself as modulated by variation in the shape of the flesh-supporting surface. Neck muscular stimuli associated with g loading of the helmet and head are limited to those available by changing the attitude of the torso so that the 1-g gravitational weight of the helmet/head loading varies neck load. Displacement of body extremities through interplay of the skeletal structure and cushion surface attitude is limited to that range of attitudinal change which is compatible with the tactile and pressure cuing being delivered. Inertial load buildup in the arms and visceral effects and their perceivable by-products cannot be provided.

A limitation identified with the first generation g-seat is its low bandwidth (less than 1 Hz). Because of this low bandwidth, it is impossible for the pneumatic g-seat to pass high frequency acceleration cues such as buffet. Furthermore, in the absence of a platform motion system whose principal purpose is to track and reproduce the leading edge of an acceleration profile, it is almost impossible for a low bandwidth pneumatic g-seat to present onset acceleration cues in a tactical aircraft simulator. This limitation was recognized soon after the development of the g-seat for the ASUPT.

Two studies were initiated in 1975. The objective of the first study was to improve the g-seat's pneumatic control system by investigating a closed-loop air bellows/servo valve arrangement. The bandwidth employing feedback techniques was extended to approximately 3 Hz, but displays enough overshoot to warrant continued control system investigations. The objective of the second study was to investigate a simpler, low cost g-seat configuration. Using dual celled air bladders for the seat pan and a single celled bladder for the backrest, a much simpler g-seat was simulated on the ASUPT g-seat. This emulation on the ASUPT was quite effective and resulted in the recommendation for a different approach to g-seat geometry for future seats.

2.4 Advanced g-Cuing System Development

Because of the response limitation of the first generation seat, and also g-suit and seat shaker devices, in 1976 the Air Force Human Resources Laboratory contracted with the Link Division of the Singer Company for the development of an advanced g-cuing system. The objective was to develop a simpler, more responsive g-cuing system for the tactical aircraft simulators.

Since the first generation g-seat was designed to provide only a sensation of sustained acceleration it employs a cuing philosophy which does not make use of transient onset cuing. This cuing philosophy has been well received for sustained cuing and, somewhat unexpectedly, it was found that a measure of onset cuing is delivered as a by-product of the sustained cuing philosophy. Nevertheless, ongoing work in sensory systems modeling indicates that improved tactile and pressure cuing should be attainable through more sophisticated transient cuing drive schemes. To support the development of transient motion cuing drive schemes, it was considered extremely important to be able to employ very responsive hardware as the starting point and then to experimentally degrade the response to that level wherein transient cuing concepts are noticeably and adversely affected.

With the foregoing desired hardware and drive concept improvements in mind, it was concluded that a g-cuing system research test bed was required in order to develop a g-cuing system with the optimum cost/capability tradeoff as well as specifications for future operational systems. Certain specific objectives were established for the development of a device called the Advanced Low Cost g-Cuing System (ALCOGS):

1) Bring seat, suit, and shaker together as one integrated system with common control.

2) Improve the response characteristics of primarily the g-seat, and secondarily the g-suit, over those existing in today's operational seat/suit systems.

3) Incorporate closed-loop servo operation in order to provide an accurate means for measuring system outputs which produce a given cue.

4) Investigate, develop, and embody within the final system mechanical concepts which improve the somatic cuing quality of the g-seat over that available in the first generation of g-seat approach.

5) Broaden the resultant hardware and software design to accommodate F-16-type tilt-back seat configurations as well as the more conventional upright seat configurations associated with the F-15 and other aircraft.

6) Attempt to design this system so as to lower the aggregate cost of a seat/suit/shaker system.

7) Build and deliver a system with the above characteristics as well as a software drive module to support further research and development.

The ALCOGS was delivered to the Air Force Human Resources Laboratory at Wright-Patterson AFB, Ohio and accepted in late 1977. Several pictures of the system are provided (Figures 4, 5, & 6). The most noticeable changes from the first generation g-seat are:

1) The departure from a mosaic element cushion approach, but the retention of cushion attitudinal and elevation change capability.

2) The implementation of thin cushion surface bladders for localized pressure and tactile area-of-contact stimuli generation.

3) Hydraulic actuator servo systems to provide the desired response characteristics.

4) Adoption of passive rather than active seat pan thigh panels.

5) The implementation of lower backrest radial elements to provide strong area-of-contact cues for vertical and longitudinal acceleration.

6) Differential lap belt drive for inclusion of lateral as well as longitudinal and vertical belt cuing.

7) The addition of a seat pan longitudinal degree of freedom cascaded on seat pan cushion pitch, roll and heave.

The ALCOGS g-seat cushion assemblies are mounted in a replica of the F-15 seat frame which in turn is mounted on a test bed frame which can either be inserted into a laboratory version T-38 simulator cockpit or left free standing external to the cockpit. The seat frame is supported on the test bed frame by linkages which permit the seat to be oriented at any angle of inclination between that employed by the F-15 and F-16 seats. The seat frame is pinned to the test bed so as to permit the frame to be vibrated by a seat shaker actuator at $\pm$ 1/2 g in the 4.5 - 40 Hz range. Buffet and other vibratory effects may be displayed by the seat frame shaker or, alternately, the seat pan cushion itself. The suitability of the latter will determine if the role of the seat frame shaker may be absorbed by the g-seat and if the seat frame shaker system can be totally eliminated from future g-cuing systems.

The g-suit features a press-to-test and pressure/g instructor input which are handled all-electronically rather than by mechanical and software means, respectively. A high volume pneumatic servovalve design serviced by compressed air and vacuum provide more rapid suit pressurization and exhaust than that available, for example, in the suits built for the Simulator for Air-to-Air Combat (SAAC) and the F-4E18 simulator.

Similar to many motion system installations, the ALCOGS is supported by an electronics control cabinet which houses the electronics associated with the system control logic and the sixteen servo loops. The electronics control cabinet permits system operation in a "maintenance" mode wherein the servos may be driven manually, or by two software drive modes: one wherein system control is maintained at the location of the electronics cabinet and a second wherein system control is transferred to a remote location such as a simulator instructor/operator station. The electronics cabinet employs two variable frequency oscillators to permit the generation of superimposed vibratory effects at any frequency in the 4.5 to 40 Hz region. A discrete "bump" channel is further superimposed upon the vibratory output. The electronics cabinet also controls the activity of the system pumping station wherein hydraulic, pneumatic compressor, vacuum pumps, and associated reservoirs are located.

The primary design problems faced were centered in the g-seat system and in two areas: system response and packaging. The g-seat specification called for seat pan and backrest cushion excursion of 6.35 cm and a rise time of all servo actuators of 30 ms or less. The latter implies a system bandpass of 10 Hz or an order of magnitude larger than that available in the first generation g-seat. The bandpass objective necessitated the use of hydraulic actuators and, to ensure that hydraulic resonant frequencies are maintained well above the bandpass frequency, servovalve mounting in close proximity to the actuator.

Even more challenging, the same 30 ms rise time objective was sought in the cushion pneumatic surface bladders (firmness bladders) overlaying both seat pan and backrest cushions. A dual compartment (right and left) bladder is employed on a seat pan and a single compartment bladder is employed on the backrest. Although only 2.54 cm thick when inflated, these bladders represent significant volumes. Based on the function of the bladders, pressure and tactile area of contact stimuli generation induced by depressurization and resultant flesh contact with the undersurface supporting the bladders, it was felt the driving medium must be air. After considerable searching and testing, a two stage pneumatic servovalve assembly was developed which can handle the large air volume at the desired 30 ms rise time objective.

It is apparent that the response design objective required the utilization of servo actuators considerably more mechanically sophisticated than that employed in the first generation g-seat. System cost reduction could be realized, therefore, only if the cushion assemblies could be packaged in such a manner as to permit a broad application to many different seat styles with minimum redesign. A design objective then was to package the cushion assemblies within volumes commensurate with those occupied by the standard seat cushion survival kit, and parachute pack. This task was made difficult by the number of actuators employed, the fact that these actuators are hydraulic, the desire to keep actuator and servovalve in close proximity to one another, and the 6.35 cm cushion stroke requirement coupled with ram end cushion capability. The resultant design packages five servo systems in a backrest assembly which is approximately 38 x 53 x 9.5 cm in dimension. The seat pan assembly packages six servo systems in a volume approximately 38 x 38 x 15 cm in dimension. A modular design approach has been employed in the actuator assemblies themselves in order to permit actuator set up and service. The ALCOGS performance capabilities are shown in Table I.

TABLE I. ALCOGS PERFORMANCE CAPABILITIES

Component	Axis	Excursion	Response
Seat Pan	Roll, Pitch	±12°	10 Hz
	Heave	±3.175 cm	
	Fore-Aft	±2.54 cm	
Backrest	Pitch	±6°	10 Hz
	Yaw	±9°	
	Surge	±3.175 cm	
Seat/Backrest Bladders	Roll, Heave, Surge	2.54 cm	6 Hz
Seat Shaker	Heave	±.635 cm	34 Hz
Lap Belt	Fore-Aft, Roll	+3.81 cm	10 Hz

The ALCOGS system has been integrated with the Air Force Human Resources Laboratory Simulation and Training Advanced Research System (STARS) complex at Wright-Patterson AFB. It is being used in an engineering and psychophysical test, evaluation, and development program, with the primary objective being the determination of the optimum seat g-cuing hardware and drive algorithms for use in tactical aircraft simulators. The program will involve: (1) A complete characterization of the system performance by individual axes and combined axes to assess synergistic effects; (2) psychophysical evaluation of static and dynamic cuing capability using the full range of seat performance and initially postulated and implemented drive algorithms; (3) further development and refinement of drive algorithms using psychophysical experimental test and evaluation techniques (both sustained and onset algorithms for the conventional and tilt-back (F-16) aircraft seat configurations will be developed. The onset cuing algorithm development will investigate washout techniques to possibly extend the range of seat onset cuing capability); and (4) and investigation of the effects of degraded hardware performance (excursion and frequency response) on cuing capability. Also buffet induced through the seat pan versus buffet through the seat shaker will be investigated. The final product is to be a specification for minimum seat hardware and optimized drive algorithms to be used in the procurement of future seat cuing systems for operational tactical aircraft training simulators. These activities will be performed throughout 1978 and early 1979. This technology will be of prime importance to such simulator programs as the A-10 and F-16 and to future g-cuing system retrofit programs.

2.5 High-g Augmentation Device Study

As mentioned earlier, the g-seat may be considered a mid-range g-level cuing device. Newly developed tactical aircraft exercise a flight regime wherein high-g loading is more often experienced and the physiological stimuli associated with this condition may gain importance in aircraft maneuvering control patterns. Based on this, it is appropriate to commence consideration of the types of simulator systems which might provide high-g effect stimuli.

A combined Air Force Human Resources Laboratory/Massachusetts Institute of Technology/Link effort is currently studying potential force simulation systems in an attempt to identify those systems which:

a. Are likely to produce stimuli important to high-g maneuvering control,

b. are able to create encumbrances in the simulator equivalent to those experienced in the actual high-g flight environment, and

c. appear to be able to generate stimuli artifically in a 1 g environment by means which are safe and which are acceptable to operational pilots.

The current effort is a study leading to characterization of the type of hardware/software systems required to produce the desired end effect. The system characterization is to form the foundation for eventual construction of experimental systems to determine the adequacy and usefulness of the simulation stimuli source. Some of these potential devices are depicted in Figure 7.

The study will attempt to set forth the most reasonable methods of generating g loading stimuli in the following areas:

a. Shoulder harness

b. Head/helmet coupling

c. Limb loading

d. Aural effects

e. Visual effects

The effort in addition to addressing the above specific areas will investigate the potential of stimuli production via some of the following methods:

a. Body negative pressure

b. Respiratory control

c. Lacrimation control

d. Flesh pressure/temperature interrelationships

2.6 Myoelectric Control of Simulator Visual Displays

Myoelectric feedback techniques are also being considered for the tactical aircraft simulator pilot. The University of Dayton (Dayton, Ohio) is currently developing for the Air Force a method for myoelectric control of the simulator cockpit visual environment.

State-of-the-art training devices have the capability for dimming the visual display of the simulator as a function of positive g. This effect simulates the loss of vision pilots experience under very high, positive acceleration. The Simulator for Air-to-Air Combat (SAAC) is a good example of this technology. The problem with this simulation is that the pilot has no physiological control over the (1) intensity and (2) onset of this dimming in the SAAC. He cannot, for example, perform the M-1 maneuver (a straining and grunting action a pilot performs to increase his tolerance to high positive acceleration) and brighten the dimmed display; he has no direct means of affecting the display in the simulator other than unloading the simulated aircraft. In the actual aircraft, however, the pilot can control the loss of vision through the M-1 maneuver. The purpose of this effort is to develop a means by which pilot straining, via the M-1 maneuver, can be sensed through myoelectric signals and used in conjunction with a g loading to control the brightness level and field-of-view of the visual display and instruments in the simulator. Such a development should enhance the tactical air combat simulation and provide valuable training in pilot energy management.

This effort encompasses the design and development of a model implemented in software and associated hardware for the myoelectric control of acceleration induced dimming of the simulator pilot's visual display and instruments (Figure 8). To accomplish this, two algorithms are being developed. One will be a dynamic algorithm of the human visual system which will be driven by the pilot's g-environment. The other will be an algorithm to predict the effectiveness of the pilot's M-1 maneuver, which will be driven by electromyographic potentials from selected muscle groups. The outputs from these two algorithms will be integrated to drive a brightness and visual field-of-view for the visual display and cockpit instruments. The integrated system will be implemented at the AFHRL STARS facility on the T-38 simulator. If successful, the system may be implemented on the SAAC and other Air Force tactical simulators.

CONCLUSIONS

Data base development efforts which are in process have provided a better understanding of the type of motion and force cuing required for U.S. Air Force tactical aircraft simulators and the type of devices necessary to effectively and efficiently provide this cuing. An advanced g-cuing system has been developed which provides both rapid onset and sustained cuing. It is capable of stimulating the important tactile and pressure, as well as some nonvestibular proprioceptive, human sensory modalities throughout the frequency spectrum and for the duration of motion and force cuing presented during most tactical flight maneuvers. High-g augmentation devices are also being investigated and designed which should efficiently provide some of the additional cuing present during extremely high-g flight environments.

REFERENCES

1. Borah, J., Young, L., Curry, R. Sensory Mechanism Modeling, Oct 1977, AFHRL-TR-77-70

2. Gum, D., Albery, W. Time Delay Problems Encountered in Integrating the Advanced Simulator for Undergraduate Pilot Training, Journal of Aircraft, Vol. 14, No. 4, April 1977, pp. 327-332

3. Kron, G. Advanced Simulation in Undergraduate Pilot Training: g-Seat Development, Dec 75, AFHRL-TR-75-59(III), AD-A017 468

4. Gum, D., Albery, W., Basinger, J. Advanced Simulation in Undergraduate Pilot Training: An Overview, Dec 75, AFHRL-TR-75-59(I), AD-A030 224

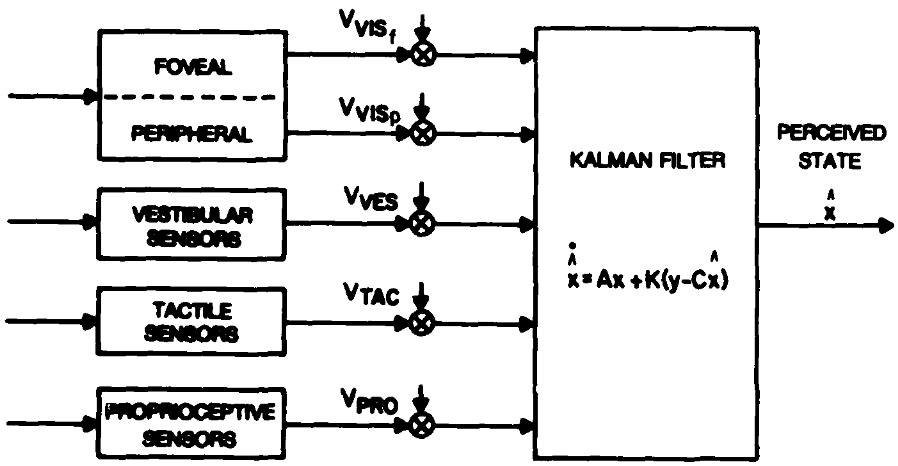


Fig. 1. Composite Sensory Model. The unified model for motion and orientation perception integrates the four sensory modalities at the left via a Kalman Filter.

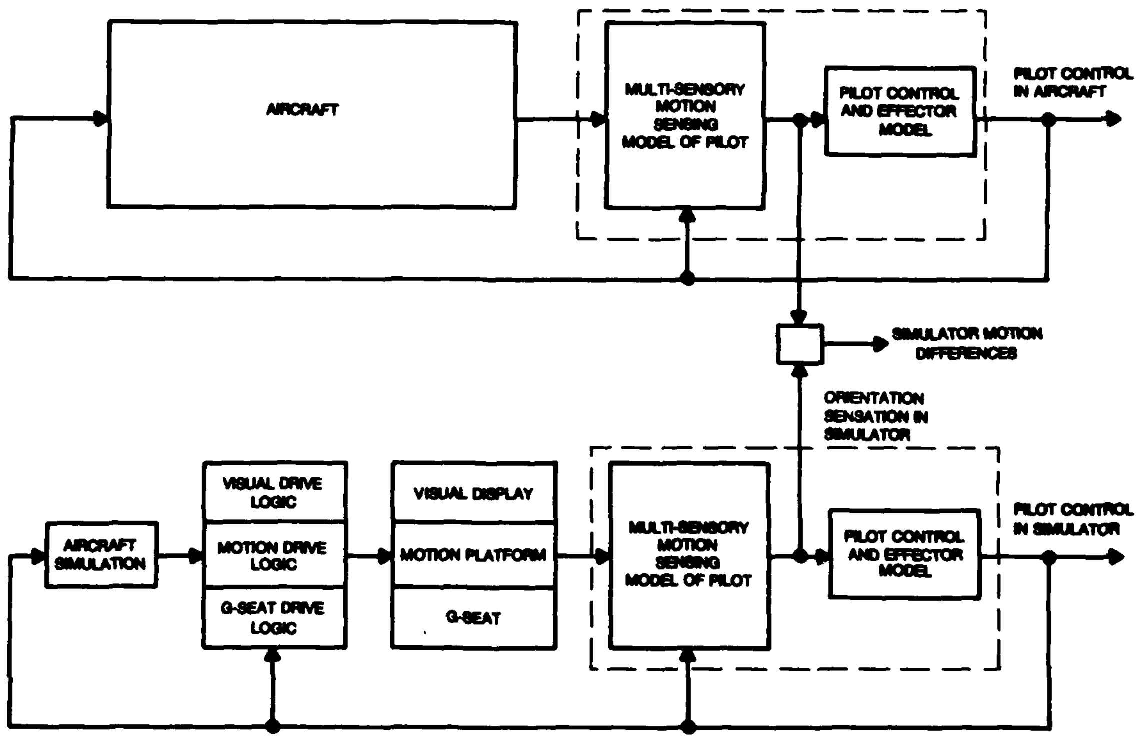


Fig. 2. Sensory Modeling Approach to Simulator Planning. Differences of pilot perception in the actual aircraft (at top) and in a simulator (bottom) can be examined more realistically provided a human sensory model exists (dashed box). Such a model permits a comparison of the perceived motions and forces as created by an aircraft simulation directly and by various cuing hardware and drive concepts driven by a simulation.

Fig. 3. First Generation g-Seat. Developed for AFHRL by the Singer Co. - Link Division in 1971, this pneumatic g-seat which employs 16 movable plates (bellows actuated) in the seat pan and 9 in the back rest has been installed in U.S. Air Force and Navy and Swedish Air Force simulators.

Fig. 4. Advanced g-Cuing System. This second generation g-seat was also developed for AFHRL by the Singer Co.-Link Division and employs hydraulic actuators instead of pneumatic actuators for better response. The seat was developed for tactical aircraft simulators.

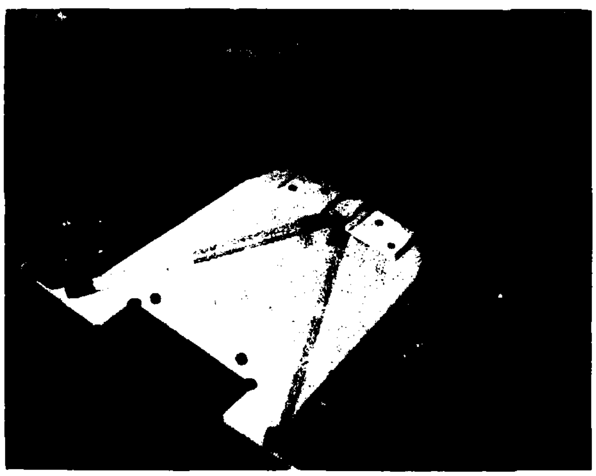


Fig. 5. Exposed Seat Pan of Advanced Seat. The advanced seat pan and backrest planes are driven in roll, pitch and heave. Inflatable rubber bladders overlay these planes. The seat pan has passive thigh ramps (pictured) and tuberosity stimulating blocks.

Fig. 6. Advanced g-Seat Exposed. The slip covers and firmness cells have been folded back to reveal the seat pan and backrest planes. The backrest also has left and right radial elements which are flaps at the base. These elements stimulate the lower back.

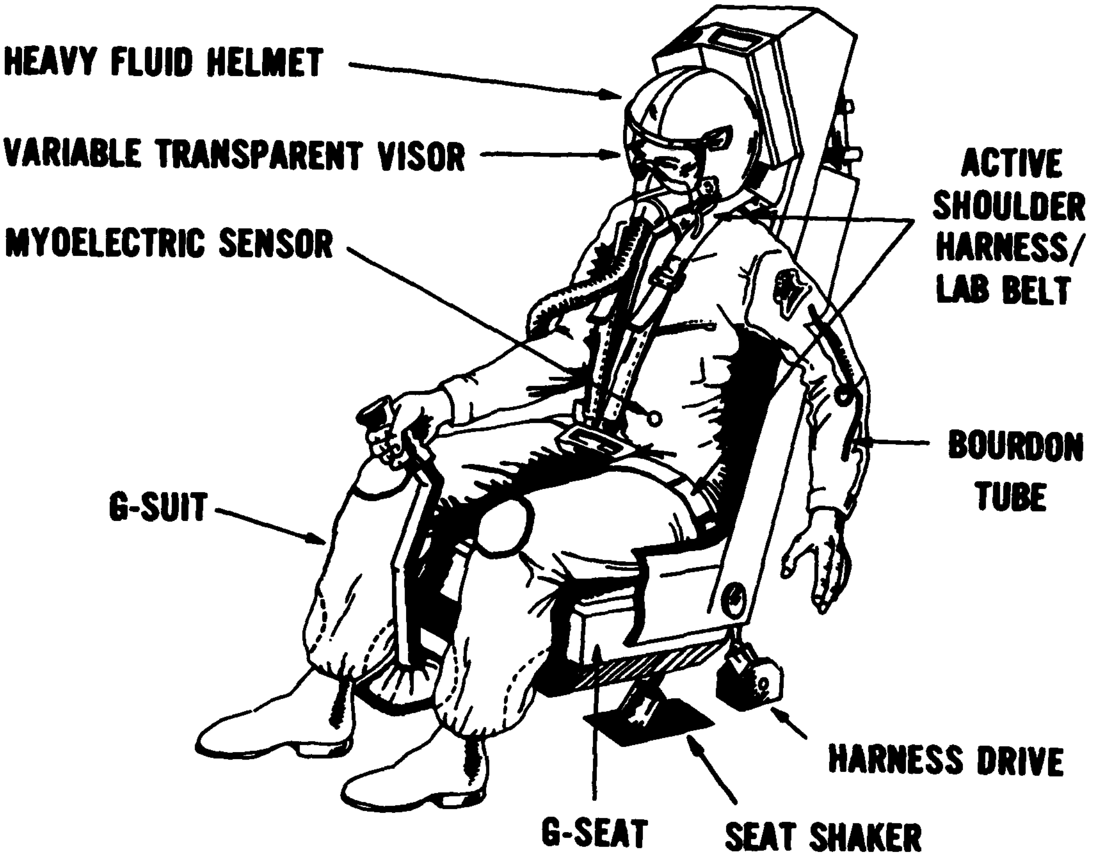


Fig. 7. Future High-g Simulation Devices. Devices other than g-seat, g-suit and seat shaker devices are being designed for the tactical aircraft simulator environment. Mechanisms for loading the helmet, limbs and torso of the pilot are shown above.

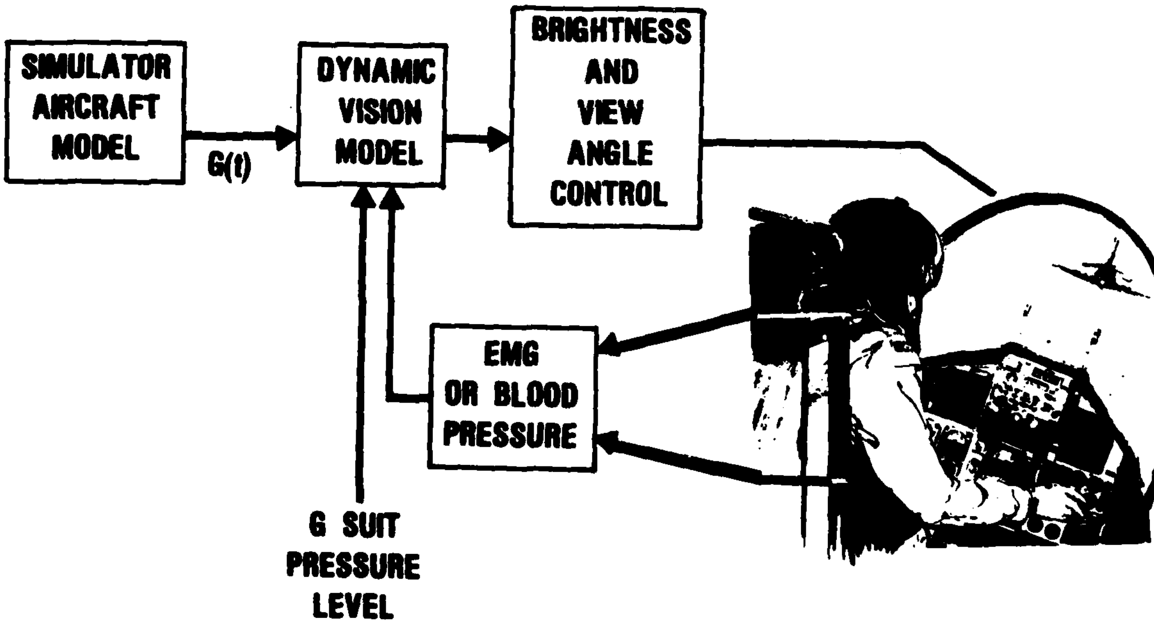


Fig. 8. Electromyographic Feedback Control of Simulator Visual System Dimming. A more realistic method of simulating the physiological effects of increased g is being developed by AFHRL. The simulator pilot is in the loop and can control dimming or loss of his display by virtue of how well he performs the M-1 maneuver.

INFLUENCE OF MOTION WASH-OUT FILTERS ON PILOT TRACKING PERFORMANCE

by
M.F.C. van Gool
National Aerospace Laboratory NLR
Anthony Fokkerweg 2
1059 CM AMSTERDAM
The Netherlands

SUMMARY

An investigation has been carried out on the NLR moving base flight simulator to establish the influence of the simulator motion wash-out filters in the pitch and roll axis on the performance of four pilots when stabilizing an aircraft disturbed by turbulence in either of these axes. For this compensatory tracking task, pilot describing functions, remnant spectra and other performance measures have been determined.

The results lead to the conclusion that, for the task under consideration, no significant differences can be observed when the break frequency of the (linear second-order) wash-out filter is varied from 0.1 rad/sec to 0.5 rad/sec. However, performance in either condition is considerably better when compared to fixed-base results. This is also reflected in the pilot comments and effort ratings, stating that the task is easier with motion.

1. INTRODUCTION

It is generally acknowledged that motion cues have an important effect on performance in manual control of aircraft. For that reason many flight simulators are provided with complex and expensive motion systems to present the motion cues to the pilot.

To make optimum use of a motion system, it is necessary to know which motion quantities must be simulated and with what fidelity. This is not a simple matter, because it depends on several factors of which can be mentioned:

- the simulated aircraft dynamics
- the task the pilot has to perform
- the sophistication of the outside view.

Moreover motion may influence one pilot in a different way than the other.

In a flight simulator, the motion cues are very dependent upon the way in which aircraft motion is translated into simulator cockpit motion, or in other words which motion wash-out filters are used. The influence this will have on pilot behaviour is expected to be task dependent, so it is important to specify the task. Since the majority of the investigations in a flight simulator are experiments involving approach and landing, the task of stabilizing aircraft attitude disturbed by turbulence has been selected for study.

This paper presents the results of the investigation in a condensed form. More detailed information is presented in reference 1.

2. HUMAN MOTION PERCEPTION AND WASH-OUT FILTERS

Due to the limited motion capability of a flight simulator, it is only possible to simulate certain aspects of the aircraft motion. Which aspects of motion must be simulated depends on the motion perceptive properties of the human which have certain limitations.

Motion is assumed to be perceived mainly through the vestibular organs consisting of semicircular canals and utriculae. Moreover proprioceptive cues play a part in motion perception. For a detailed description of the properties of vestibular organs, which is considered to be outside the scope of this paper, one is referred to the literature (e.g. reference 2). For the present experiment it is important to note the following:

For the rotational degrees of freedom (pitch, roll and yaw) the subjective impression of rotation is assumed to be linearly related to the rotational <u>velocity</u> for frequencies important in manual control of aircraft (0.2-10 rad/sec). Thresholds are involved below which the human cannot perceive rotation, which are believed to have the following magnitudes:

pitch threshold : 3.2 deg/sec
roll threshold : 2.6 deg/sec
yaw threshold : 1.1 deg/sec.

Moreover the human can perceive direction and magnitude of the specific force, being the difference between force due to body acceleration and due to gravity. A specific force due to an acceleration of 0.1 m/sec^2 is supposed to be the threshold value for perception in the translational degrees of freedom.

The above-mentioned limitations in human motion perception are used in motion simulation in two ways.

A. To make optimum use of the simulator motion capabilities, only the onset of motion is simulated after which the simulator returns to its mid-position with a rate (or acceleration) below the human perception threshold. Moreover the time during which components of the force of gravitation along the body X and Y axes exist when pitch and roll angles are different from the mid-position is reduced. In frequency domain terms this means that only the high frequency part of rotational motion is simulated. High-pass "wash-out" filters are used for this purpose.

B. Use is made of the component of gravitational force existing in longitudinal or lateral direction through angular tilt of the simulator cockpit to simulate forces due to longitudinal or lateral aircraft acceleration. The rotation to the desired pitch or roll angle must be carried out with a rate not perceivable by the pilot. In frequency domain terms this means that only the low frequency part of translational motion is simulated. Low-pass filters are used for this purpose.

In this paper the attention will be focussed on the high-pass wash-out filters in the pitch and roll axis mentioned under A.

3. LITERATURE

Several researchers have tried to establish a pilot model that could account for measured effects of motion on pilot behaviour. A very comprehensive literature survey on the effects of motion on pilot models has been reported in reference 3. The approach taken in references 4 and 5 has been to include physiological models of motion sensors in a pilot model using classical servo analysis techniques (pilot describing functions, crossover model). Only recently vestibular models have been incorporated in the optimal control model of the human operator (Refs 3, 6).

Information of particular relevance to the study of wash-out filter influence on pilot control behaviour in a disturbance regulation task is contained in reference 5. The influence of variation of the first-order motion wash-out filter time constant in the roll axis between 0.5 and 2 seconds on pilot performance was part of the investigation. Only little influence on pilot performance was observed although differences in the effects on the three subjects existed. It must be kept in mind, however, that these conclusions were based on one run carried out per pilot for each wash-out filter time constant (0.5, 1 and 2 seconds). In reference 3 this experiment has been analyzed with the optimal control model and wash-out filter variation did not lead to changes in the performance indicators either.

Two differences exist between these experiments and the circumstances for the NLR flight simulator. In reference 5 the roll motion was accompanied by lateral translations to minimize false specific forces accompanying nonzero roll angles in the simulator. The NLR simulator does not have this lateral degree of freedom. In reference 5 first-order linear wash-out filters have been used whereas in the NLR flight simulator second-order linear wash-out filters are used. For second-order filters the phase error at low frequencies is much higher than for first-order filters.

Because of these differences it was decided to carry out an experiment to investigate the influence of wash-out filter characteristics on pilot behaviour in a disturbance regulation task for the circumstances existing at the NLR flight simulator. Description of pilot behaviour has been carried out in the classical frequency domain terms because in earlier experiments on command-type pitch attitude tracking for different motion environments favourable experience with this technique had been obtained (Ref. 7).

4. HUMAN PILOT DYNAMICS

Pilot models have been developed based on classical servo analysis techniques, which assume that the pilot adjusts his dynamic behaviour to the dynamics of the controlled element in such a way that the closed loop of pilot and aircraft shows the properties of a "good" servo system. This is a.o. expressed by good regulating properties over the frequency band of interest and adequate damping.

A model that has been very successful in describing pilot-vehicle behaviour for a wide range of dynamic properties of the controlled element is the "crossover model" which states that the pilot always adjusts his dynamic behaviour, Y_p, to the dynamics of the controlled element, Y_c, in such a way that the expression for the dynamics of the pilot-vehicle combination has the following form:

$$Y_pY_c = \frac{\omega_c}{j\omega} e^{-j\omega\tau_e}$$

in which ω_c = crossover frequency (frequency where $|Y_pY_c|$ goes from > 1 to < 1).
τ_e = effective time delay (combined delay of pilot and vehicle).

This model is restricted to frequencies in the neighbourhood of the crossover frequency. Its most salient feature is the -20 dB/decade slope of the magnitude curve at crossover frequency. Apart from crossover frequency, indicating the bandwidth of the servo system, another important measure is the "phase margin" φ_m, being the phase angle at crossover frequency plus 180 degrees. It indicates control loop stability, a small value corresponding to a small value of the damping of the system.

For the current "state of the art" in applying the crossover model and its adjustment rules, one is referred to reference 8.

5. EXPERIMENT

5.1 Tracking task

The task the pilots had to perform was to keep the aircraft pitch and roll attitude error as small as possible while the aircraft was disturbed in either the pitch or the roll axis. The principle of this situation is indicated in the block diagram presented in figure 1. Coupling terms in the mathematical model of the aircraft between aircraft pitch and roll axis were removed so all attitude deviations in the undisturbed axis were caused by the pilot himself (crosscoupling). In practice crosscoupling was negligible so the tasks can be regarded as single loop compensatory tracking.

Description in the frequency domain means that the aircraft is represented by the transfer function of aircraft attitude over stick inputs at the trimmed condition Y_c. The pilot is described as a quasi-linear system consisting of

1. describing function Y_p, representing the linear part of his response behaviour
2. remnant, representing the difference between the actual pilot response and the response based on the linear element.

5.2 Disturbances

A disturbance signal for this type of experiment must be unpredictable and generally low-pass filtered white noise or a random appearing sum of sinusoids with suitably chosen frequencies and amplitudes is used. The latter possibility has been selected because of advantages in the spectral analysis of the various signals in the control loop.

The disturbances have been chosen such that the pitch and roll attitude disturbance power spectra have a second-order low-pass shape with a cut-off frequency of 1 rad/sec and a root mean square value of 4 degrees in the pitch axis and 5.4 degrees in the roll axis.

5.3 Aircraft transfer functions

The simulated aircraft was a DC9-10 in the landing approach (trimmed condition, flaps 50 degr, landing gear down, approach speed 120 KIAS).

The full equations of motion were computed with an update rate of 20 Hz. For reasons explained in

section 5.1 the coupling terms between the pitch and the roll axis were removed.
The frequency responses of pitch and roll attitude to stick deflection have been determined and are presented in figure 2.

5.4 Flight simulator

The four degrees of freedom moving base simulator with simulated outside view of the National Aerospace Laboratory NLR has been used for the experiments. Elevator and aileron deflections were commanded through a side stick controller. This NLR-developed side stick controller is a moving type controller with a 2-gradient spring and a hydraulic damper for pitch and roll control. The simulated outside view consisted of the "above clouds" situation of a sharp straight division of the display in a white and blue part. The total field of view is 48 degrees in the horizontal plane and 36 degrees in the vertical plane. Superimposed on this picture was an aircraft-fixed red reference line which the pilot was supposed to keep as close as possible to the horizon (Fig. 3). The instrument lights were not illuminated so the only visual information for the pilot was the outside view. Of the 4 degrees of freedom of the motion system (pitch, roll, yaw and heave), the yaw degree of freedom was not used because it could influence the results of the roll stabilizing task.

A special feature of the motion system is its smooth operation, which is the result of the application of hydrostatic bearings in the hydraulic jacks, thus eliminating stick-slip phenomena.

5.5 Wash-out filters

The influence of the high-pass wash-out filters in the pitch and roll axis are investigated. These filters may have linear or non-linear properties. For simplicity, and because these kind of filters are widely used, in the present experiments linear second-order high-pass filters are used.

It was decided to vary only the break frequency of the filters and to keep gain and damping ratio unity so the filter transfer function was

$$H = \frac{s^2}{(s+\omega_o)^2}$$

in which s is the Laplace variable and ω_o the break frequency of the filter expressed in rad/sec. On the basis of comments of pilots in the check-out phase, variation of approximately half to twice the values of the break frequency normally in use at the NLR (0.25 rad/sec) has been chosen as investigation range. In each axis a fixed-base configuration has been added for comparison. This led to a total of 8 configurations (between brackets the value of the break frequency is indicated, (∞) standing for fixed-base):
Pitch: P(0.1); P(0.25); P(0.5); P(∞).
Roll : R(0.1); R(0.25); R(0.5); R(∞).

5.6 Experimental plan and procedures

The total number of 8 configurations has been evaluated by 4 pilots. Evaluating a configuration meant carrying out five familiarization runs and five evaluation runs of approximately 4 minutes each. In the familiarization phase the pilots were informed about their performance (root mean square attitude error and stick deflection) but no feedback of information was given in the evaluation session. The order in which pilots evaluated the configurations was randomized to eliminate effects of this order on the results.

After each evaluation run the pilots completed a questionnaire in which they were asked to rate on a 10-point non-adjectival rating scale the effort they had to spend to carry out the task.

6. RESULTS

6.1 Pilot describing functions

Pilot describing functions have been computed by deviding the Fourier transform of the pilot output (stick deflections) by the Fourier transform of the pilot input (attitude error) at the forcing function frequencies. Magnitude and phase show very small inter- and intrapilot differences for each configuration so the results are presented, averaged over the pilots (5 runs each) for the configurations in pitch in figure 4 and for the configurations in roll in figure 5.

No differences can be observed between pilot describing functions for configurations with wash-out filter break frequencies varying from 0.1 to 0.5 rad/sec. However, rather large differences exist between this group of moving-base results and the fixed-base pilot describing functions at low frequencies in the magnitude (higher gain with motion) and at high frequencies in the phase angle (less phase lag with motion) as illustrated by the lines connecting the points in the figures.

6.2 Remnant

Remnant is defined as that part of the pilot output signal not linearly correlated with the disturbance. For a disturbance composed of a sum of sinusoids, remnant is simply all power at frequencies different from the sinusoid frequencies. This closed-loop remnant spectrum can be considered as the result of a signal having a specific power spectral density injected into the control loop at the pilot input position.

In all cases these spectra have a second-order low-pass shape with a cut-off frequency in the neighbourhood of 1 rad/sec, which contradicts with the first-order shape most often observed in the literature. No consistent differences can be observed between remnant spectra for the different configurations, not even between fixed-base and moving base results.

6.3 Performance measures

The average open-loop describing function of the combination of pilot and aircraft Y_pY_c shows a -20 dB/decade slope for the magnitude curve in all cases, thus showing crossover model characteristics, and indicating that the pilot-aircraft system behaves as a "good" servosystem. System bandwidth indicated by the crossover frequency ω_c and system stability indicated by the phase margin φ_m are indicated for all configurations in figure 6.

From this figure no significant differences between moving-base configurations can be observed but crossover frequency is higher with motion than without and in pitch phase margin is smaller with motion than without.

Another measure of performance is the score which is defined as the factor by which the pilot has reduced the error variance

$$\text{score} = \frac{\sigma_e^2}{\sigma_d^2} \quad .$$

This measure has been computed for all runs and averaged over pilots the results are presented for each configuration in figure 6.

Obviously score is not influenced when the motion wash-out filter break frequency is varied from 0.1 to 0.5 rad/sec but fixed-base the pilot performance is much worse for the pitch as well as the roll stabilizing task.

A measure of how much effort it has cost the pilot to obtain this performance is indicated by his effort rating on a 10-point non-adjectival rating scale. For every pilot the ratings are transformed to standard normal form (zero mean, unity variance) to account for rating style differences. Averaged over pilots the normalized effort ratings are presented for each configuration in figure 6. A positive value means more than average effort.

The pilot effort for the configurations with a motion wash-out filter break frequency of 0.5 rad/sec and fixed base is higher than for the configurations with a break frequency of 0.1 and 0.25 rad/sec.

Answers to explicit questions to the pilot regarding the perceived relation between motion and visual cues did not indicate that pilots were aware of gain or phase differences between what they saw and what they felt.

6.4 Pilot model

A more quantitative reflection on the influence of motion on pilot behaviour can be given by using a mathematical pilot model that approximates the describing functions. The most simple and often used pilot model has the following form:

$$Y_p = K_p \frac{(1+j\omega\tau_L)}{(1+j\omega\tau_I)} e^{-j\omega\tau_e}$$

in which K_p = gain
τ_L = lead time constant
τ_I = lag time constant
τ_e = effective time delay.

The parameters of the model that shows the best fit to the measured describing functions for each configuration, averaged over the pilots are presented in figure 7.

The following remarks can be made on the parameter values

- K_p: The values for the moving-base configurations do not show consistent trends but fixed-base the value is definitely lower.
- τ_L: The values for the moving-base configurations are about the same and fixed-base the value is almost twice as high.
- τ_I: The values are zero in all cases.
- τ_e: The values for the moving-base configurations are about the same and fixed-base the time delay in 0.15 (pitch) and 0.19 (roll) seconds higher.

7. CONCLUSIONS

The main conclusion that can be drawn from the results of the experiments is that pilot behaviour in an attitude stabilizing task in the pitch or roll axis is negligibly influenced by the break frequency of the second-order high-pass wash-out filter used in the pitch and roll axis. Obviously for the task under consideration pilots are not very sensitive for low-frequency gain and phase differences between what they see and what they feel. Still large differences are observed in pilot behaviour when comparing these moving base results with fixed-base results.

When looking at a frequency domain pilot model, motion as existing in the experiment has the following effect on the pilot model parameters as compared to the fixed base situation:

1. Increase of low frequency pilot gain combined with decrease of pilot lead.
2. Reduction of the effective pilot time delay. For the pilot-aircraft system this means higher crossover frequencies (system bandwidth) and better regulating properties (less error).

Furthermore the subjective impression of the pilots, as expressed in effort ratings and pilot commentary is that the task is easier with motion, but that no differences could be observed for different wash-out filter break frequencies.

8. REFERENCES

1. Gool, M.F.C. van, The influence of simulator motion wash-out filters on the performance of pilots when stabilizing aircraft attitude in turbulence. NLR TR 78022 U (1978).
2. Peters, R.A. Dynamics of the vestibular system and their relation to motion perception, spatial disorientation and illusions. NASA CR 1309 (1969).
3. Curry, R.E., Hoffman, W.C., Young, L.R. Pilot modeling for manned simulation Vol I. AFFDL TR-76-124 (1976).
4. Shirley, R.S., Young, L.R. Motion cues in man-vehicle control. Effects of roll motion on human operator behaviour in compensatory systems with disturbance inputs. IEEE Trans. on Man Machine Systems. Vol. MMS-9, No.4 (1968).

5. Stapleford, R.L., Peters, R.A., Alex, F.R. Experiments and a model for pilot dynamics with visual and motion inputs. NASA CR 1325 (1969).

6. Levison, W.H., Junker, A.M. A model for the pilot's use of motion cues in roll axis tracking tasks. BBN report No.3528 (1977).

7. Gool, M.F.C. van, Mooij, H.A. Human pilot describing function, remnant and associated information for pitch attitude control; results from in-flight and ground-based experiments. NLR TR 75062 U (1975).

8. McRuer, D.T., Krendel, E.S. Mathematical models of human pilot behaviour. AGARDograph No.188 (1974).

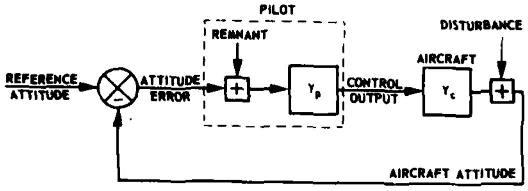


Fig. 1 Blockdiagram of the experimental situation

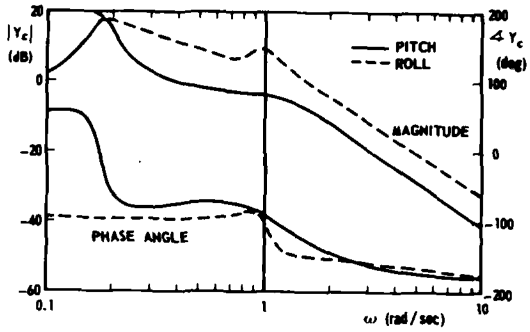


Fig. 2 Frequency response functions of the aircraft pitch and roll attitude to stick deflections

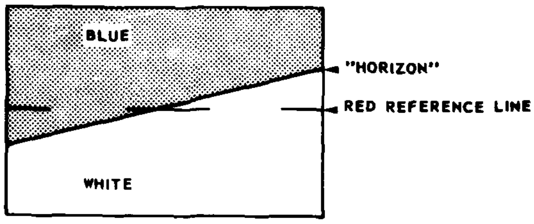


Fig. 3 Simulated outside view

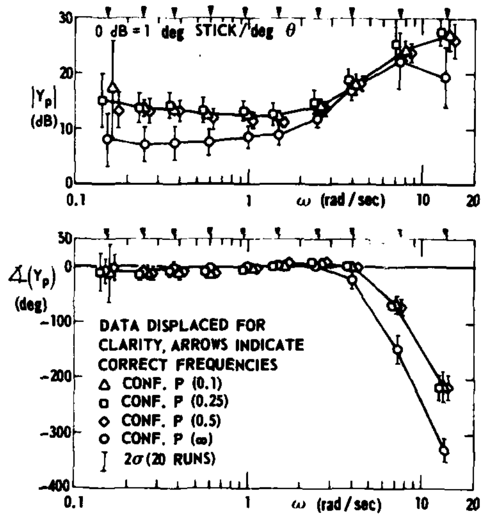


Fig. 4 Pilot describing functions for the pitch task, averaged over 4 pilots

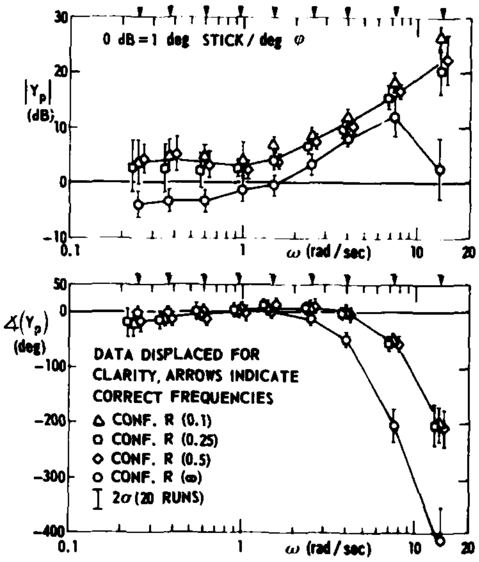


Fig. 5 Pilot describing functions for the roll task, averaged over 4 pilots

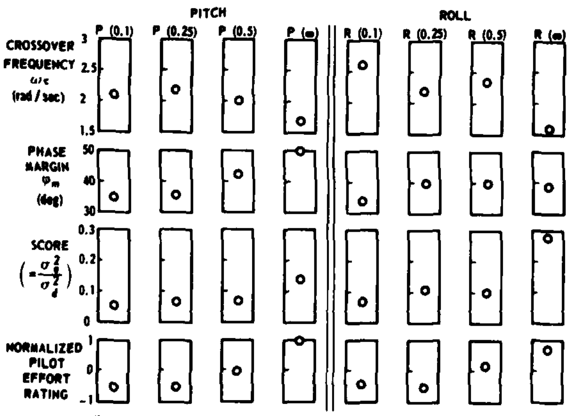


Fig. 6 Performance measures and pilot effort

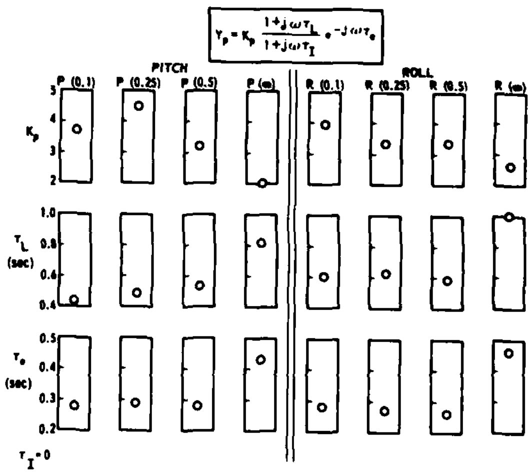


Fig. 7 Pilot model parameters

DYNAMIC CHARACTERISTICS OF FLIGHT SIMULATOR MOTION SYSTEMS

Paul T. Kemmerling, Jr, Lt Col, USAF
Director, Equipment Engineering
Deputy for Engineering
Aeronautical Systems Division
Wright-Patterson AFB, Ohio 45433

SUMMARY

Recognition is made of the complete lack of substantive data on the quality of motion produced by multiple degree of freedom aircraft simulator motion systems, and efforts made to produce this data are discussed. Working Group #07 of the Flight Mechanics Panel of AGARD has been given the charter to identify and define the pertinent physical characteristics of flight simulator motion systems, establish procedures for their measurement and prepare a report on their findings. The seven main characteristics identified by the Group are outlined, and efforts by several of the members to apply the characteristic techniques in laboratory measurements are discussed. Acknowledgement is made of the difficulties in establishing universally workable definitions and techniques for cataloguing motion characteristics, and alternatives are suggested. The conclusion is reached that a taxonomy of motion characteristics is a valuable asset in determining the optional use of currently available motion systems.

INTRODUCTION

In the last few years there has been a sharp rise in the number of simulation facilities employing multiple degree-of-freedom motion systems; however, until recently no substantive attempts to systematically measure the quality of motion produced by these devices have been made.

The Flight Mechanics Panel (FMP) of the Advisory Group for Aerospace Research and Development has maintained a continuing involvement in assessing the fidelity of aircraft simulation. Based on work performed by an earlier FMP Working Group on Approach and Landing Simulation and in recognition of the growing need for a common method of assessing motion quality the FMP, in September 1976, established Working Group #07 - FMP Working Group on Flight Simulation Motion Quality. The Working Group was charged with defining and determining metrics of the hardware-delivered performance of the various degrees of freedom of the motion system, etc. Because "quality" could be inferred to include a study of the drive algorithms of motion systems as well as the hardware-delivered performance, the Group suggested in May 1977 a change in its title to FMP Working Group on the Dynamic Characteristics of Motion Systems. The objectives of the group are:

1. To identify those physical characteristics of flight simulator motion generation systems that are important and significant in providing high fidelity realistic motion cues to the pilot.

2. To define the techniques and procedures most applicable for the accurate measurement of the important characteristics identified above.

3. To summarize experiences, problems and solutions encountered in the measurement of motion generation system characteristics according to the methods defined above.

4. To document complete quantitative data on the important characteristics of several simulation motion generation systems obtained using the recommended measurement methods.

5. To prepare a report summarizing the findings of the Working Group.

The scope of the Working Group includes giving attention not only to the "classical" characteristics of motion generation systems, such as maximum travel and bandwidth of operation, but also to characteristics expressing smoothness of motion and the levels of interaction between various degrees of freedom.

The purpose of this paper is to discuss some of the efforts of Working Group #07 and, in particular, outline the recommended definitive characteristics promulgated by the Group.

BACKGROUND

In recent months two United States facilities have conducted studies bearing on the assessment of motion dynamic characteristics. These facilities are the Franklin Institute Research Laboratories (FIRL) and the NASA Langley Research Center. The FIRL is currently under contract with the US Air Force to develop an improved hydraulic servo valve in order to reduce or eliminate the classic "turn around bump" which occurs in many motion systems when the platform slows down, stops, and changes direction. NASA

Langley has conducted extensive research on its six post motion system, with the principal emphasis on the development of improved software or drive algorithm techniques for a six degree of freedom motion system. NASA's contribution to motion dynamic characteristics has been restricted to improvement of the platform legs. In January 1977, the Department of Aerospace Engineering at Delft University, The Netherlands, published a pioneering study which brought into direct focus the need for the development of a universal understanding of flight simulator motion dynamic characteristics. The Delft study identified the characteristics of a motion system which determine the fidelity of motion cues as:

a. The performance limits in each degree of freedom.

b. The motion system describing function.

c. The power spectral distribution and RMS value of the acceleration noise in each of the various degrees of freedom of the motion systems.

The initial efforts of Delft included not only the identification of these characteristics, but also the development of generalizable procedures for measuring these parameters. This work has contributed significantly to the definitions and procedures described in this paper.

RECOMMENDED DEFINITIVE CHARACTERISTICS

Working Group #07 of the Flight Mechanics Panel has defined the need for the characterization of the engineering parameters that contribute to simulation motion system dynamic characteristics. Of particular concern are those characteristics that result in unwanted cues, whether correlated or uncorrelated with the command signals. These characteristics are:

a. Performance limits for single degree of freedom operation

b. Linearity

c. Describing function

d. Threshold

e. Backlash

f. Hysteresis

g. Noise

h. Jerk (included in g)

i. Smoothness (inverse of noise g)

Smoothness and jerk are two terms commonly used in discussion of motion quality. These are considered to be subsumed by (g) noise.

The Working Group has chosen the acceleration vector as the metric for a number of these characteristics, even though it is not the metric that is conventionally used for some of them such as threshold and backlash. There are several reasons for this choice:

1. The synergistic nature of several of the platform motion system designs makes accurate measures of displacement in the various degrees of freedom difficult, if not impossible.

2. Acceleration is the characteristic sensed by the pilot of a simulator.

3. Even if acceleration is not the input signal of the motion system, the input signal is computed from the desired acceleration.

This section describes each of the characteristics in terms of its definition, suggested measurement techniques and method of display. These characteristics were defined by Working Group #07 at its November 1977 meeting and form the basis for preliminary measurements by its contributing members.

a. Performance Limits:

Definition

Certain limits on simulator motion system performance are inherent in the basic engineering design. Displacement is limited by the usable length of stroke of the actuator. Velocity is limited by the maximum capacity of the servo valve. Acceleration (with rated load) is limited by the maximum available supply pressure. These inherent limits are further compromised by simultaneous combination of displacement, velocity and acceleration demands and, in some cases, by simultaneous motion in other degrees of freedom.

Measurement

There are two generally accepted methods for measuring performance limits. One isolates the inherent limits into their simplest form. In this case, measurements are made by applying the appropriate command signal (increasing displacement and step change in displacement) and recording the response with appropriate transducers.

The second accepted method for measuring performance limits is to apply a sinusoidal command signal which creates simultaneous demands for combinations of displacement, velocity and acceleration. The response is monitored with suitable instrumentation to indicate displacement, velocity or acceleration limits. The frequency of the sinusoidal command is set at a discrete frequency and the magnitude is increased until limiting of one of the variables is noted. This is repeated through the entire band of usable frequencies to define the limiting envelope.

Display

When performance limits are measured by isolating each variable: displacement, velocity or acceleration, they can be displayed simply in tabular form - typically as shown below:

	TRAVEL	VELOCITY	ACCELERATION
HEAVE	± .3 m	± 1. m/sec	+ 15. / - 28. m/sec^2
ROLL	± .28 rad ±16°	± 1.28 rad/sec ± 73 °/sec	± 19. rad/sec^2 ± 1090 $°/sec^2$
PITCH	± .27 rad ± 15.5°	± .9 rad/sec ± 50 °/sec	+ 5.5 / - 8. rad/sec^2 +315 / -460 $°/sec^2$

Table 1 - Performance Limits for Single Degree of Freedom Operation

When the performance limits are measured dynamically using a sinusoidal command signal, the results are displayed as a frequency dependent graph as illustrated below:

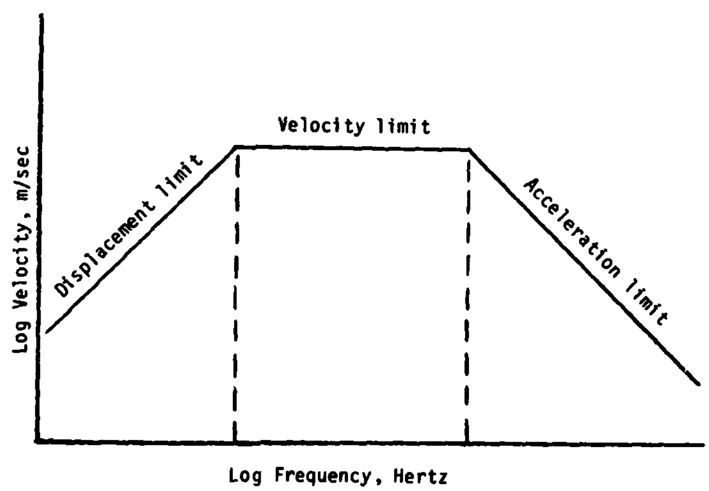


Figure 1 - Frequency Dependent Graph

b. Linearity (of Acceleration Step-Response)

Definition

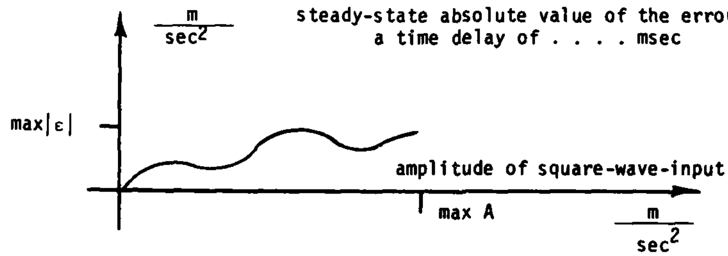
The linearity-error of acceleration is defined as the absolute value of the difference between a constant acceleration input and the measured steady-state acceleration output at the pilot's seat. This amplitude error may be plotted against the amplitude of the input acceleration. The maximum of this function is called the maximum absolute linearity-error.

Measurement

Most of the members of the Working Group reported difficulty with the measurement technique prescribed for linearity. As proposed, the measurement is made using a square wave function with variable amplitude as acceleration-input. The absolute value of the difference between input and acceleration-output at the pilot's seat is sampled at a constant time after up-or-down-going of the input signal and plotted against the amplitude of the input, which is varied very slowly from zero to the maximum acceleration. The output may be filtered with a first-order filter and a time constant which is not more than 10% of the time-delay. The problem with this measurement technique involves inherent differences in the method of reaching a "steady state acceleration output" and the Working Group is presently studying ways to clarify the issue.

Display

The constant time-delay for sampling the error must be given in milliseconds. The result is plotted as an xy-plot and scaled for both directions in $\frac{m}{sec^2}$:



The result can also be expressed in words in the following form: The maximum absolute linearity-error is less than .... percent of the maximum acceleration of .... $\frac{m}{sec^2}$ sampled at a constant time-delay of .... msec.

c. Describing function:

Definition

The transfer function or motion system describing function is defined as the ratio of the Discrete Fourier Transformed (DFT) measured output and input signal:

$$H(k) = \frac{X_u(k)}{X_i(k)}$$

$X_i(k)$ is the DFT of $X_i(n)$, being the sampled sequence of the specific force or rotational acceleration input equal in each degree of freedom, e.g., $A_{x_i}(n)$, $A_{y_i}(n)$, A_{z_i} + g) (n) or $\Psi_i(n)$, $\theta_i(n)$ and $\phi_i(n)$.

$X_u(k)$ is the DFT of the corresponding output signal, measured at the pilot's seat in each degree of freedom.

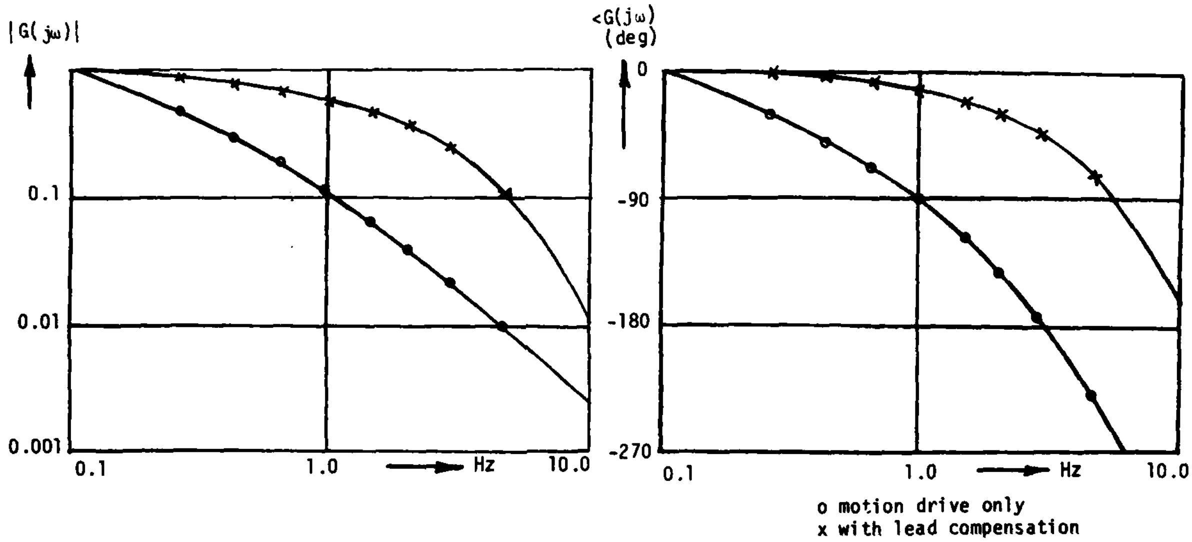
Measurement

The measurement is carried out: (a) for usable limits and (b) for 10% of performance limits defined in (a), at sufficient discrete frequencies to define the curves up to such a frequency that 90° phase lag or usable limit is obtained, using a sum of sinusoids as the input signal in each degree of freedom, spanning the frequency range of interest in that degree of freedom. The dynamic response characteristics are measured for motion drive only as well as with lead compensation and the describing function in each degree of freedom can be calculated at each of the input frequencies, after one measurement run.

Where coordinated axes are available (pitch and surge, roll and sway), the dynamic response characteristics shall be measured and the describing function computed, when both these axes are driven simultaneously.

Display

The test results are displayed in the form of Bode-plots showing the amplitude ratio G(jω) and phase angle G(jω) in each degree of freedom.



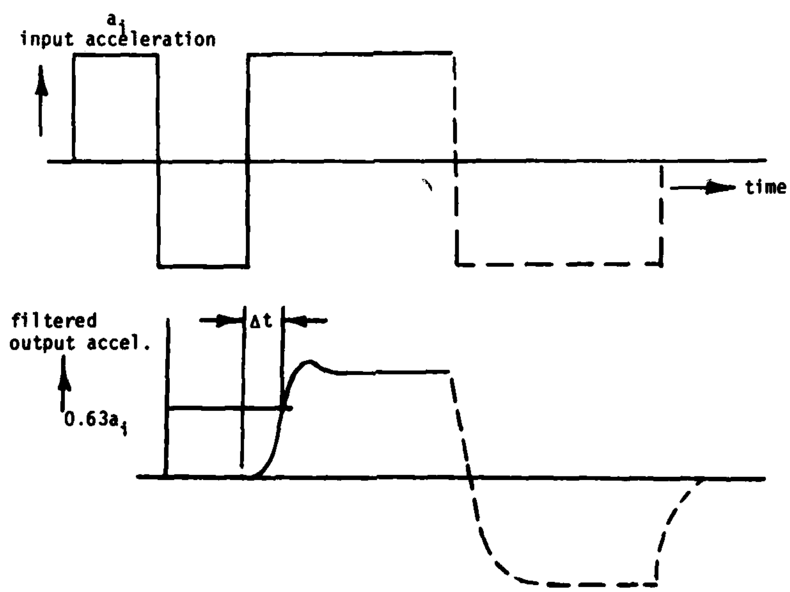
d. Threshold:

Definition

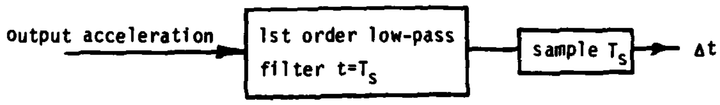
An indication for the threshold of a system is defined here as the time Δt required before the output acceleration to reach 63% of the input acceleration. This time Δt is an indication for the threshold of a system, whether it has a position or velocity threshold. The larger the time Δt the more threshold the system will have.

Measurement

An acceleration step input, from which the appropriate drive signal is derived, is used as input signal to the motion system in its neutral position. Δt is measured at several input acceleration levels in both directions. To remove the influence of backlash, the neutral position must be reached by means of a premeasurement square wave input as indicated below, prior to the measurement being given.

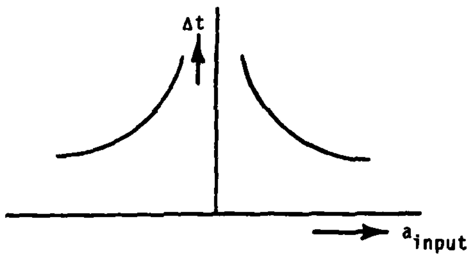


The output acceleration will be sampled with a sample time T_s being 1 msec, or if that is not feasible with T_s as small as possible. A pre-sample first-order lowpass filter with $t = T_s$ will be used.



Display

Δt is plotted as a function of a_{input}



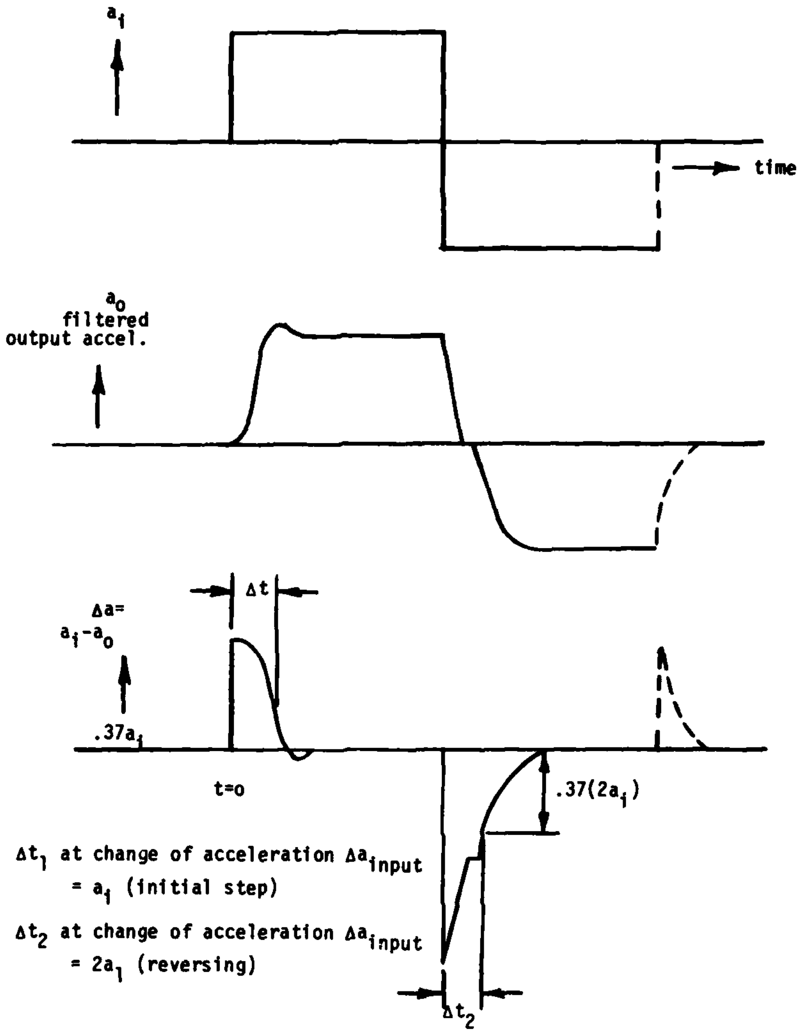
e. Backlash:

Definition

The Working Group was unable to arrive at a satisfactory definition of, and test for, backlash. This was primarily due to the deliberate choice of acceleration as the basic measuring unit (see page 2). "Backlash," as commonly understood, is a positional hysteresis characteristic of a mechanical system. Thus, measurement of its extent via acceleration at a point downstream in the system is compounded by inertial and friction effects. As a result the measurement technique prescribed often yielded "negative backlash." Although unsatisfactory, this technique is included here merely to make the later discussions of backlash more meaningful see page 11).

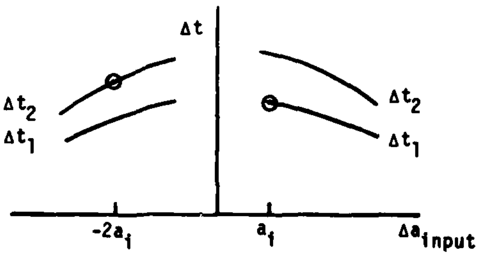
Measurement

An acceleration square wave is used as input signal to the motion system in its neutral position. The difference between the 1st and 2nd peak of the difference between input and output acceleration is a measure for the backlash. To eliminate the effect of static friction the motion system should have a small velocity (0.01 m/sec, 0.5°/sec) at its neutral position in the direction of the input displacement.



Display

Δt is plotted as a function of a_{input}



f. **Hysteresis:**

Definition

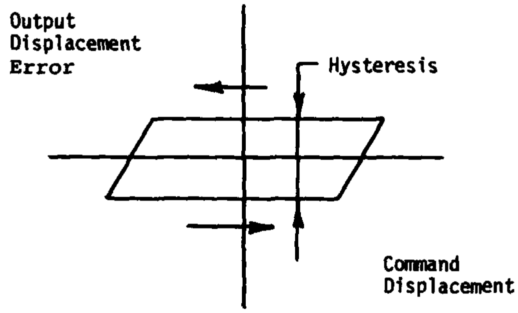
Hysteresis is defined as the difference in command displacement required to produce the same output displacement for different direction of motion. The result is expressed as an absolute displacement and as a percentage of total available displacement. This definition includes backlash of systems where backlash is not forced to one side due to gravity forces.

Measurement

The measurement is made using a very-low frequency (0.01 Hz) sinusoidal command signal to avoid the effects of dynamics. Amplitude is as great as possible before any limiting devices come into operation.

Display

The test results are recorded on an xy plot with equal calibration factors. The plot is in the form of a closed loop with the upper and lower ends being nearly straight lines.



If the hysteresis is small a plot for an amplitude of 10% of the maximum displacement will facilitate the measurement.

g. Noise:

Definition

Noise is defined as the perturbations from the nominal specific force and rotational acceleration output signals $x_u(n)$ (acceleration noise), being the IDFT of $X_u(k)$, which is computed from the product of $X_i(k)$ and $H(k)$:

$$X_u(k) = X_i(k); \quad H(k),$$

The acceleration noise includes:

1. The nonlinear static and dynamic output signals, which are correlated with the input (control error).

2. The uncorrelated output signals.

3. Jerk, due to coulomb friction or imperfect hydraulic servo valve characteristics.

Two kinds of acceleration noise can be distinguished:

- The acceleration noise in the stimulated degrees of freedom, e.g., heave acceleration noise caused by heave motion.
- The acceleration noise in the non-stimulated degrees of freedom, called parasitic acceleration, e.g. yaw, pitch and/or roll accelerations due to heave motion, expressing the levels of interaction between the various degrees of freedom.

Both the levels of the acceleration noise and the parasitic accelerations indicate the smoothness of the motions produced by a motion system in each degree of freedom. Therefore the smoothness will not be measured separately.

Measurement

The acceleration noise as well as the parasitic accelerations in the various degrees of freedom can be measured by means of linear and rotational accelerometers appropriately aligned at the pilot's position along the flight simulator X, Y, and Z axes, dependent on the number of degrees of freedom. The measurements shall be carried out for the following experimental conditions:

1. Motion off; motion system in rest position.

2. Motion on; motion system in neutral position.

3. Motion system moving at constant velocity.

4. Motion system following single sinusoids of .5 Hz with different amplitudes.

The results of the measurements will be expressed by means of:

- The standard deviations of the acceleration noise and parasitic accelerations as a function of motion system velocity in each degree of freedom.

- The peak values of the acceleration noise and parasitic accelerations in each degree of freedom.

The measurements will be carried out using the following priorities:

1. Measurement of heave ($\pm$ Z), other axes live but undriven

   Measurement of pitch, other axes live but undriven

   Measurement of roll, other axes live but undriven

   Measurement of yaw, other axes live but undriven

   Measurement of ($\pm$ Y) lateral, other axes live but undriven

   Measurement of ($\pm$ X) longitudinal, other axes live but undriven

2. Measurement of undriven pitch, with heave driven

   Measurement of undriven roll, with heave driven

   Measurement of undriven yaw, with heave driven

   Measurement of undriven longitudinal, with heave driven

3. Same as 2, except the remaining combinations of undriven axes with one axis driven.

Display

The test results will be displayed:

- For the measurements at constant velocity according to Figure 2, covering the velocity-range in each degree of freedom.

- For the sinusoidal measurements according to Figure 3 where the standard deviations and peak values at 10% of the maximum excursion in each degree of freedom will be shown.

The measurement point for the experimental conditions mentioned under 1 and 2 will also be shown in these figures.

PRELIMINARY SIMULATION STUDIES

One of the most difficult tasks before the Working Group was to define and establish measurement techniques that could be applied across a wide variety of motion systems and still produce some common denominator of quantitative judgment for each characteristic. For example, not all of the motion systems used by members of the Working Group operate in the same fashion. Most are operated as velocity servomechanisms, and others are position systems. While, theoretically, in the ideal system, one can use the driving computer to command velocity in a position system or vice-versa, the resulting motion will not be identical due to nonlinearities. Compensation of the motion systems tested is not applied in a uniform fashion. Compensation may be built into the motion system hardware, it may reside in a separate computer, or it may reside in the same computer used to solve the aerodynamic equations. In some cases, moreover, to remove this compensation would cause the motion system to operate in an unstable, or otherwise dangerous manner. Consequently, the Working Group decided that it could not specify that motion systems be tested in an uncompensated manner. Instead, all systems were tested with the least compensation possible.

During the course of the Working Group's efforts, several of its members conducted preliminary measurements in their own simulation facilities. Much of this work is a continuing effort and will be reported in full at the conclusion of the Working Group's activities; however, some examples of representative measurements are shown here in order to demonstrate the application of the characteristic techniques defined by the Working Group. Since hysteresis and backlash provided the most interesting results, the discussion will be confined to these topics.

The complete range of recommended measurements have been made by Mr. Staples and associates at RAE Bedford, on their three degree of freedom position-controlled simulator illustrated in Figure 4. Measurements were made on the basic system without any compensation, and the results recorded digitally for later analysis.

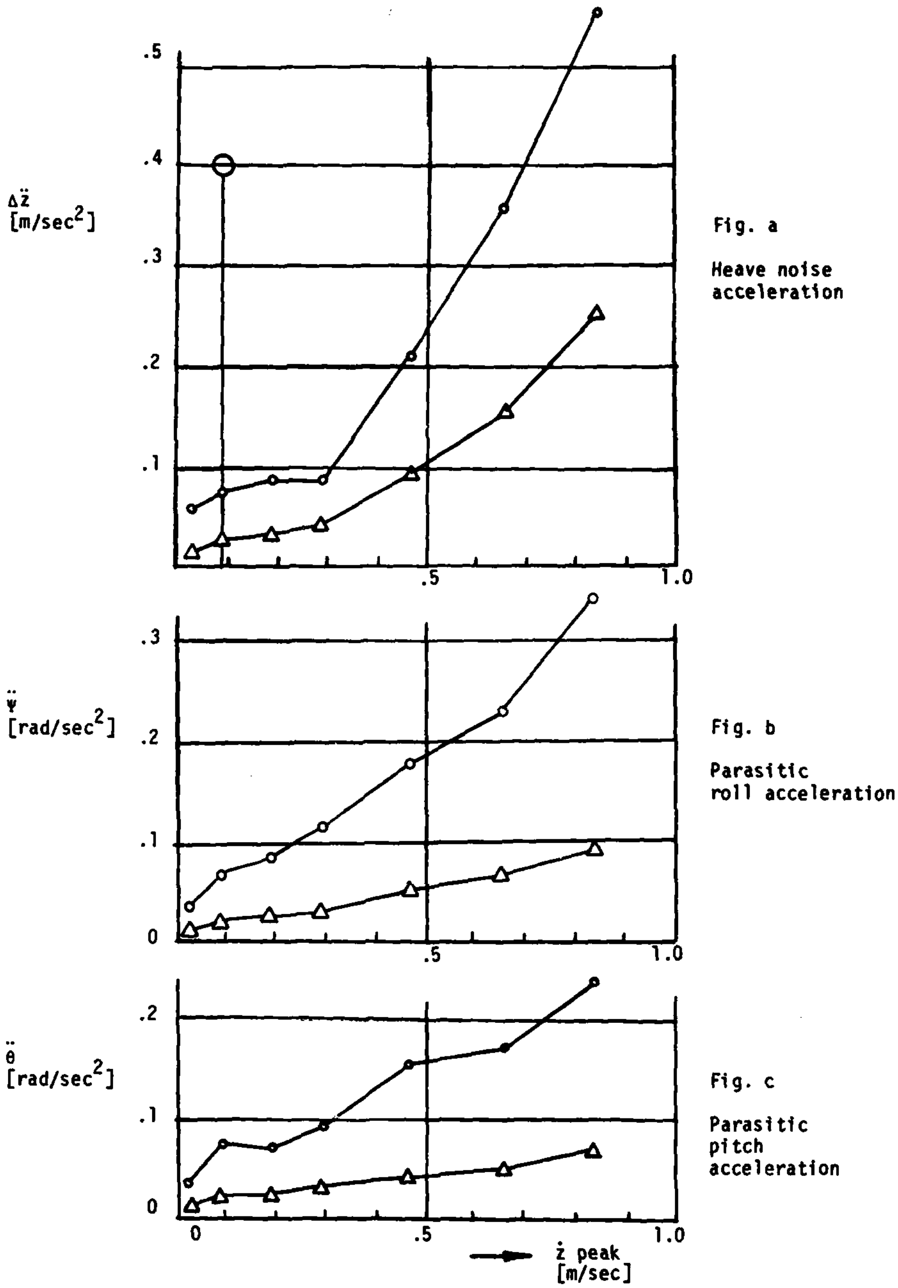


Figure 2 - Acceleration Noise and Parasitic Accelerations due to .5 c/sec Sinusoidal Heave Input Signal

Figure 5 shows their measurement of hysteresis. The Working Group has defined hysteresis as the difference in command displacement required to produce the same output displacement for a different direction of motion. It is apparent that the very small error of under .2% of full travel means that the method of measurement prescribed is not very revealing. Mr. Staples recommended that rather than display actual output, the output displacement error should be plotted against the input command, and the suggestion has been adopted by the Working Group.

Mr. Erdman and associates at DFVLR (Braunschweig [Figure 6]) measured hysteresis on their three degree of freedom velocity-controlled systems and had the same general results (Figure 7). Mr. Erdman noted that the characteristic is a quality which only seems to appear when very small accelerations and amplitudes are displayed, on the order of two or three powers of ten lower than the identification limits of human sensors.

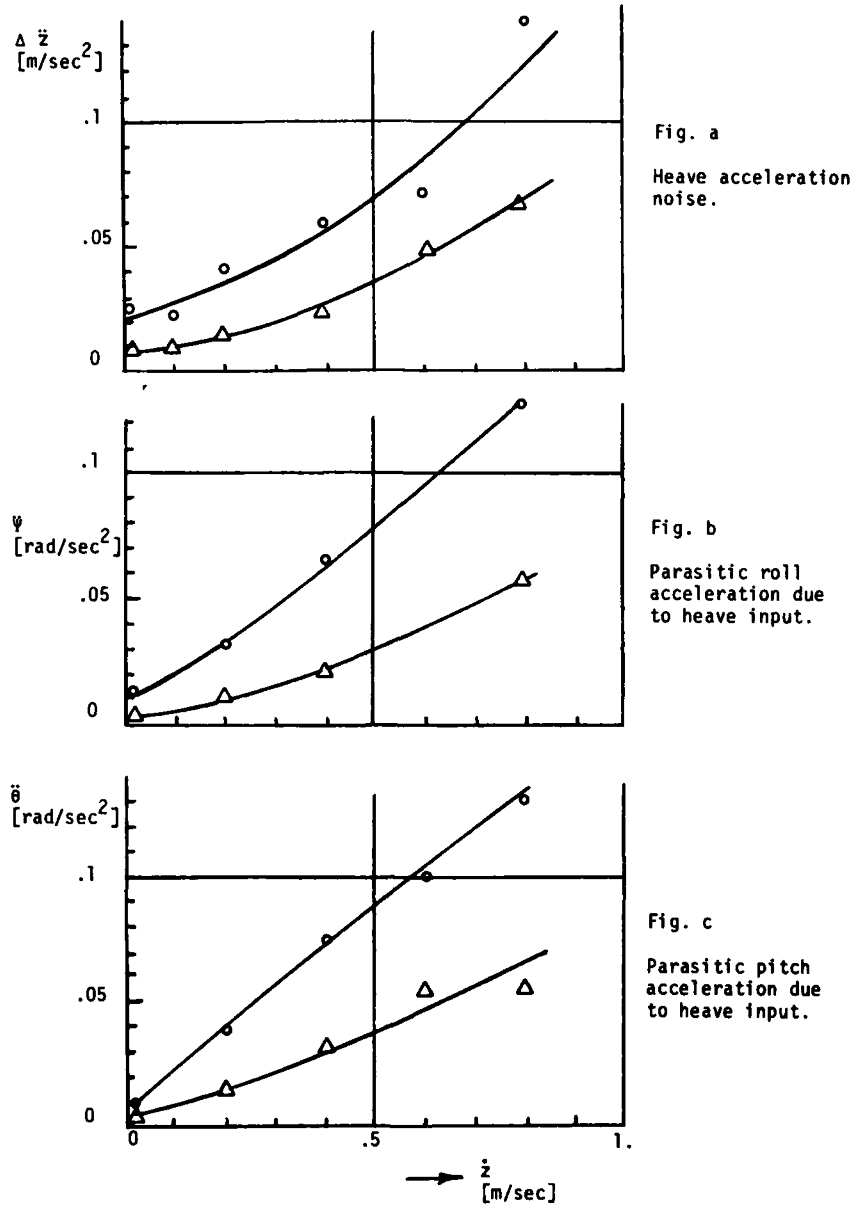


Figure 3 - Acceleration Noise at Constant Speed During Heave Excitation

Mr. Baarspul and others at Delft University measured hysteresis on their three degree of freedom compensated system (Figure 8). Their position measurements did not take place at the pilot's station because it was considered unfeasible to acquire an accurate position signal with separable linear displacement transducers, or gyros. Consequently, the Delft researchers measured the hysteresis of each actuator separately and converted the resulting values to hysteresis per degree of freedom. The Delft and National Aerospace Laboratory teams both recommended that better measurements of hysteresis could be obtained through the display of displacement error, rather than actual displacement.

Perhaps the most interesting characteristic measured was backlash, since all researchers but one reported anomalies in their results. In defining backlash, Working Group #07 assumed a system with backlash would continue to move with constant velocity at the moment that the input acceleration is reversed, until it has consumed the available backlash; from that moment the system will follow the input acceleration as system without backlash.

At NLR (Figure 9), Messrs Koevermans and Jensen explored the validity of these assumptions. Using their four degree of freedom motion system, they mounted a fixed accelerometer and one which could move with an adjustable backlash. For a backlash above one millimeter the expected theoretical behavior was recognized (Figure 10). However, at more practical values of backlash - for example .2 mm - the expected time delay was obscured by the effect of friction and/or structural dynamics. Contrary to the theory the time delays at reversal (referred to as T_2) were found to be shorter than the initial time delay T_1. See Figures 11 and 12.

Figure 4 - RAE Bedford Three Degree of Freedom Simulator

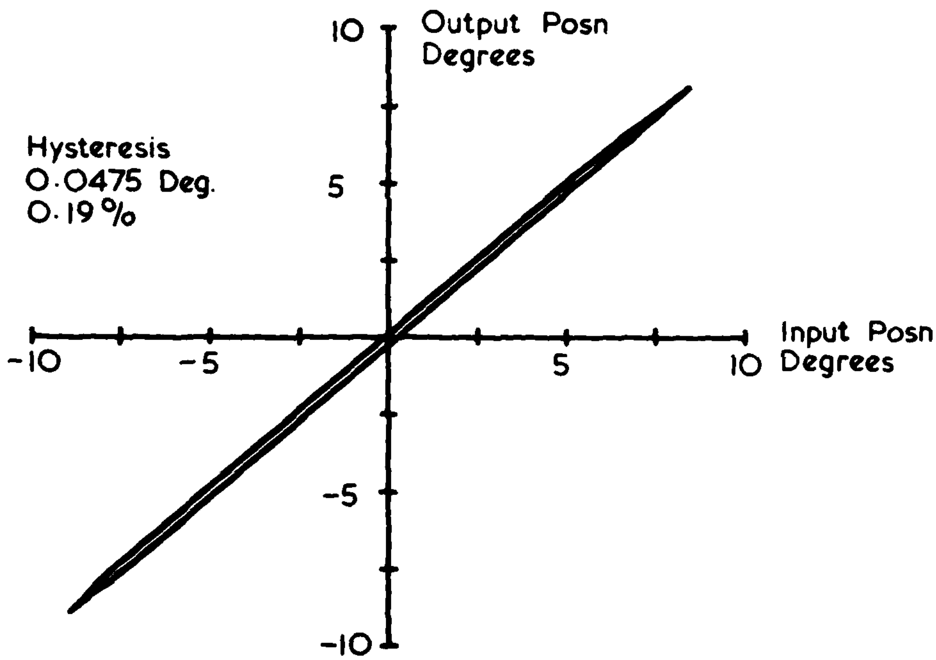


Figure 5 - Hysteresis in Pitch Axis

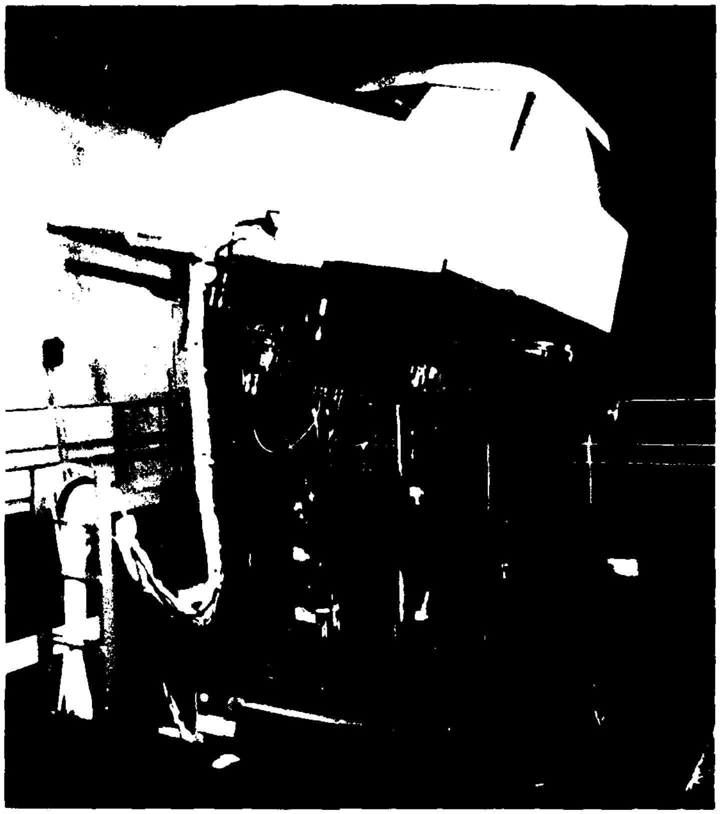


Figure 6 - DFVLR Three Degree of Freedom Simulator

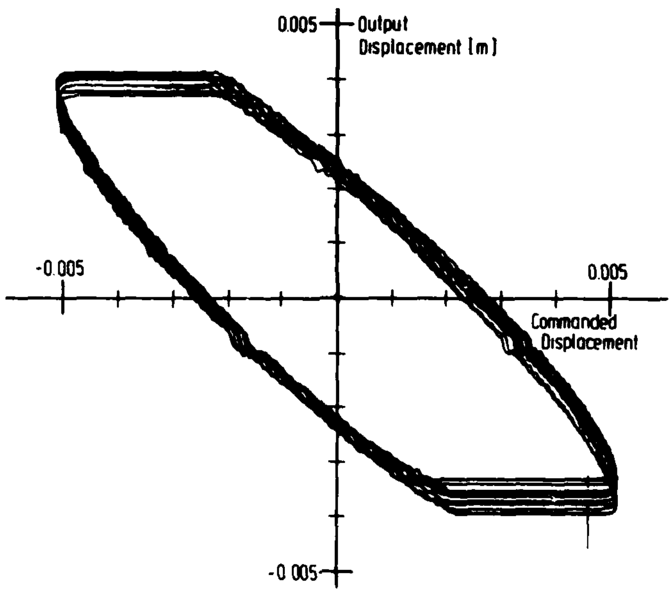


Figure 7 - Hysteresis of Displacement at .1 Hz

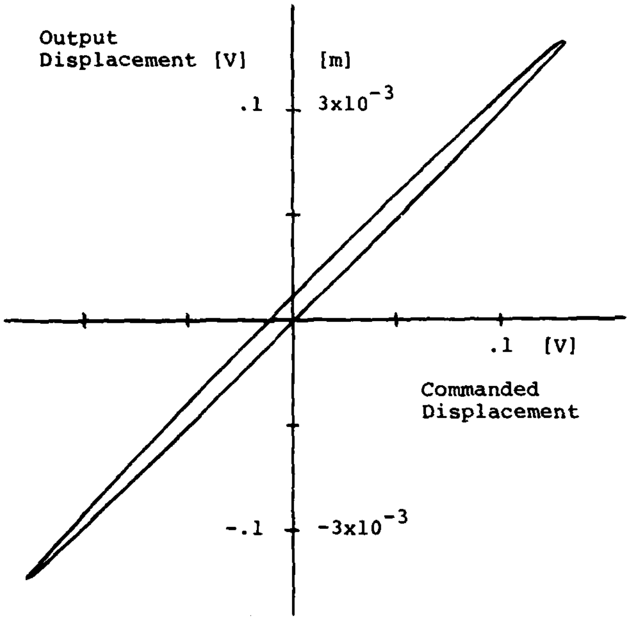


Figure 8 - Hysteresis Plot of R.H. Actuator of DUT Motion System

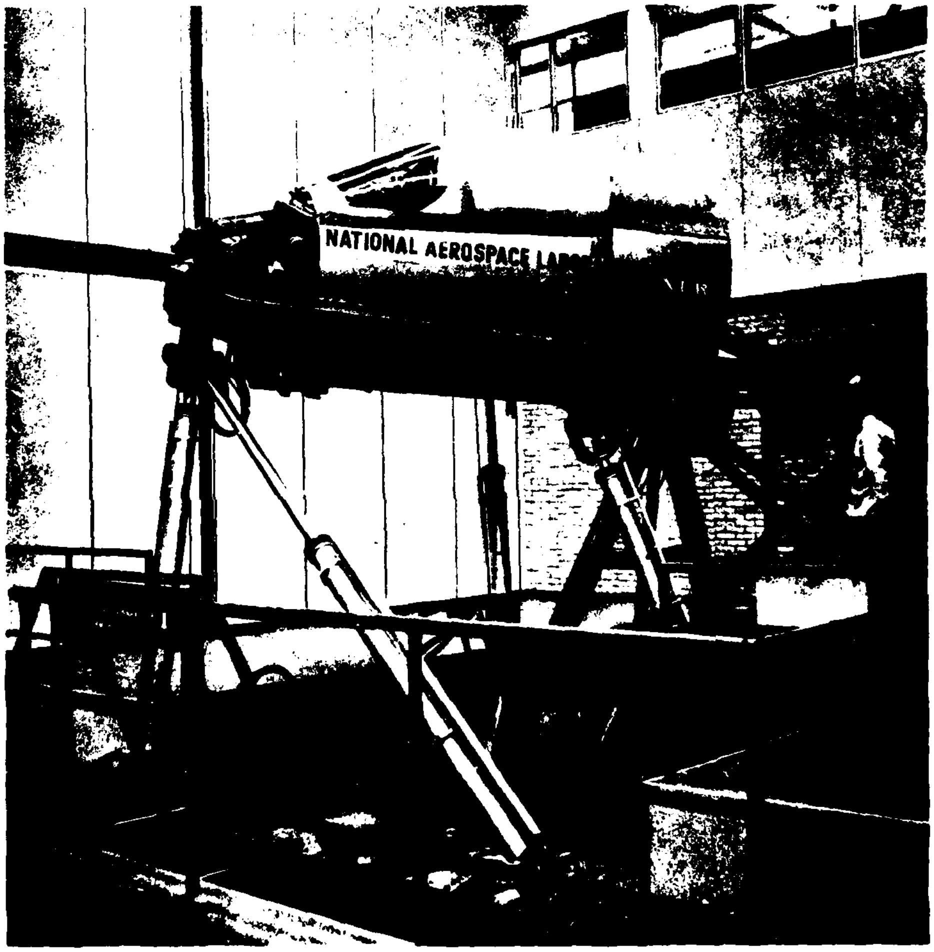


Figure 9 - The Four Degree of Freedom
Flight Simulator with Single Seat Fighter Aircraft

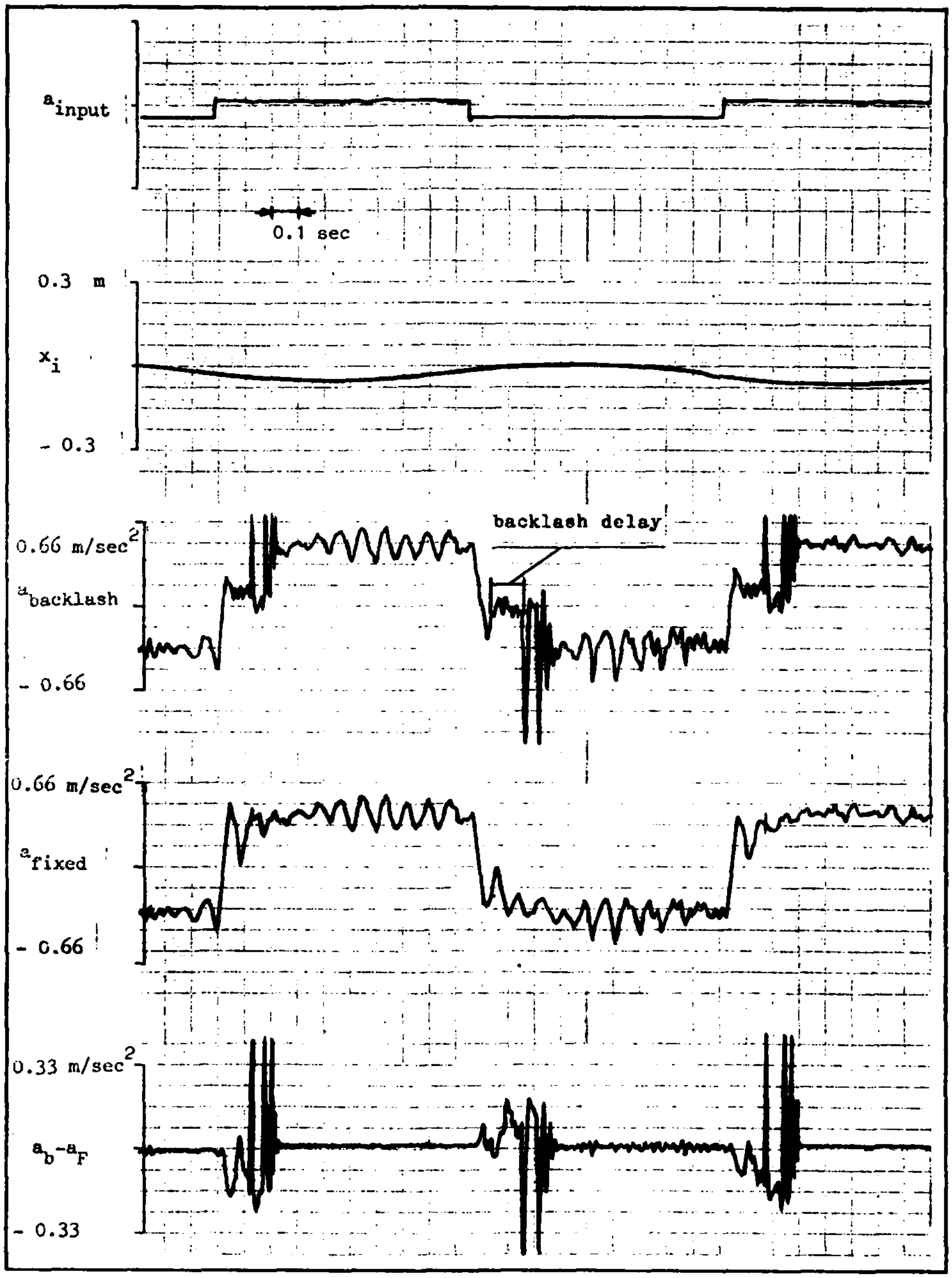


Figure 10

Acceleration Signals of a System with a Backlash of 2 mm

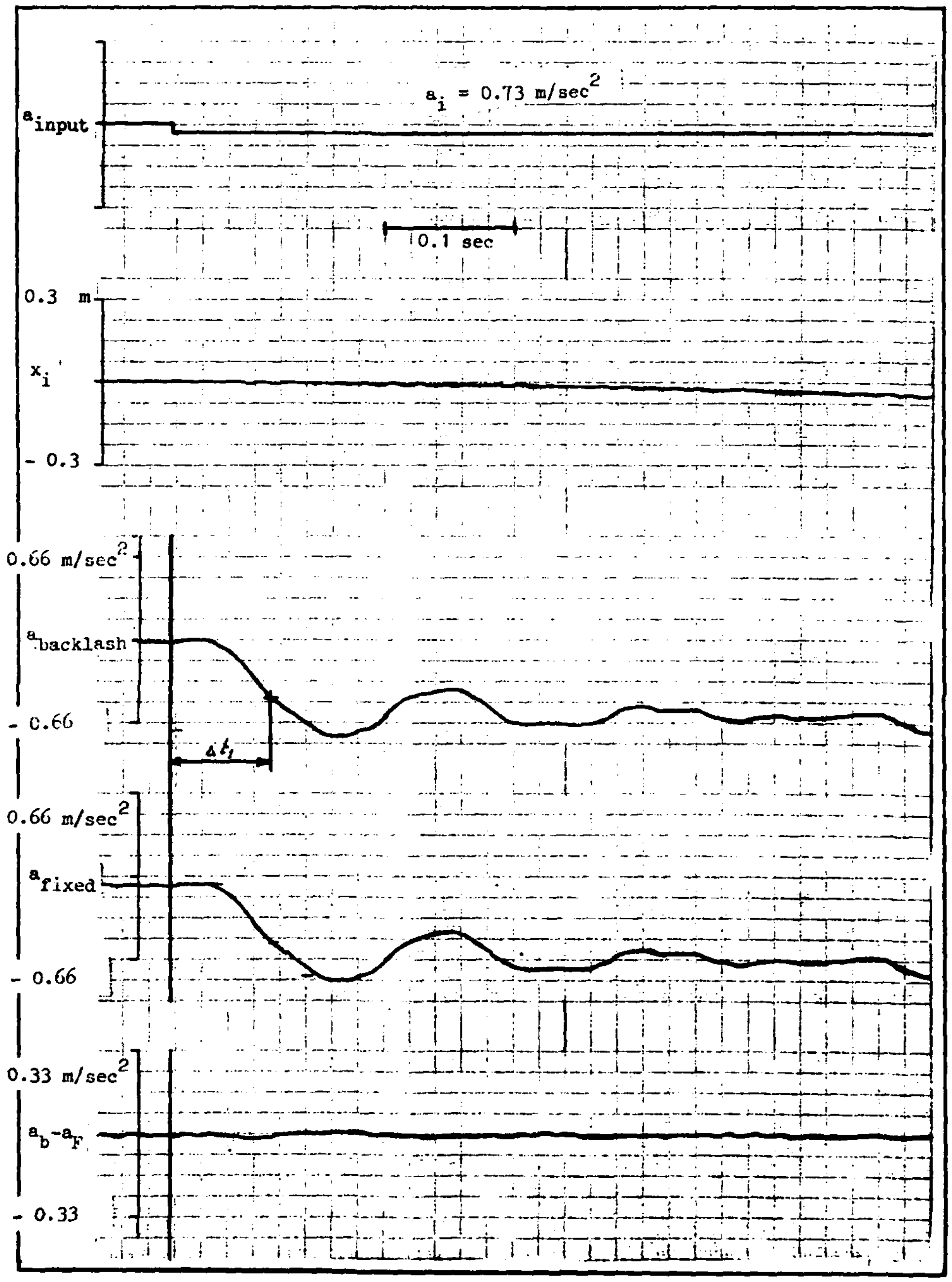


Figure 11

Acceleration Signals of a System with a Backlash of 0.2 mm

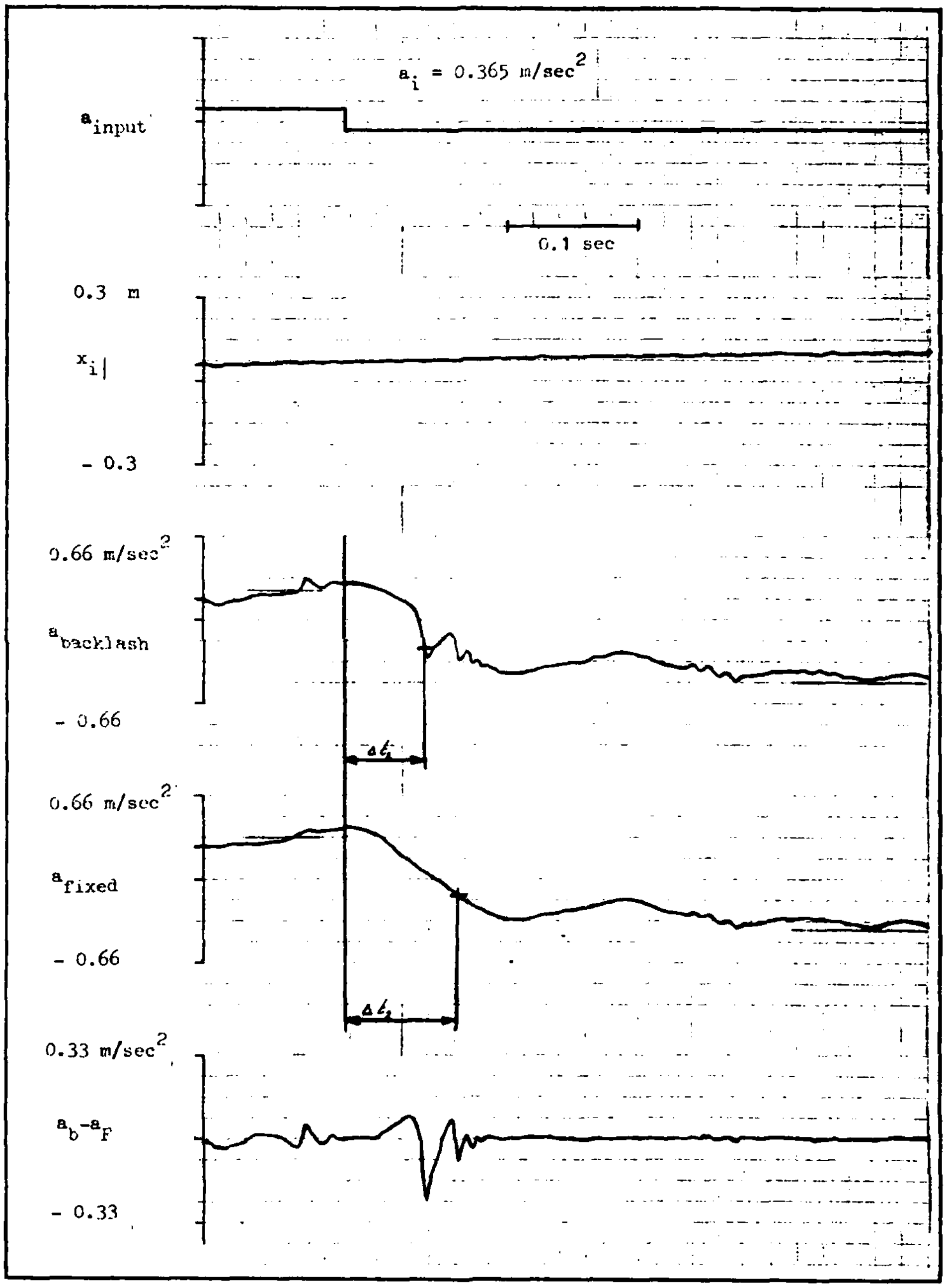


Figure 12

Acceleration Signals of a System with a Backlash of 0.2 mm

Another example of this phenomena was taken at RAE Bedford using the agreed upon measurement techniques. Figure 13 shows T_1, the time taken to reach 63% of a commanded input in one direction and T_2, the same time in the opposite direction, with both being taken from a square wave input. T_2 is in all cases less than T_1.

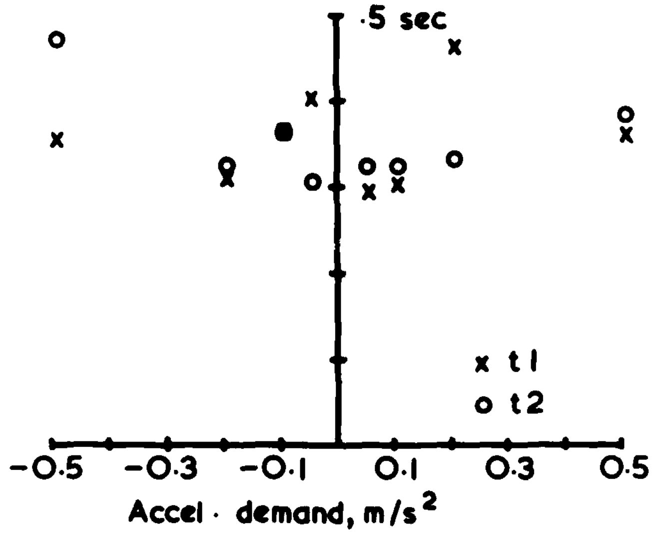


Figure 13 - Backlash, Heave

Mr. Erdman and associates reported the same difficulties (Figure 14), with T_2 lower, in each case, than T_1.

Mr. Dusterberry and associates at the NASA Ames Research Center got different results. They made measurements of backlash on the sway and roll degrees of freedom of the Flight Simulator for Advanced Aircraft (Figure 15). This motion system is different from the other tested because it is the only nonhydraulic system. The drive systems of all six degrees of freedom are independent of each other, and they are all electromechanical. Electronic and rotating amplifiers drive direct current motors which, in turn, move the independent drive systems through gears and by toothed chains working against rubber-faced surfaces.

NASA's measurements of roll backlash are shown in Figure 16. Since in all experimental points T_2 is greater than T_1 measurements on this motion system alone would have led the Working Group to believe that it had successfully specified a method of measuring backlash. Because of the reports of negative backlash by the other members, we are left to ponder whether the NASA device has an unusually large amount of backlash, or whether the faults of the proposed measurement technique apply only to hydraulic motion systems.

CONCLUSIONS

In the course of the work accomplished by Working Group #07, many different approaches to the goal of establishing a set of meaningful characteristics of motion systems have been considered. Recent tasks of the measurement techniques promulgated by the Working Group confirmed that, of the seven characteristics defined, those for performance limits, transfer function estimation, hysteresis, threshold and acceleration noise need little or no changes. On the other hand, it was obvious that the definition of, and tests for, backlash were totally unsatisfactory. As indicated earlier, this is probably due to an attempt to measure a positional hysteresis characteristic via acceleration metrics. As of this writing no solution to this anomaly has been found, and it may well be that an alternative term and/or measurement technique will have to be invented that is compatible with acceleration measurements.

Refinements of the measurement techniques and attempts to resolve the anomalies will continue through October 1978 as individual members of Working Group #07 perform their independent studies, culminating in a final report to be issued in June of next year. This work is of major importance, because it will provide, for the first time, a valuable taxonomy of characteristics for making precise comparisons of motion quality across virtually all types of motion platforms. In addition, it can serve as an excellent yardstick for the procurement and evaluation of new or proposed motion devices. Finally, it will form the baseline by which the joint Aerospace Medical Panel-Flight Mechanics Panel Working Group #10 can evaluate the relative merits of hardware delivered performance and the generation of motion cues.

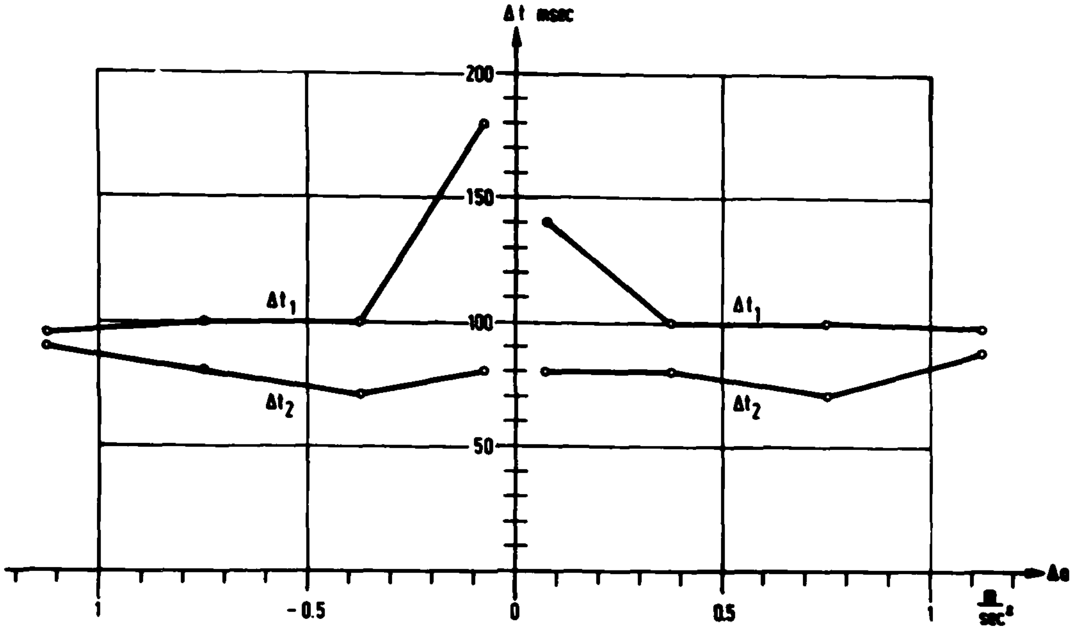


Figure 14 - Threshold and Backlash of Heave Motion

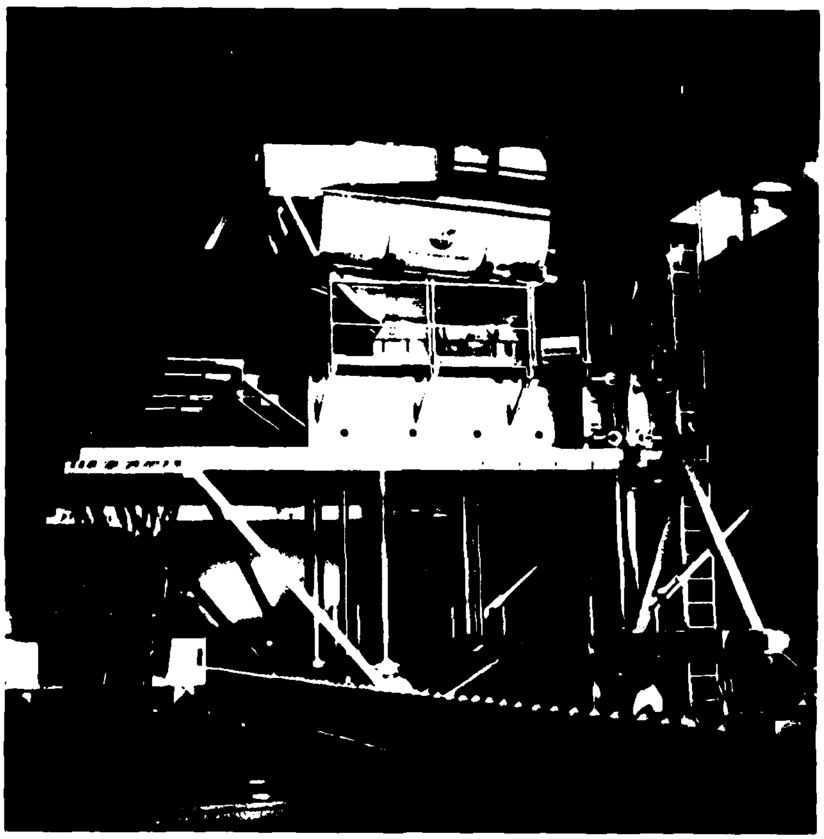


Figure 15 - NASA Flight Simulator

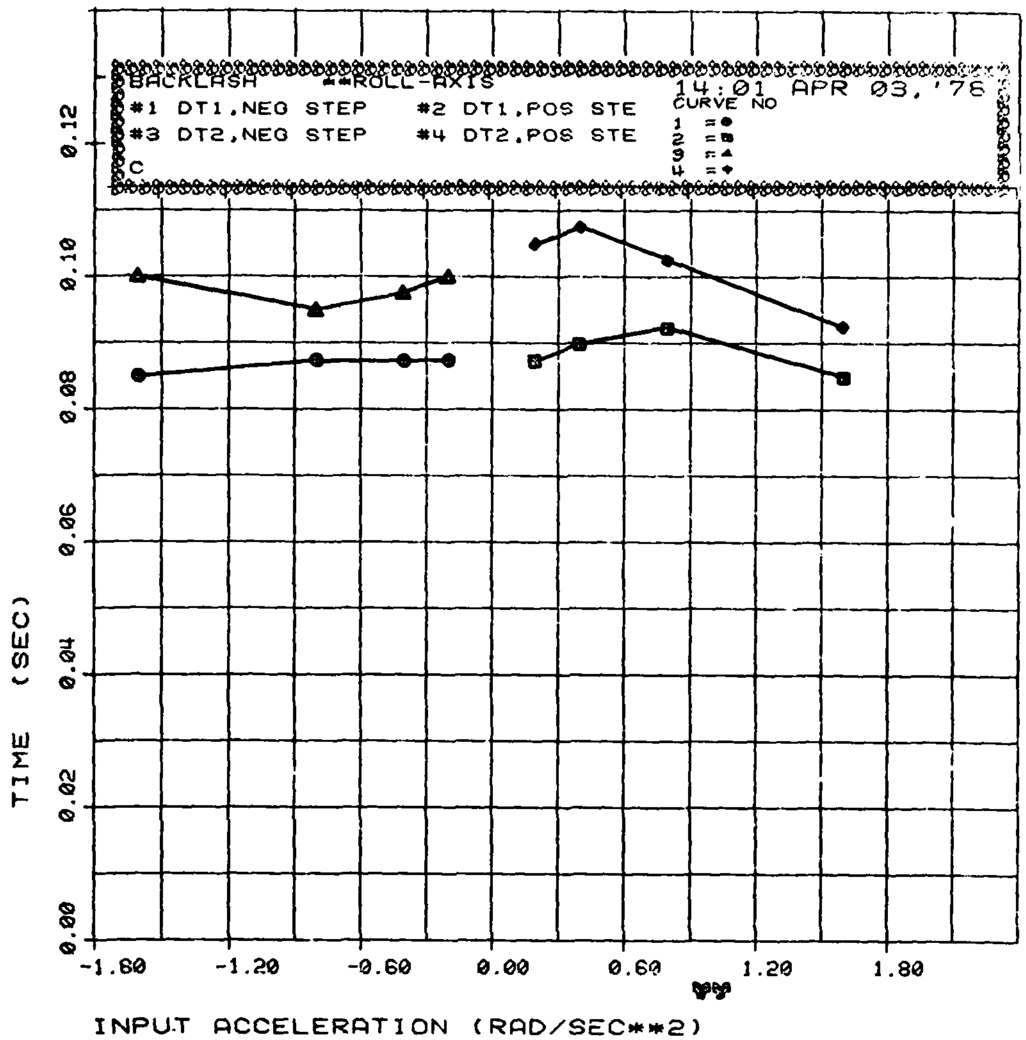


FIGURE 16

NASA'S MEASUREMENT OF ROLL BACKLASH

REFERENCES

Belsterling, C., Franklin Institute Research Laboratories, 4 Feb 78, personal communication.

den Hollander, J. G., and Baarspul, M., Measurement of the Motion Quality of a Moving-Base Flight Simulator, Delft - The Netherlands, January 1977.

Erdman, F., and Biertümpel, E., Comments about New Measured Qualities of a Velocity-Controlled Hydraulic Servo-System for Heave, Delft - The Netherlands, 20 Apr 78.

Erdman, F., and Biertümpel, E., Measured Qualities of a New Velocity-Controlled Hydraulic Servo System for Representing Acceleration in Moving Systems for Flight Simulators, DFVLR (Braunschweig), November 1977.

Jensen, C. J., Some Exploratory Measurements at the Motion System of the NLR Flight Simulator in Behalf of AGARD FWP WG 07, National Aerospace Laboratory, The Netherlands, 10 Apr 78.

Staples, K. J., Flight Systems Division, RAE Bedford, 17 Aug 77, personal communication.

THE DEVELOPMENT AND EVALUATION OF A "G" SEAT FOR A HIGH PERFORMANCE MILITARY AIRCRAFT TRAINING SIMULATOR

by

N.O. Matthews
C.A. Martin
Cranfield Institute of Technology, Cranfield, Bedford
England, MK43 OAL

SUMMARY

Early 'g' seats fitted in British military training simulators had been unsatisfactory in that they produced incorrect and, in some cases, negative cues to the pilots and, in addition, were incapable of providing simulated steady-state 'g' cues.

The programme of development work described in this paper will cover the examination of the original type of seat and attempts to improve its performance, leading to the design of a completely new concept in simulator 'g' seats. The philosophy behind the changes in design will be considered and the implementation of these in terms of hardware will be described.

Tests of the proto-type model of the new seat have been carried out in conjunction with a 3-axis motion system of improved performance characteristics at Cranfield Institute of Technology, and the results of evaluations by a number of service test pilots and pilots will be described.

The seat has now been accepted for installation in a service training simulator for the next generation of high performance aircraft.

1. INTRODUCTION

A number of RAF flight simulators for high performance aircraft have, for many years, been fitted with 'g' seats. Almost without exception, these seats, as fitted, have given misleading cues to the pilots and, in consequence, they have not been used in training. As a result of this situation, a team at the College of Aeronautics, Cranfield Institute of Technology, Cranfield were asked to examine this problem, and initial investigation involved measurements of the dynamic performance of the seat as designed. The result of this investigation was the discovery that the seat servo-performance was inferior to that of the motion platform on which the seat was mounted. This led to the conclusion that there was no way in which such a seat could be driven from the computer to provide any effective cues to the pilot which could not already be provided by the motion platform itself.

In an endeavour to improve this situation, the design of the hydraulic actuator under the seat pan of the standard 'g' seat was re-designed to give an improved dynamic performance. This initial work led to an actuator performance which was linear up to around 20 Hertz with greatly improved phase shift. When this seat was driven realistically from the computer, it was found that, although the cues were now satisfactory in terms of their performance characteristics, the sense of the cues provided was still incorrect. For example, the onset of a positive 'g' cue resulted in elevating the seat pan and pilot, followed by "wash-out", whereas, in these circumstances, the pilot expected to sink relative to his cockpit surroundings. A different approach was then adopted to endeavour to overcome this problem. The technique now used employs the conception of a change in the area on which the pilot sits, leading to an apparent change in pressure on the bone structure of his thighs and buttocks. In addition, the strap tension is adjusted to be consistent with the effect on a strapped-in pilot of both positive and negative 'g' cues.

A development seat based on this philosophy has been evaluated by service and test pilots, and work is now proceeding with the design of an engineered seat which will be installed in a service simulator.

2. THE 'G' SEAT

The seat was developed from a basic Martin-Baker Lightning ejection seat. The general arrangement of the current version is shown in Figures 1 and 2. A hydraulic ram is fitted under the seat pan and to this is attached a shaped horseshoe which is moved vertically under the direction of the normal 'g' signal, the position of the ram being controlled by a linear transducer.

The shaping of the seat pan and associated leaf springs was determined by experiments during the development phase of the programme. The shaped moving parts of the seat pan are surrounded by a normal seat cushion and, under conditions of earth gravity only, the seat pan is just below the level of this cushion so that the pilot is sitting on a relatively comfortable seat as he would be in the real aircraft. When he pulls 'g', the horseshoe rises through the padding so that his bone structure and buttocks are now resting on a relatively narrow contact area which is lifting him marginally above the soft cushion. The effect can best be described as that which occurs when a spring comes through the padding of an old armchair, a condition which is immediately recognised as being less comfortable than the fully padded condition. In the case of the 'g' seat, this less comfortable condition has been arranged to be consistent with the pressure a pilot feels under sustained normal acceleration. This, however, is only half the story. When a pilot is flying a modern high performance aircraft, he not only feels positive 'g' forces, which are simulated as described above, but negative 'g' cues as well. These tend to be felt essentially by a reduction in the pressure on the buttocks, but more especially by an apparent tightening of his shoulder straps.

In addition, his apparent eye level in the cockpit will change, going down for positive 'g' and up for negative 'g'. These changes in position are arranged by moving the seat bucket on its seat position guide bars (Fig.2) which are normally used by pilots for seat height adjustment. The strap tensioning is obtained from a combination of seat bucket movement and by the attachment of the lower end of the straps to the seat pan actuator (Fig.1). It is, thus, possible with this seat to present pilots with a sustained cue of both positive and negative 'g' coupled with a realistic movement of the eye level in the cockpit associated with the application of these forces. Because of the increased duty cycle, the seat positioning actuator has been replaced by a more powerful hydraulic ram which is capable of providing the seat movement cues over a range of normal aircraft operating conditions.

The seat assembly is installed normally in the Lightning cockpit and all cockpit facilities, including the ability to use a 'g' suit in conjunction with the seat, are provided as they would be in the operational aircraft. The additional cues provided by the 'g' suit greatly help to enhance the realism of the simulation.

3. AIMS OF THE EVALUATION

The concept of the Cranfield 'g' seat evolved from a study of previous attempts to simulate normal 'g' and from limitations of early 'g' seats. The progressive development of an experimental seat to give the desired cues was carried out on the basis of the subjective opinions of the engineers involved and of one pilot.

Whilst the opinions of those involved could reflect general opinion, it is known, using 'experimental terminology', that the reliability of results determined from a small biased sample using subjective methods of measurement is very low. In consequence, an evaluation programme was carried out by a sample of twenty pilots from RAF Training and Operational Squadrons and from Flight Test Establishments. The evaluation was carried out using subjective assessments in conjunction with pilot performance measurements. The aim of the assessment was:-

(a) To investigate if a 'g' seat operating on the principle of the Cranfield 'g' seat would have training value in a full Mission Simulator.

(b) To determine areas in which the simulation was satisfactory, inadequate, or even incorrect.

Note, the evaluation did not attempt to measure training effectiveness.

4. DESCRIPTION OF EXPERIMENTAL EQUIPMENT

A description of the Cranfield 'g' seat was given in Section 2. The seat bucket was driven proportionally to cockpit normal acceleration and, for the evaluation, was set at 10mm per 'g'.

The drive to the seat pan was from aircraft normal acceleration via a shaping network. The effect of the shaping, as shown in Figure 3, was to give large movement per 'g' at high positive 'g' and small movement per 'g' at 'g' levels below zero 'g'. The gain settings for pan and bucket movement were selected to give an overall increase in pilot eye height for negative 'g' and a decrease for positive 'g'.

The simulator is an RAF Lightning training simulator mounted on a three axis (pitch, roll and heave) motion system. The simulator is used for research purposes and is not furnished to training standards. The aircraft motion is calculated on a purpose built analogue computer and is programmed to represent a T-33 aircraft. Whilst the simulation is limited at large angles of pitch and bank and is not capable of take-off and landings, it is considered to be satisfactory for the 'g' seat evaluation programme. The simulator does not have a visual system, which restricts the evaluation programme since many flight tasks involving sustained 'g' manoeuvres are carried out in visual flight conditions.

Two methods of evaluation were used in the programme. Primarily, the evaluation was based on pilot subjective assessment but, to augment this information, a tracking task was used to provide a meaningful basis for evaluation and also from which pilot performance measurements could be made. The problems of using performance measurements with even very simple control tasks were recognised, and so the results are considered to be of secondary importance to the subjective evaluations.

In the absence of a visual system, the most realistic instrument flight task involving sustained 'g' levels of reasonable magnitude was considered to be a head down terrain following task. For this purpose, ten minutes of flight record in the form of flight path angle demand was used to drive a director bead on the simulator artificial horizon. This gave command signals in the pitch plane requiring manoeuvres in the range 0 to 3g. The simulation did not have heading commands.

The terrain flight path demand signal was fed to the simulator from a digital computer, and the flight path angle error signal was returned to the computer for storage on a disc file for further analysis.

The terrain following tests were organised as shown in Figure 4. This arrangement is intended to remove the effect of task learning on the performance results. Following the terrain following task, a period of general manoeuvring involving pull-ups, push-overs, and tight turns was carried out. To aid the subjective assessment, a questionnaire was used, primarily with the purpose of focussing the pilot's attention on the different aspects of the simulation. During all the tests, the pilots used a 'g'-suit which was also driven from the 'g' signal. The suit was not included as an item for evaluation although its usefulness in complementing the 'g' seat was considered.

5. RESULTS OF THE ASSESSMENT

In addition to providing information on the 'g' seat, the evaluation also revealed useful information on the planning of large subjective tests and on the interpretation of single pilot evaluation.

The answers to the questionnaire show many cases where the opinions on particular aspects of the simulation differ completely, and clearly a number of reasons could be suggested for these differences such as flying background, simulator experience and general attitude to simulation. In the assessment, no attempt was made to reconcile the differing opinions except where these are due to physical differences between pilots which may affect the distribution of the sensations produced by the 'g' seat.

The three cues provided by the seat are shoulder strap pressure, eye height change, and buttocks pressure change. Most comments concerning shoulder strap pressure varied between "hardly noticeable" and "good", and suggested that this is an important cue. An increase in the amount of tightening would be a benefit.

The majority of pilots considered the eye height movement was too great, particularly at the larger 'g' levels, although, in contrast, some pilots found the movement quite natural. It appears from the comments that eye height movement in aircraft under 'g' is small. (In the experiment ± 5g produced approximately ± 20 mm eye movement). The cue was shown to be an important one, but it was considered that further effort should be made to reduce the pilot's awareness of overall seat movement.

In general, the variation of buttocks pressure was thought to be realistic, although quite a number of pilots commented that the cues were in the reverse sense. It became apparent that certain pilots are more aware of the contact between the seat and thighs rather than with the change in pressure on the tuberosities. Further investigation showed that small pilots tend to adjust the rudder pedals fully aft to gain mechanical advantage and, in consequence, there is little contact between seat and thighs. For these pilots, the cues simulated were correct. The large pilots adjusted the rudder pedals fully forward which resulted in contact between the seat and thighs. For pilots with fleshy buttocks, this effect was magnified. This problem has been overcome by reducing the seat area beneath the thighs.

Whilst many comments on individual aspects of the 'g' seat were favourable, most pilots found deficiences in the interaction of cues. Although no strong pattern emerged in the comments, the criticism indicates that further effort is required to improve the phasing of the different cues and the balance of the cues during steady 'g'. There was considerable agreement on the importance of the 'g' suit in complementing the 'g' seat.

The majority of pilots considered that the seat had no effect on the closed loop terrain tracking task.

Analysis of the performance measurements showed that a small number of pilots adopted a control strategy which caused large simulator movements and produced large standard deviations. These results were not included in the analysis.

The changes between run 1 and 2, 'g' seat off, show no evidence of task learning.

The increase in standard deviation, shown in Figure 5, of flight path error with 'g' seat on would not be regarded statistically as significant for the sample of 9 pilots who carried out this part of the exercise. The result is in agreement with the general opinion of the pilots. It is quite probable that the change in pilot tracking performance with 'g' seat on is not significantly affected since studies have been reported previously where gross changes in motion cues produce little effect on pilot performance. The situation is not simple, however, since other factors such as type of input, type of system (whether stable or unstable) and the complexity of the task can have a large influence on the results.

In general, it was found that the collection of pilots' comments showed a wide range of opinion, and highlights the dangers of relying on single pilot opinion in simulator assessment. In this evaluation, the simulation cues are directly applied to the pilot through the seat and harness, and it was apparent that differences in physique can be very important.

6. CONCLUSIONS

As a result of the evaluation exercise, the current seat appears to be accepted by the pilots. One of the problems of such an evaluation is to be able to compare similar situations with the 'g' seat functional and non-functional. As will be seen from the evaluation programme, it is not sufficient just to switch the seat on and off because "seat off" not only provides an easier environment for the pilot when performing a controlled exercise, but also gives a situation which is less realistic than the real aircraft. The best that can be achieved may well be a situation where the pilots under training accept the cues provided by the 'g' seat as realistic rather than being false cues (as in the original seat fitted to this simulator) which caused them to switch the seat off in training. On the limited evaluation programme so far conducted, this pilot acceptance of the new facility has been established in the non-training environment of the evaluation programme. It is now intended to instal one of these seats in a Squadron Training Simulator for a final test of its acceptability to pilots. Seats for future simulators have been specified by the Ministry of Defence but, as the standard Martin-Baker seat for each new type of aircraft is different, some re-design of the 'g' seat will be necessary to match the differing ejection seat requirements.

The application of these techniques to the simulation of longitudinal and lateral 'g' is now under investigation, and it is hoped that this development will lead to simulator 'g' seats which are suitable for fixed wing aircraft and helicopters.

ACKNOWLEDGEMENT: This work has been carried out with the support of Procurement Executive, Ministry of Defence.

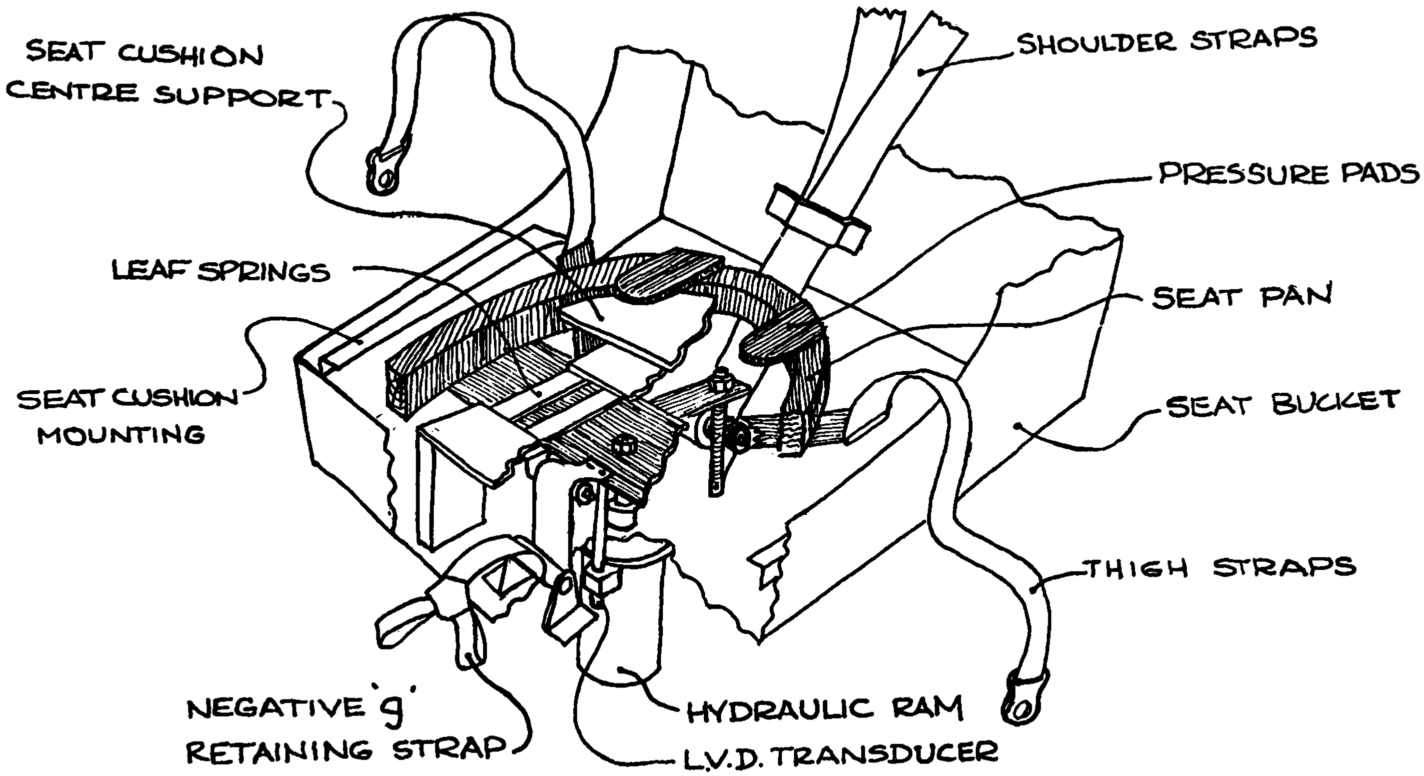


Fig.1 'g' seat pan actuator

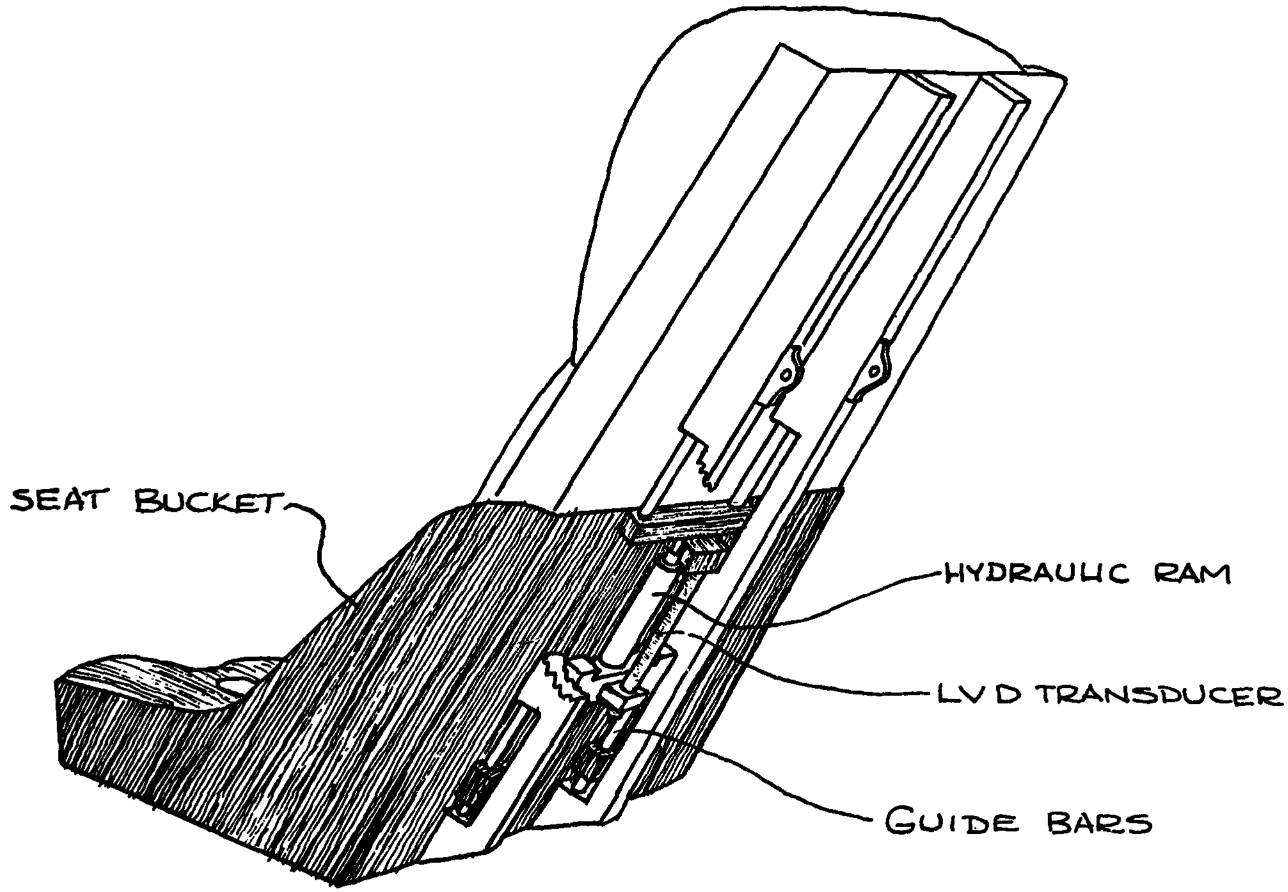


Fig.2 'g' seat bucket actuator

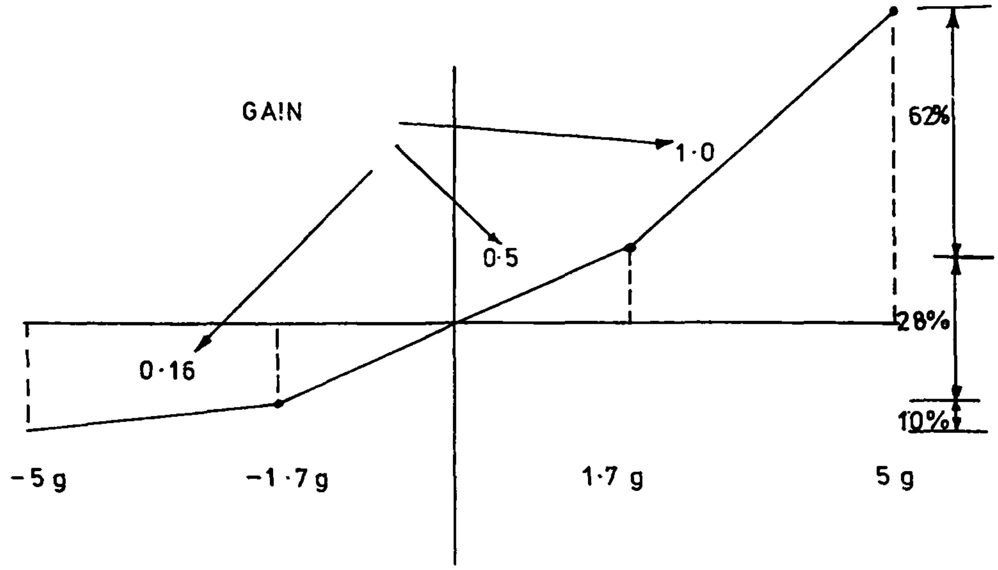


Fig.3 Seat-pan drive signal shaping

	Pilot A	Pilot B	
5 Minutes	Familiarisation 'g' Seat off	Familiarisation 'g' Seat off.	5 Minutes
10 Minutes	Terrain Following 'g' Seat off	Terrain Following 'g' Seat off.	10 Minutes
10 Minutes	Terrain Following 'g' Seat on	Terrain Following 'g' Seat off.	10 Minutes
5 Minutes	General Handling 'g' Seat on	Terrain Following 'g' Seat on (not recorded)	10 Minutes
		General Handling 'g' Seat on	5 Minutes

Fig.4 'g' seat evaluation procedure

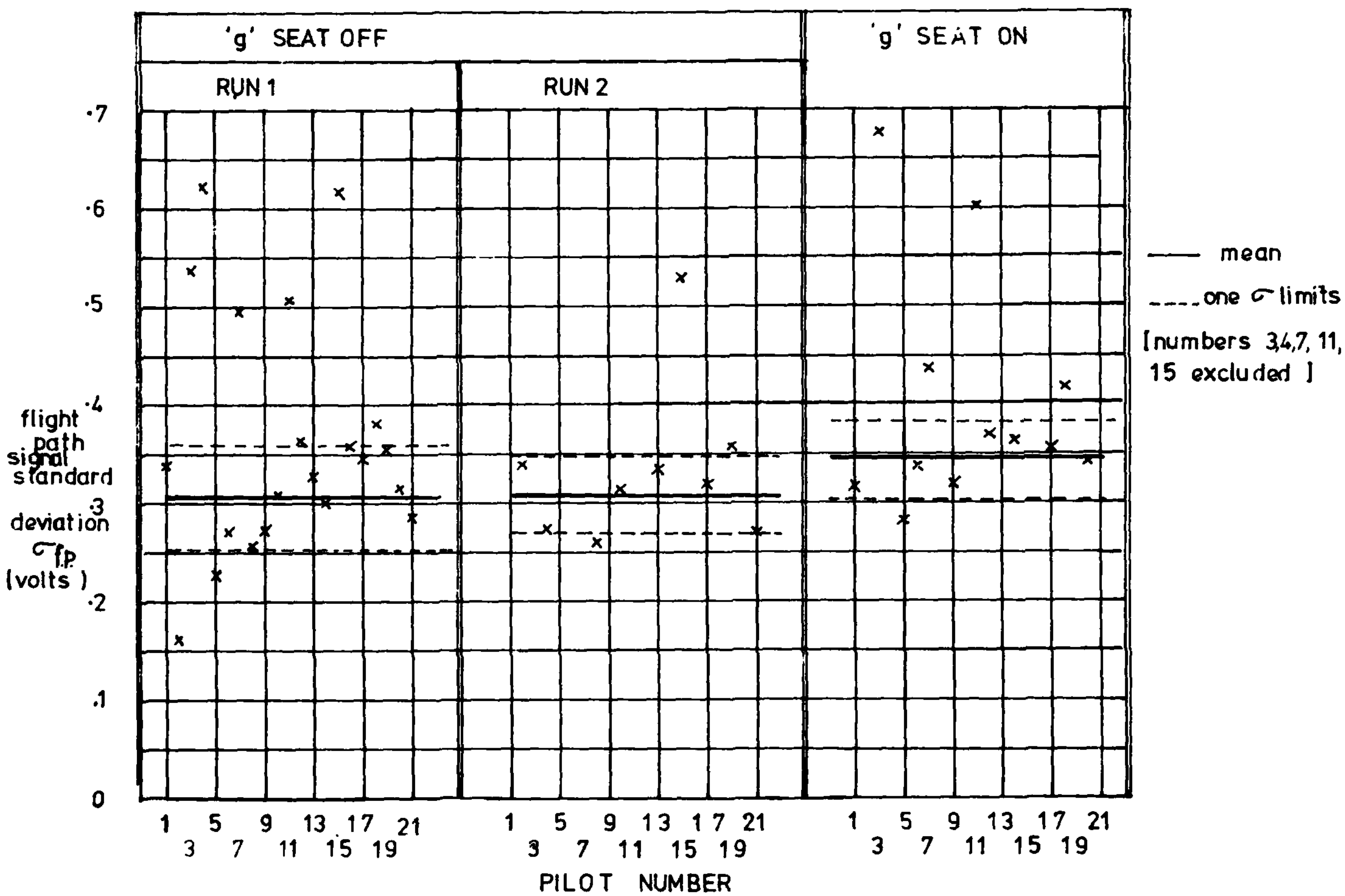


Fig5 Terrain following analysis

SIX DEGREES OF FREEDOM LARGE MOTION SYSTEM FOR FLIGHT SIMULATORS

Michel Baret

le Matériel Téléphonique
Division Simulateurs et Systèmes Electroniques

3 avenue Albert Einstein
78192 Trappes Cedex France.

SUMMARY

The special feature of the six degrees of freedom large motion system described in this document is the long-stroke, hollow-rod jack with hydrostatic bearings.

This technique provides an improved performance and considerably reduces the level of the unwanted accelerations normally generated by motion systems, while offering new possibilities in the study of control laws.

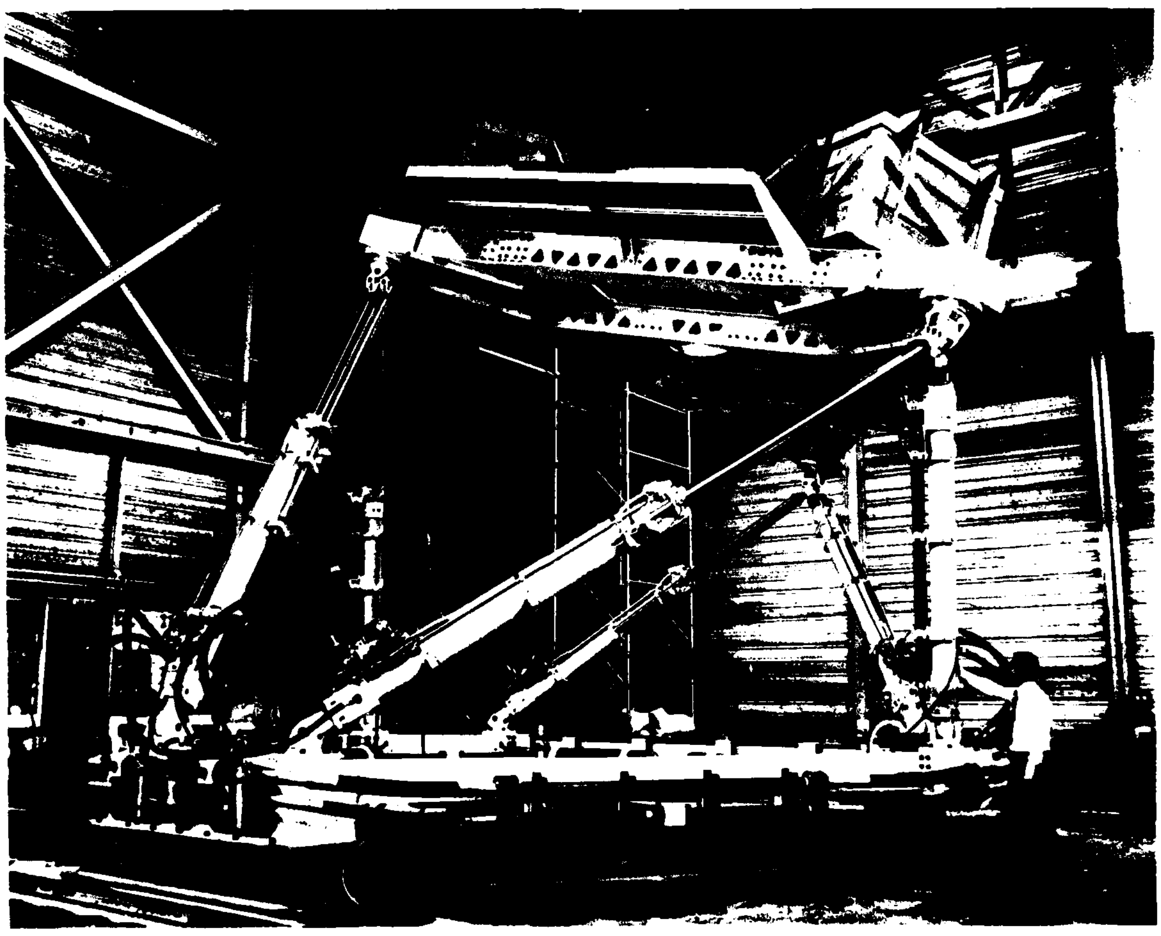


Figure 1

1 INTRODUCTION

The large, high-performance motion system with six degrees of freedom, developed by LMT has features which are advantageous in the following three areas :

- static performance
  . large linear and angular excursions,
  . high nominal payload : 10 tons (22000lb).

- dynamic performance
  . very smooth movements,
  . high back rod speed,
  . high pass-band.

- safety and maintenance
  . high degree of intrinsic safety,
  . simple maintenance.

This paper deals particularly with the jacks, which are the largest and the most original system component, and with overall performance and safety features.

2 GENERAL DESCRIPTION (Figure 1)

2.1 Base Frame

The base frame comprises three base sections, joined by three steel beams.

The base frame fulfils the following main functions :

- it accepts the lower pivots,

- it provides the attachment structure to the concrete base, specially prepared for the motion system,

- it houses the servo-jack hydraulic and electrical power supply components.

This base is hexagonal in shape, the long sides being 5.4 meters long (212in) and the short sides, 1.6 meters long (63in).

2.2 Pivots

The six lower pivots on the base are identical to the three upper pivots, mounted on the cradle frame.

In order to reduce friction and play, the pivot spindles are mounted on two conical roller bearings and the hinge pins are specially treated in order to avoid seizing-up and fretting and to facilitate maintenance by reducing the amount of lubrication required.

2.3 Cradle Frame

The cradle frame is triangular, rigid steel structure, designed to accept the nominal payload.

The triangle has 5.7 meter sides (224in).

Metal extensions can be added to the frame in order to increase its working area.

2.4 Control Cabinet

The system electronic control and monitoring circuits are contained in a cabinet which :

- provides the interface between commands prepared by the simulator computer and the mobile platform,

- controls the motion system in maintenance mode (the jacks can be checked individually or in combination in each of the six degrees of freedom),

- contains the electrical safety circuits.

2.5 Hydraulic Power Supply

The hydraulic power supply comprises :

- a hydraulic generator unit comprising two variable flow piston type main pumps, connected in parallel, each delivering nominally 230 l/mn (61 gpm) at 140 bars (2000 p.s.i.) working pressure,
- a double hydraulic ring supply system, pressure and return, with star distribution from the center of the base structure,
- a six large capacity hydraulic accumulators.

3 SERVO-JACKS (Figure 2)

The cradle frame is powered by six identical double-action jacks. Their special features are their stroke, their hollow rod and the use of hydrostatic bearings.

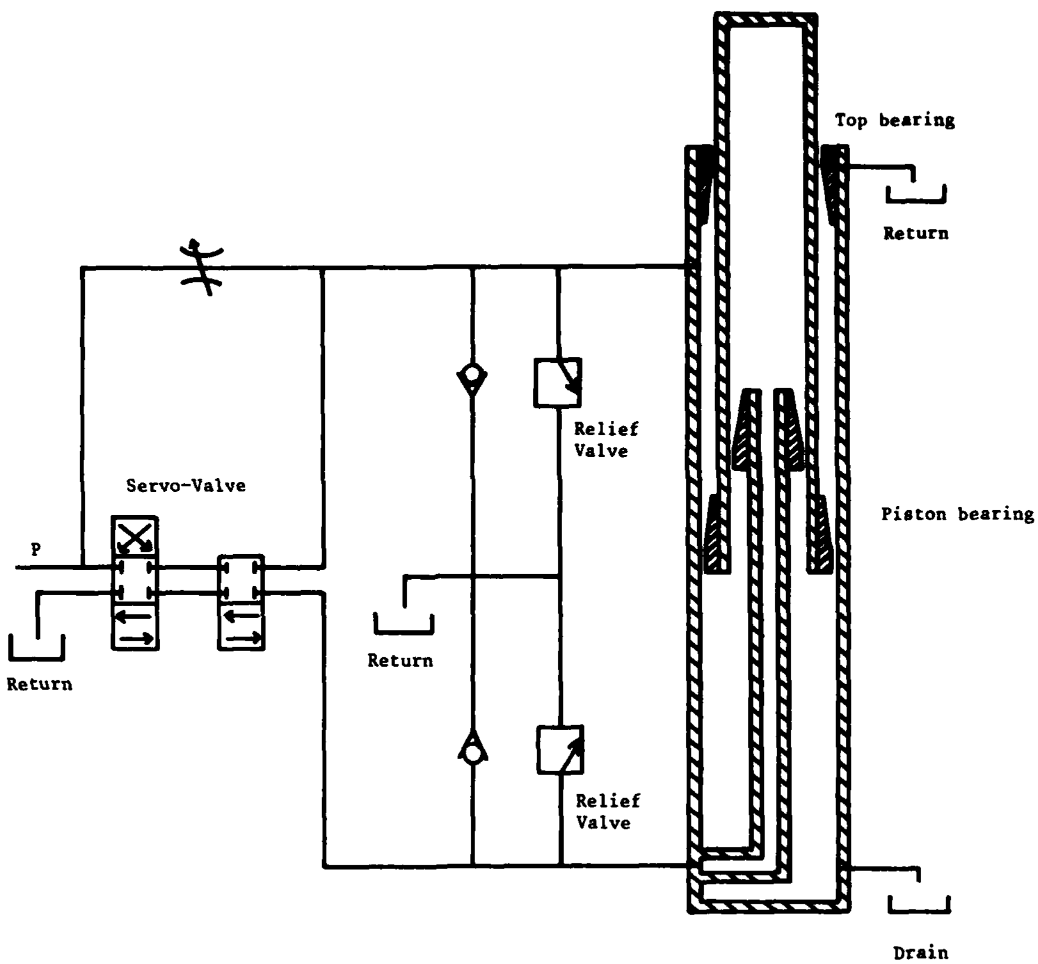


Figure 2

3.1 Description

The body, the main rod and the inner rod are machined from steel tube to the highest manufacturing specifications, especially concerning irregularities, diameter tolerances, treatment and surface condition.

DIMENSIONS	
Total stroke	: 2 000 mm (79in)
Main rod external diameter	: 140 mm (5.5in)
Main rod internal diameter	: 88 mm (3.5in)
Body internal diameter	: 157 mm (6.2in)

The head, main rod piston and inner rod piston bearings are single, conical, bronze hydrostatic bearings. Shapes, diameter tolerance, surface condition and assembly are extremely accurate. The safety bearing surfaces are off-loaded under pressure.

DIMENSIONS	
Taper/Radial clearance	: $2 < \frac{t}{c} < 3$
Radial clearance	: c = 0.08 mm (0.003 in)
Axial bearing length / Nominal diameter of bearing	: $\frac{L}{D} = 0.8$

A low-pressure seal and a scraper ring are on the end of the head block.

End of travel hydraulic buffers are incorporated in the head of the main rod and in the head block.

3.2 Principle of Operation

The bearing lateral force is proportional to the difference between the two pressures continuously applied at each side of the gap. One of the advantages of the hollow rod jack design is the zero pressure on one side of all hydrostatic bearings, thus allowing the operating pressures to be used for bearing centering. However, when the system is not working and during dynamic operation, the pressure in the reentry chamber drops momentarily to zero. To provide continuous bearing centering force under these conditions a pressure of 40 bars (570 p.s.i.) is injected into the reentry chamber. Chamber pressure balance is achieved by electrohydraulic servo. Leakage flow from the head bearing, 1 litre/mn/jack (0.26 gpm/mn/jack), is directly reinjected into the return circuit. Leakage flow from the main rod and inner rod piston bearings, 6 litres/mn/jack, (1.6 gpm/mn/jack) is de-gassed at the outlet from the third chamber and is drained to the main tank, through a secondary hydraulic circuit.

Leakage flow represents approximately 10% of the hydraulic unit capacity.

Coulomb friction of less than 4 da N at the end of the jack rod, is entirely due to the head block scraper ring and low pressure seal.

3.3 Conclusions

Use of the hydrostatic bearing jack results in the following :

- stick-slip phenomena are eliminated,
- backlash during changes of direction are reduced,
- the level of wear is very low, as the piston and the cylinder are not in contact,
- positioning accuracy is improved,
- maintenance is simplified as there are no seals,
- leakage flow is less than that of the servo-valve leakage and is negligible in relation to the hydraulic unit capacity. A leak recovery system must be provided.
- the negative influence of the relative piston speed inside the cylinder on bearing force has proved to be negligible,

- the main difficulty of this technology lies in the definition of the manufacturing procedures,
- the improvement in jack quality has clearly shown up the proportion of random accelerations due to the servo-valves and has resulted in the definition of a special servo-valve.

4 PERFORMANCE

4.1 Static and Dynamic Performance

Performance maxima shown in the table (Figure 3) are those provided in each degree of freedom, defined individually with respect to a nonmoving coordinate system centered at the centroid of the platform in its neutral position.

PARAMETER	MAXIMUM EXCURSION	MAXIMUM VELOCITY	MAXIMUM ACCELERATION
Vertical	± 1,37 m (± 54")	-0,75 m/s + 1 m/s (-29,5 in/s) (+39,4 in/s)	- 1,9 g + 2 g
Lateral	± 1,60 m (± 63")	±0,9 m/s (± 35,4 in/s)	± 0,7 g
Longitudinal	± 1,85 m (± 72,8")	-1,3 m/s + 0,9 m/s (-51,2 in/s) (+35,4 in/s)	± 0,9 g
Pitch	- 31° + 34°	- 19°/s + 13°/s	± 300°/s²
Roll	± 28°	- 16°/s + 16°/s	± 240°/s²
Yaw	± 29°	- 15°/s + 15°/s	± 240°/s²

Figure 3

The logarithmic diagram (Figure 4) shows the excursion, speed and acceleration boundaries of the system, for vertical motion.

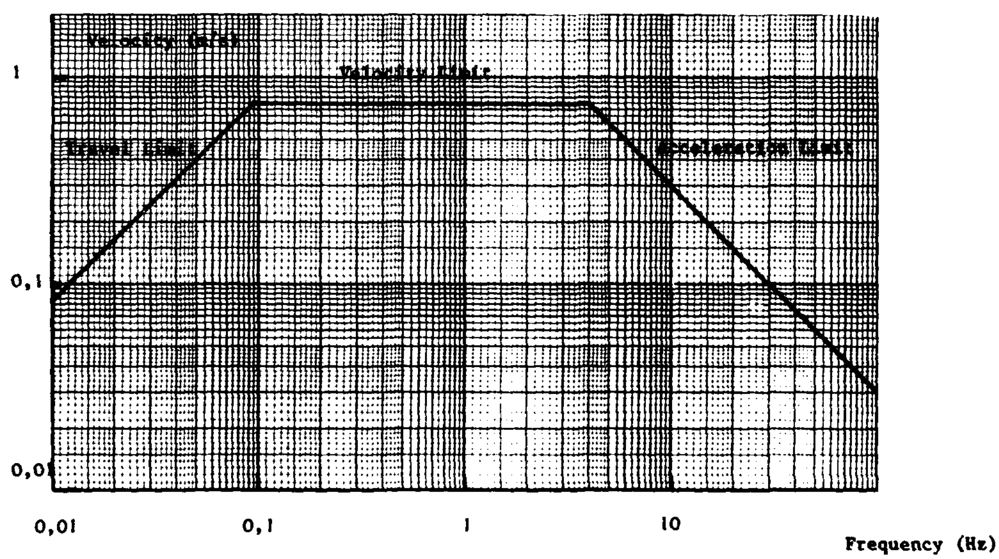


Figure 4

4.2 Frequency Response

Each jack is provided with positional feedback and a position-speed drive signal.

Stabilization is provided by pressure feedback.

The Bode diagram (Figure 5) shows the systems frequency response for vertical motion.

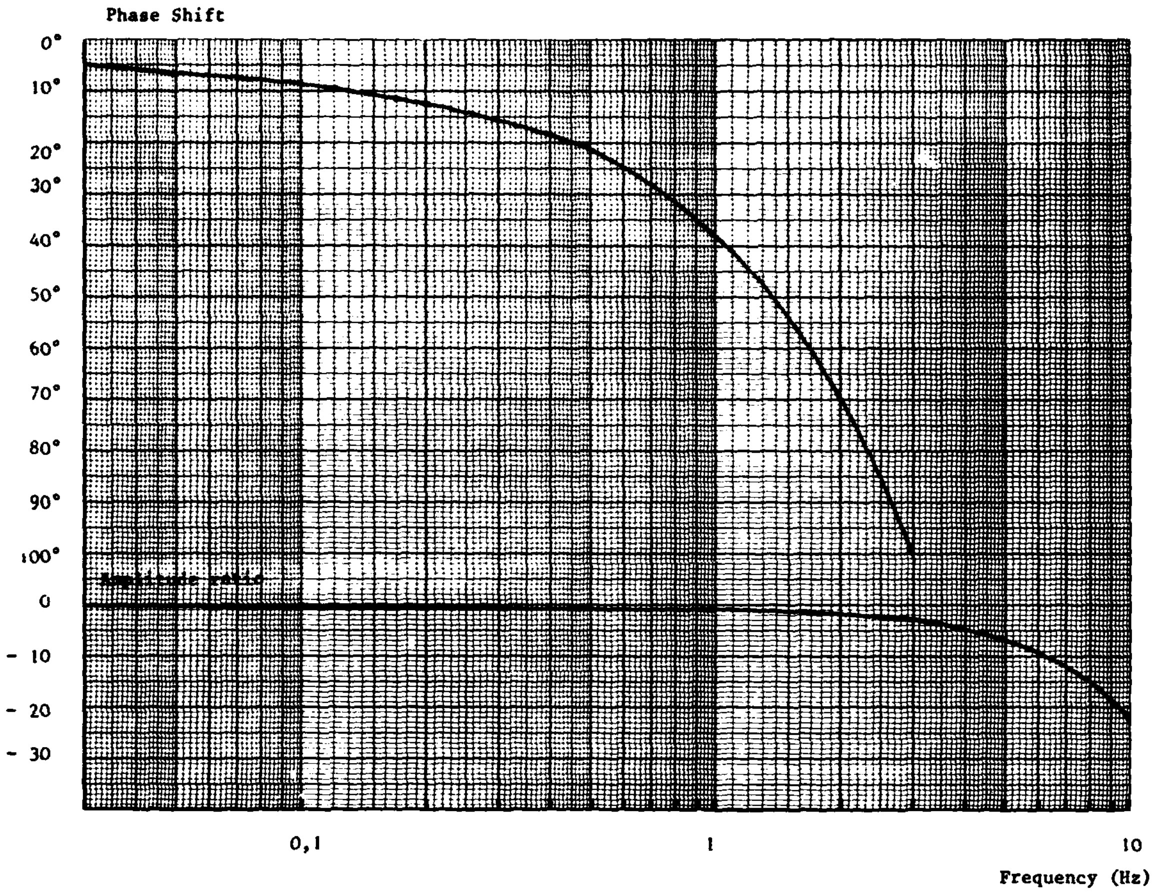


Figure 5

Damping,stability, static accuracy, natural frequencies and position drift in the system meet the requirements of standard MIL STD-1558.

4.3 Acceleration Noise

Spurious accelerations recorded for vertical motion, with servo-jacks fitted with standard servo-valves are as follows :

- movement without direction of acceleration reversed. The acceleration noises are negligible and include :
  - . the nonlinear static and dynamic output signals,
  - . jerk due to coulomb friction,
  - . imperfect hydraulic caracteristics.

- movement with direction of acceleration reversed

SINUSODIAL SIGNAL F = 0,5 Hz	AMPLITUDE ± 0,05 TRAVEL		AMPLITUDE ± 0,1 TRAVEL	
backlash	upwards to downwards	downwards to upwards	upwards to downwards	downwards to upwards
vertical acceleration noise	0,015 g	0,02 g	0,035 g	0,05 g
lateral parasitic acceleration	0,015 g	0,02 g	0,015 g	0,03 g
longitudinal parasitic acceleration	0,02 g	0,03 g	0,02 g	0,03 g

These values are decreased by 35 % using special servo-valves.

5. SAFETY PROVISIONS

The safety of motion system operation is provided by :

- the design of the mechanical and hydraulic units,

- the presence of a number of electrical monitoring circuits.

In the worst case failure, accelerations meet the requirements of standard MIL STD - 1558.

5.1 Mechanical and Hydraulic Units

In the design of the motion system, the following points were given special attention :

- natural frequencies of the components fall outside the band width of simulated motion frequencies,

- in the case of failure, the platform returns directly to the down position, using the power remaining in the accumulators,

- progressive restriction of oil flow, to isolate the jack chambers,is provided by a distributor with completely separate mechanical and electrical controls,

- the jacks are fitted with internal end-of-travel hydraulic buffers.

5.2. Electrical Monitoring Circuits

Monitoring is provided at two levels :

- at the servo control level, a monitoring system detects abnormal servo control behavior,

- at the level of the motion system logic circuits.

Monitoring is centered on the "unlocking" function.

The unlocking of the motion system,i.e. its starting operation, is only possible if none of the following conditions is validated :

For the hydraulic power supply :

- cooling pump oil pressure too low,

- pump oil pressure too low,

- oil level too low,

- oil temperature too high.

For the electrical power supply :

- electrical power outside value tolerances.

For software :

- non-operational program,

- software locking command.

For the servo control :

- servo control error on one of the jacks.

For cabin and maintenance :

- pilot's door open,

- access steps in active position,

- emergency shut-down from the instructor's station,

- emergency shut-down from maintenance station.

If one of these conditions appears, the motion system is automatically locked. The locking of the motion system results in the cabin descending to the down position. This movement is obtained by the closing of the distributors, thus isolating the servo-valves from the hydraulic power circuit and by the opening of the emergency descent electro-valves, which apply pressure to the jacks' upper chamber, while connecting the jacks' lower chamber to the return line through a flow limiter.

6 CONCLUSION

Technical tests confirmed by pilot mode experiments have shown two considerable advantages in the L.M.T. motion system :

- the very smooth movements, mainly due to the use of hydrostatic bearings,

- the high value of linear excursion and the fairly high pass band, due to system geometry and to the use of large hollow-rod jacks.

These characteristics will give a noticeable improvement in the platform control laws and, therefore, an improvement in motion cues.

SIMULATION DE COMBAT AÉRIEN DU CELAR

par

Y. Hignard
Département Évaluation de Système et Simulation
Centre d'Électronique de l'Armement
35170 Bruz France

RÉSUME

En 1971 le CELAR a entrepris à la demande de l'Armée de l'Air française la réalisation d'un simulateur de combat aérien. Ce simulateur a été utilisé pour des études techniques et tactiques liées à l'emploi de missiles de combat aérien rapproché.

Ce simulateur comporte un certain nombre de sous ensembles qui ont été réalisés de façon originale. Les solutions matérielles et informatiques ont été recherchées en vue d'arriver à une réalisation de coût modéré.

L'environnement d'un simulateur d'étude est aussi important que le matériel fonctionnant en temps réel si l'on veut arriver à une certaine efficacité pour l'expérimentation. Le CELAR a effectué un effort important dans ce domaine.

1 - INTRODUCTION

La construction du simulateur de combat aérien au CELAR résulte d'une demande, fin 1971, de l'État Major de l'Armée de l'Air qui se prososait d'étudier par simulation des méthodes de combat rapproché adaptées aux possibilités du Missile Magic 550.

Le simulateur est opérationnel depuis 1975 et l'Armée de l'Air, tout en continuant l'étude du combat avec Missile Magic, entreprend des recherches tactiques adaptées à de nouveaux missiles ou à de nouveaux matériels relatifs au système d'arme avion.

Cette méthode de travail permet aux Services techniques et à l'Armée de l'Air d'étudier l'emploi des matériels proposés par le constructeur et de contribuer à l'optimisation de certains paramètres, ceci dans un contexte proche des conditions d'emploi.

2 - DESCRIPTION DE L'INSTALLATION

Elle comprend 3 parties :

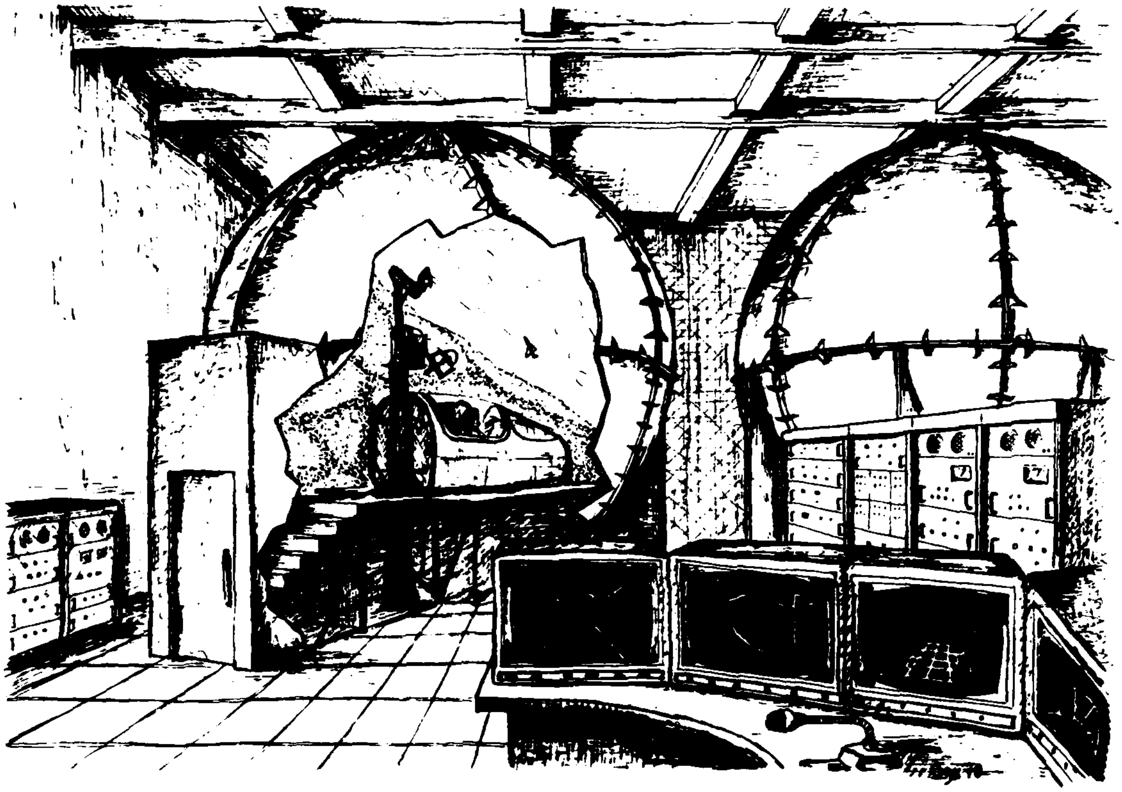
- l'environnement du pilote
- le pupitre du chef des opérations
- les calculateurs et le logiciel

2.1 - L'environnement du pilote

2.1.1 - Les sphères

Le simulateur est constitué de 2 sphères identiques en polyester de 6,40 mètres de diamètre qui constituent des écrans à grand champ. A l'intérieur de chaque sphère, sont installés un cockpit d'avion de combat, une lanterne horizon qui permet de projeter sur 360° un dessin simplifié du sol, et un dispositif de projection de l'avion adverse. La lanterne occupe le centre de la sphère, la tête du pilote est située en-dessous et en avant de ce centre et le projecteur de l'avion est placé au-dessus et en arrière. Les deux projecteurs sont ainsi positionnés au-dessus de la tête du pilote selon un axe incliné de 30 degrés vers l'arrière par rapport à la verticale, dans une direction très peu accessible à la vue du pilote.

Les cabines de pilotage sont fixes ; elles sont équipées des appareils de bord indispensables au combat aérien, sans conformité avec un avion particulier. La restitution d'effort est celle d'un Mystère B2. Le pilote est équipé d'une combinaison anti-g active.



Croquis du simulateur de combat

2.1.2 - La lanterne horizon

Elle projette une image de l'horizon sur 360° (fig.2). Elle est constituée d'une demi-sphère translucide (c) prolongée par un cylindre imprimé de taches colorées figurant le terrain. Le dessin est reproduit sur la sphère par ombre projetée à partir d'une source lumineuse ponctuelle (L).

Le globe est monté sur un système mécanique cardan à 4 axes de rotation. Ce montage supprime les accélérations exagérées sur les moteurs d'entrainement.

La source d'éclairage est munie d'un mouvement de translation selon l'axe oz pour simuler la variation d'altitude et corriger les erreurs de parallaxe introduites par la distance séparant l'œil du pilote de la lanterne horizon.

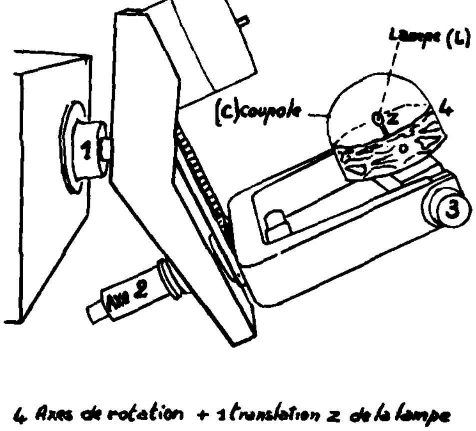


Fig.2 - Lanterne horizon

2.1.3 - Le projecteur de cible

L'image de l'adversaire est projetée sur l'écran sphérique à l'aide d'une optique équipée d'un dispositif de mise au point commandé par calculateur. Cet asservissement est nécessité par l'excentration du projecteur par rapport au centre de la sphère. Un périscope à deux miroirs tournant sur 360°, en gisement et en site, prolonge l'optique et permet d'orienter le faisceau lumineux dans toutes les directions.

L'axe en gisement du périscope est incliné de 30° par rapport à la verticale avion ; ceci permet de placer les zones de fortes accélérations angulaires des asservissements du périscope d'une part sous le nez de la cabine, d'autre part au-dessus et en arrière de la tête du pilote.

L'image avion projetée sur l'écran est générée par calculateur et envoyée sur un tube de haute brillance à balayage cavalier. Cette image stylisée ne comporte que les lignes essentielles (fig.3). Elle est le résultat d'un calcul perspectif avec élimination des lignes cachées. L'effet zoom est entièrement produit par calcul au niveau de la grandeur de l'image générée. Le renouvellement de l'image se fait 25 fois par seconde.

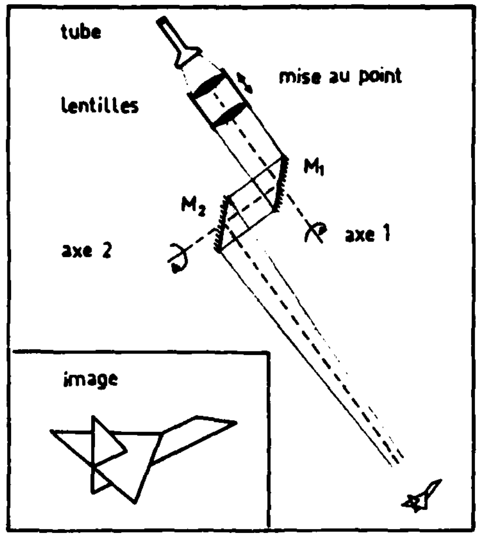


Fig.3 - Image et projecteur de cible

2.2 - **Le pupitre du chef des opérations**

Dans un simulateur d'étude, il est apparu indispensable de donner la vue d'ensemble du combat ainsi que des informations sur l'utilisation des systèmes d'armes de chacun des adversaires. Les informations sont présentées, en temps réel, au pupitre du chef des opérations. Le chef des opérations peut être le responsable technique d'une étude ou le pilote chargé de l'expérimentation. Le contrôle se fait sur 3 consoles graphiques.

2.2.1 - **La vue perspective du combat**

La vue perspective des 2 avions en combat et leur trajectoire sont présentées au chef des opérations sur une console graphique couleur à balayage cavalier. Les avions sont schématisés par une figurine triangulaire avec dérive. La longueur de la trajectoire est proportionnelle à la vitesse de l'avion et apparaît également en projection sur un sol quadrillé. (fig.4).

Le cadrage est automatique ainsi que l'échelle qui varie dans les rapports 8, 16, 32... km. Il faut noter que le cadrage automatique qui se traduit par une translation des mobiles ou une contraction instantanée des trajectoires en cas de changement automatique d'échelle ne gêne nullement l'observateur. Les projections au sol des trajectoires sont repérées par un quadrillage toujours orienté vers le nord (axe de référence des avions) puisque nous avons supprimé volontairement la possibilité du choix du point d'observation, ce qui facilite les opérations de contrôle.

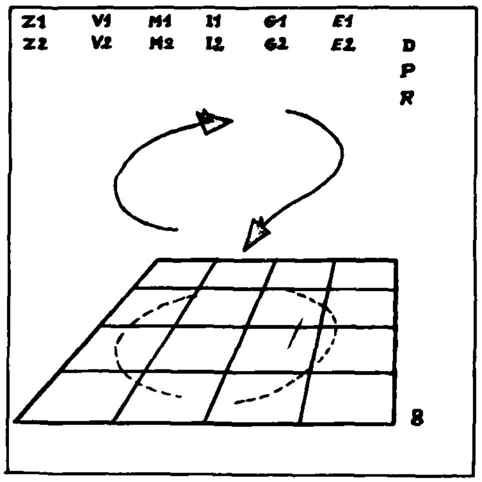


Fig.4 - Vue perspective du combat

Les paramètres de vol de chaque avion (altitude, vitesse, incidence, énergie totale...) apparaissent en chiffres sur la console.

2.2.2 - **Visualisation dynamique du domaine de tir instantané du missile**

Cette visualisation présente au Chef des opérations, en temps réel, le domaine de tir dans lequel l'avion chasseur (c) doit pénétrer pour réussir le tir de son missile face à l'hostile dont la vitesse est $\vec{V}_B$ (fig.5).

La cible, schématisée par le triangle, occupe le centre du système d'axe polaire (Bx, By).

Le plan polaire P (Bx, By) est constitué par le vecteur vitesse $\vec{V}_B$ de la cible et la ligne de visée CB qui joint le chasseur à la cible. Le vecteur V_c représente la projection de la vitesse du chasseur dans le plan P, η_B désigne la composante de l'accélération de la cible dans le plan P, δ_{Bo} est l'angle de présentation vitesse et δ_{co} la projection dans P de l'angle de dépointage (fig.5).

Les limites du domaine de tir relatif au missile étudié sont tracées sur la console graphique en utilisant un algorithme rapide (Domaine de tir instantané, DTI). Le calcul, fourni par le constructeur, permet de retrouver, dans la direction δ_{Bo}, la limite courte et longue du domaine de tir en fonction des vitesses et des altitudes des mobiles, du facteur de charge de l'hostile et de l'angle de dépointage. En reconduisant le calcul pour des δ_{Bo} allant de 0° à 180°, on obtient le contour du domaine de tir qui, au cours du combat est régénéré toutes les secondes avec de nouveaux paramètres d'entrée ($Z_B, Z_c, \vec{V}_c, \eta_B, \delta_{co}, V_B$).

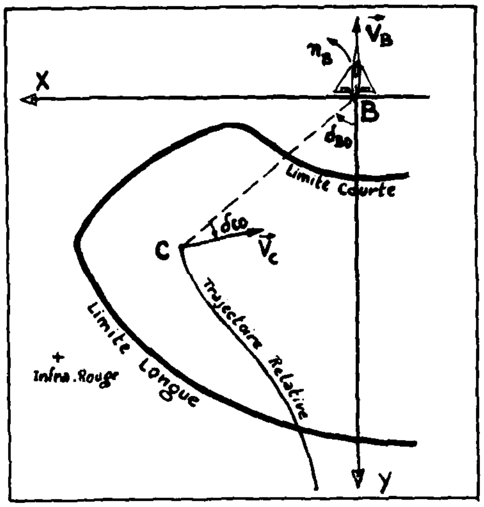


Fig.5 - Visualisation dynamique du domaine de tir instantané

La trajectoire de pénétration du chasseur (C) dans le domaine de tir ainsi que la projection de son vecteur vitesse $\vec{V}_c$ sont visualisées et remises à jour 15 fois par seconde et la trace de cette pénétration est maintenue avec une longueur proportionnelle à la vitesse relative des 2 mobiles. De plus une marque indique la portée infra-rouge du missile étudié dans la direction δ_{Bo}.

Cette visualisation permet au Chef des opérations :

- de juger facilement de l'efficacité d'une manœuvre de combat qu'elle soit offensive ou défensive,
- d'apprécier la durée de la pénétration,
- d'en vérifier la stabilité.

2.2.3 - Visualisation cockpit

Pour que le chef des opérations connaisse, pendant le combat, ce qui se passe dans les cockpits,nous avons ajouté 2 visualisations qui représentent la vue que chaque pilote a de son adversaire (fig.6).

L'image que l'on fabrique sur chaque console est celle que fournirait un objectif grand angulaire (fish-eye) mis à la place de l'œil du pilote. Nous avons bâti un programme qui fait la transformation géométrique avec, en donnée, le champ de l'objectif (jusqu'à 90° et plus).

Les points caractéristiques de l'avion (arceau, visière, glace viseur) subissent la transformation et des repères angulaires sont marqués sur des axes passant par la croix fixe du viseur. L'adversaire apparaît dès qu'il pénètre dans le champ de l'objectif et sa silhouette est présentée en vraie perspective mais, pour mieux apprécier son attitude, nous avons faussé la dynamique de grandissement pour des distances supérieures à 1000 mètres.

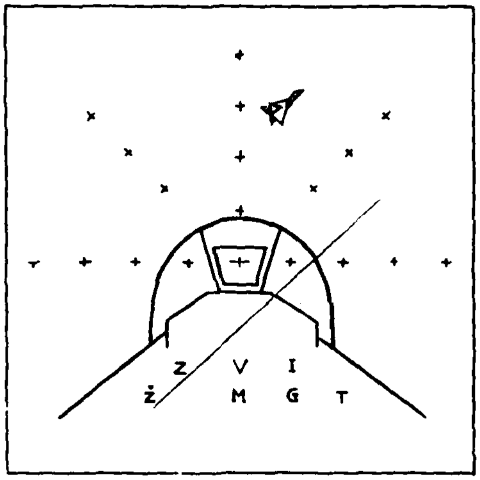


Fig.6 - Vue cockpit

Le chef des opérations a la possibilité de faire un zoom sur le viseur quand l'adversaire est situé dans son champ. Nous avons aussi introduit la trace du lobe radar,particulièrement utile pour l'étude de différents types de balayage.

Les 3 visualisations décrites ci-dessus sont presentées, simultanément, durant le combat, au chef des opérations qui peut ainsi observer et diriger les pilotes. Toutes les informations nécessaires au rejeu des consoles sont enregistrées sur une bande magnétique.

A la fin du combat, les pilotes ont ainsi la possibilité d'assister au play-back, autant de fois qu'ils le désirent, en utilisant l'arrêt sur image. Ces visualisations facilitent considérablement le debriefing des combats.

2.3 - Les calculateurs et le logiciel

2.3.1 - L'organisation informatique

Le pas de calcul de toute l'installation est de 32 ms. Pour obtenir cette vitesse d'exécution nous utilisons plusieurs calculateurs.

Le centre de simulation temps réel est organisé autour d'un calculateur 10070 (92 kmots) auquel sont reliés 5 processeurs satellites STR 400 (32 kmots) par un accès direct mémoire permettant un traitement des calculs en parellèle. Le calcul des images (avions projetés dans les sphères et visualisations du pupitre de contrôle) est effectué sur 2 calculateurs Texas 980 reliés au 10070 par voies numériques.

Tous les programmes de calcul sont écrits en langage Fortran. Les principaux programmes et leur implantation sur les calculateurs sont les suivants :

- La résolution des équations de vol des 2 avions et leur intégration au pas de 32 ms (sur 2 STR 400).
- Les programmes de transformation d'axes, de correction de parallaxe, de commande des asservissements et des appareils de bord (sur 10070).
- La gestion de l'accrochage, du balayage et de la mise à feu des missiles (sur 10070).
- Les programmes de calcul du Domaine de Tir Instantané (sur 10070).
- Les programmes de visualisation bâtis autour d'un mini-software graphique rapide (sur les 2 Texas 980).

Les programmes d'acquisition des données sont implantés sur 1 STR 400. Toutes les informations sont centralisées au niveau d'une interface comprenant un multiplexeur-démultipleur par cabine.

2.3.2 - Le logiciel d'exploitation

Chaque combat est enregistré sur une bande magnétique et les actions des pilotes sur les commandes et le système d'arme sont intégralement conservées. Le chef des opérations peut ainsi demander après chaque combat :

- un play-back complet qui met en œuvre toute l'installation ou un play-back des consoles graphiques,
- un listing immédiat relatant seconde par seconde l'histoire du combat avec, en incrustation, les principaux évènements concernant l'armement,
- un tracé perspectif d'une phase intéressante du combat. L'opérateur choisit l'échelle du tracé et le point d'observation. Les évènements concernant l'armement apparaissent sur la trajectoire (entrées et sorties du domaine de tir, accrochage du missile, tir...).
- la trajectographie d'un tir missile ; la résolution des équations de vol du missile ne peut se faire en temps réel par manque de puissance de calcul. Cependant en temps différé, le chef des opérations peut demander l'exécution du programme de résolution de la mécanique du vol du missile. A partir des coefficients aérodynamiques et de la loi de guidage fournis par le constructeur, le programme intègre les équations selon 3 axes au pas de 5 ms et fournit la trajectoire du missile ainsi que la distance de passage et les angles de présentation par rapport au but. Ce même programme permet d'obtenir avec précision les contours interieurs et extérieurs du domaine de tir en procédant par tirs successifs et avance progressive (généralement au pas de 250 mètres) le long de la frontière séparant les tirs réussis et les tirs manqués.

3 - UTILISATION DU SIMULATEUR

Depuis la mise en service du simulateur les pilotes ont poursuivi les études des tactiques de combat avec missile Magic autant pour des présentations offensives que défensives. Les règles d'emploi présumées étaient vérifiées et recalées par des essais réels. La simulation, associé aux essais réels, a ainsi permis à l'Armée de l'Air de faire progresser rapidement ses connaissances sur l'emploi tactique du missile Magic, d'apprendre à se servir du domaine de tir et de définir des règles d'emploi simplifiées et donc plus facilement applicables par des pilotes en combat.

En même temps, le dépouillement des combats enregistrés a fourni des résultats statistiques sur les distances de tir, les angles de présentation au moment du départ du missile, les temps de réaction des pilotes, les avantages apportés par des indicateurs d'aide à la décision de tir du missile. (Le plus sophistiqué de ces indicateurs est une recopie à l'intérieur de la cabine du domaine de tir instantané).

Le simulateur est aussi utilisé en permanence pour des études telles que :

- l'emploi des missiles futurs et l'optimisation de certains paramètres proposés par le constructeur,
- l'utilisation en combat d'un casque de visée,
- les balayages radar excentrés.

De plus, la visualisation perspective et la vue du domaine de tir instantané ont été reproduites au Centre de Tir des Landes. Au cours des campagnes de tir, les pilotes chargés de l'expérimentation peuvent donc suivre sur consoles et en temps réel la position relative de l'avion tireur et de la cible ainsi que la pénétration dans le domaine de tir. L'officier de tir peut ainsi confirmer la mise à feu du pilote.

4 - CONCLUSION

A la demande de l'Armée de l'Air, le CELAR a entrepris une refonte de l'installation qui comportera une amélioration de l'environnement du pilote : cabines conformes au Mirage F1, miniaturisation de la lanterne horizon, introduction d'un zoom optique dans le dispositif de projection de la cible. La nouvelle installation sera opérationnelle à la fin de l'année 1978. Cependant, le CELAR continuera à faire porter ses efforts sur la réalisation de programmes d'exploitation adaptés à l'étude des méthodes de combat.

DIFFERENCES BETWEEN SIMULATION AND REAL WORLD AT THE IABG AIR TO AIR COMBAT SIMULATOR WITH A WIDE ANGLE VISUAL SYSTEM

by

Dr E.Vogl
Industrieanlagen-Betriebsgesellschaft, 8012 Ottobrunn, FRG

SUMMARY

This paper presents the experiences of IABG with its Dual Flight Simulator (DFS) for air-to-air combat. First of all IABG has discovered that air-to-air combat simulation without a motion system is no problem to the pilots. During the verification phase it was found that the results of simulations at DFS were very good.

On the other hand IABG has researched all simulator effects in respect to human factors. All the following effects are existent, but have an unimportant influence on the results of air-to-air combat simulations.

1. INTRODUCTION

The Industrieanlagen-Betriebsgesellschaft mbH, a non profit company, which works for the MOD of FRG at Ottobrunn, near Munich, has built an Air-to-Air Combat Simulator.

There are two cockpits, each inside a spherical screen of 12 m diameter, which surrounds each cockpit with a solid angle of eighty five per cent of four π.

Figure 1 shows the cockpit, the screen, the target TV-projector, the gimballed model for TV-camera and the sky-earth-horizon projector. The sky-earth-horizon projector is a Vista-projector without any optics. The image of sky-earth-horizon is formed by point light sources, which project the image through two painted hemispheres (Fig.2).

For air-to-air combat simulation it is very difficult to install a correct operating motion system. Since the pilots fly frequently alternating high "g" loads and frequently alternating roll accelerations the motion system would get into "wash out function" quickly. The motion system would be unable to operate correctly. Therefore, we have no motion system, but a buffeting system and a correctly operating g-suit to offer a "g" cue to the pilots. This effect is intensified by "grey-out/black-out" simulation. "Grey-out/black-out" is represented by dimming all the projectors and the illumination of the instruments as a function of the time spent at high "g's". The cycle time for all hardware servos is lower than fifty milliseconds and all servos are so designed as to have the performance for the required velocities and accelerations of modern fighter type aircraft.

2. VERIFICATION

2.1 Measurements at Projector Systems

For validation of the Dual Flight Simulator we have measured the static accuracy of our projection systems. We have found an "overall accuracy" of both projectors (sky-earth-horizon and target projector) of ±0.17 degrees. The dynamic error is very important for the whole simulation. Therefore we are still involved in measuring all dynamic errors. But it is very difficult to measure the dynamic errors of all the systems of the simulator (projector, stick, aileron, throttle etc). We have no results at the moment.

2.2 Validation of Dual Flight Simulator

The program of validation consisted of three parts: aircraft authentication, pilot verification and research validation. For example, see the validation for the F-104. Figures 3 and 4 show the aircraft authentication. This validation consisted of evaluating the simulated aircraft by flight tests and comparing the results with actual flight test data. Tests included response to control inputs, accelerations, decelerations, velocities, climbs and maneuvering turns. Satisfactory agreement was achieved with the available flight results.

The superior diagram of Figure 3 shows the control/pilot input at the aileron as a function of time. The inferior diagram of Figure 3 shows the results in rolling velocity as a function of time.

There are two curves: One line is for real flight results and the dashed one is from our simulator. There is a satisfactory agreement between the two curves. Figure 4 shows three effects caused by the pilot input. Firstlv the side slip angle (ordinate) in degrees as a function of time. Secondly the yawing velocity in degrees per sec as a function of time and thirdly the rudder in degrees as function of time. Also in this figure there is a satisfactory agreement between real flight results and simulator results.

3. DIFFERENCES BETWEEN DUAL FLIGHT SIMULATOR AND REAL WORLD

At the next two phases of validation (pilot verification and research validation) we have obtained results, which show the quality of the DFS and the differences between simulation and real-world. These differences cause a lot of effects, which are unimportant for simulation results if they are well known and if the pilots are familiar with this kind of effect. We have had a lot of simple test programs with pilots at the simulator to determine whether the visual cues supplied to the pilots were comparable with real world. Also, we have performed a few research studies and a comparison between manned simulation and pure software simulation with a pilot-model.

Now we will discuss the results obtained and conclude where are the limits of the DFS in its applicability for tasks.

We have two relevant differences between DFS and real-world:

- no motion system
- a visual system without different scaling of background items

3.1 Effects caused by missing motion cues

There are two different opinions: The first is that motion cues are the most important and, therefore, flight should not be simulated by visual systems without motion cues as the pilots will be indisposed by that kind of simulation. The second opinion is that visual cues are the most important. It is possible to simulate without motion cues. It was found (by NASA-Langley, McDonnell-Douglas and LTV Aerospace Corporation) that the pilots have no problems with this kind of simulation. Also IABG has investigated that there is no effect of nausea on the pilots. It is possible to get correct results in air-to-air combat without a motion system; there are a few little differences between simulation and real-world, which can be learned by the pilots.

3.1.1 Pilot Verification of Roll-Sensitivity

The pilots have criticized the roll-sensitivity of our aircraft. They said that the aircraft is too sluggish about zero and then it is extremely sensitive. This effect does not result from a badly simulated aircraft, (see Figures 3 and 4) but is caused by missing motion cues.

In Figure 5 you see the displacement of aileron as a function of time. The second diagram shows the rolling velocity, which results from the above displacement The third diagram shows the resulting angle in degrees as a function of time.

Now, the pilot gives the input command by movement of the aileron. In real life he feels the acceleration immediately and he is satisfied. In our simulator without motion system he cannot feel the acceleration. He can only see the effect by velocity or displacement of the horizon. But you see in the figures, that velocity and displacement-angle are very small at the first moment. The pilot cannot see any effect and he feels nothing. Therefore he reacts by increasing his input command. This is represented by the dashed lines. The effects of velocity and displacement angle will be greater. But after a defined time the pilot is able to see the displacement angle and the rolling velocity. Now he observes a velocity, which is too high for his experience and an angle which is also too great. The pilot concludes all these effects in his reasonable comment: The aircraft is too sluggish about zero and then it is extremely sensitive.

We are sure that this effect exists also in the pitch and yaw axis. But the accelerations of these two axes are not so important as the accelerations about roll axis and the feeling of pilots about these axes is also lower. Therefore the pilots have never criticized the authentication of aircraft about these two axes.

We have explained this effect to the pilots. After understanding the reasons for roll sensitivity in the simulator the pilots were able to accept these effects and to live with this characteristic.

3.1.2 Pilot Verification of Speed Brakes

All pilots have criticized that the effect of speed brakes is too sluggish at accelerations near zero and extremely sensitive at greater accelerations.

This effect also is not caused by a badly simulated aircraft, but is caused by a missing linear acceleration cue. In real life he feels the linear acceleration immediately and he knows it is correct. In our simulator the pilot cannot feel the acceleration and he controls, therefore, the instrument. But the instrument is much more sluggish than his sensing of acceleration. But after about five seconds he can see the result at the instrument and he knows that this position is too much. The pilot concludes that the effect of speed brakes is too sluggish at accelerations near zero and extremely sensitive at greater accelerations.

After explanation and understanding of the effect by the pilots, they are able to accept it and to live with this characteristic of the simulator.

But it is very interesting that the criticism of pilots was only existent, if they were flying an aircraft with *very effective* speed brakes; especially flying the F-104. This shows clearly that the reasoning for this kind of simulator effect is correct.

3.1.3 Pilot Verification of Throttle

It is clear that we have found the same results for using throttle.

All pilots have criticized that the response to throttle is too sluggish at accelerations near zero and extremely sensitive at greater accelerations.

But here the effect is not so important as with speed brakes.

3.1.4 Pilot Verification of g-Suit

The missing motion cues also show effects on the g-suit. We were sure that our pressures at the g-suit were correct. In spite of this the pilots maintained, that the pressure of the g-suit was too high.

The g-suit has to press the arteries and veins to avoid an accumulation of blood in the legs and in the abdomen. Now it is clear, what the reasons were for the pilots criticism: they missed accelerations in our simulator. Therefore we have no forced displacement of blood and pilots feel the pressure of the g-suit as too high. We have reduced the pressure of the g-suit to half. But the pilots required lower and lower pressures. Now we cannot reduce the pressures of the g-suit further since the pilots fly with greater g-loads. They don't know limitations if they can strike their target and will always fly with high g-loads, if they do not feel bodily indisposition. Therefore they must accept the high pressures of the g-suit; they have been able to live with this characteristic.

3.1.5 Pilot Verification of Stick Force Feel

A similar problem may be the verification of stick force feel at high "g"s. Here the pilot misses the forces on his hand and arm and he thinks that the stick forces are not correct, although they surely are. This effect was also discussed with and understood by the pilots.

Another problem, which is also caused by missing motion cues, is the bob-weight of the stick. Here the pilot says that the bob-weight is too severe. The reason is the same as mentioned above; we have no true "g"s.

3.1.6 Pilot Verification of Grey-Out

Another effect explains this behaviour much more clearly. Grey-out is caused by a reduction of blood pressure in the eyes by positive "g"-loads. At higher "g"-loads, continuing for a longer time, grey-out results in total black-out (see Figure 6). In air-to-air combat the pilots fly frequently near the limit of black-out. Sometimes they must reduce the "g"-loads to be able to see the target. But on the other hand he wins his fight, in most cases, if he can fly higher "g"-loads. The pilots have observed that we have a dial for adjusting the grey-out on-set. During familiarization with the simulator we had permanently to raise the grey-out on-set. After this procedure we have often had the grey-out on-set at nine "g"s and all pilots have felt that this was correct and the simulator near to real life. After referring to the fact that these high "g"-loads were unrealistic they still maintained that the simulator was correct. After discussing and explaining these effects they were able to accept a reasonable grey-out on-set. It is clear that the return from grey-out is much faster than the beginning of grey-out.

3.1.7 Verification of Buffet On-Set and Wing-Rock

As mentioned above the DFS has a buffet system and no motion system. Therefore the buffet on-set comes from nothing and the pilots comment is: buffet on-set is too severe. The reason is clear: in real life the pilots always have base motion cues which become stronger and stronger until they reach the buffet. In the DFS the buffeting starts without previous warning and the reaction of the pilots is understandable. Therefore, we have tried to weaken the buffet on-set. We installed wing rock for the F-104G. Now the pilots commented: What did you change? The pilots did not like the wing rock since they had not had a motion cue before. It was found better to remove the wing rock simulation and to reduce the rate of buffet on-set.

3.1.8 Pilot Verification of Tracking

Because of missing motion cues the pilots also tend to excessive control activity when tracking. They do not feel the effect of their inputs, therefore, they make too high inputs with both throttle and aileron. The result is clear. They find the aircraft extremely sensitive and they react continuously to keep position. But they can be trained to accept this characteristic of the simulator.

We must remark here that similar effects will be caused if the time delay, between input signals and the subsequent reactions, is greater than about one hundred and twenty milliseconds. We must differentiate between the reasons for similar effects.

Another kind of effect is due to the speed brakes and the afterburner of the opponent aircraft. In real life the pilot can see if the target uses speed brakes or afterburner. Then he has only a little time delay in tracking maneuvers. Therefore, we must install speed brakes and an afterburner lamp into the gimballed model; otherwise the pilot is prejudiced in the simulator, as he cannot get accustomed to the missing speed brakes and afterburner of the opponent aircraft. He cannot guess the opponent maneuvers and therefore must see the use of speed brakes or afterburner, otherwise he gets a large time delay and his reactions are too late.

3.2 Effects caused by visual system

We have described the principles of sky-earth-horizon-projection by a Vista projector without any optics. It is clear, that the projection does not present

- altitude or
- terrain motion cues

3.2.1 Angle Between Horizon and a Horizontal Line Through Pilot's Eye

The angle between the horizon and a horizontal line through the pilot's eye is represented correctly. But this variable (with altitude) angle gives no information about altitude. We have tested with increased angles for the horizon. The pilots have not noticed these incorrect angles, except one case. If the angle between horizontal line and horizon is less than required for low altitudes the pilots have mentioned it.

3.2.2 Approaching the Ground

The DFS visual system is completely sufficient for air to air combat simulations. At altitudes greater than fifteen hundred meters there are no problems at all. Below fifteen hundred meters there exist certain difficulties with crashing. The pilot cannot estimate the altitude and therefore he cannot decide on his maneuver.

The pilot has two possibilities on which to decide: Firstly, that he will concentrate on the target, in which case he cannot look at his altimeter and since he cannot estimate the altitude from visual sight, he will probably crash. Secondly, that the pilot will not crash, because he concentrates on his altimeter, but the possibility of losing the target will arise.

We had also installed two lights lateral to the cockpit outside field-of-view which flashed below an altitude of two thousand meters with increasing frequency as the ground was approached. But as result of tests the pilots prefer an *undisturbed combat simulation with the risk of a crash* than a distortion, which disturbs the simulation effect of real flight. All pilots will avoid a crash, since they are ashamed of it. Therefore we have removed the lights warning of approach to the ground. Mr A.J.Meintel Jr from NASA-Langley has written, in a paper, the following pilot's comments for differences between operation in the simulator and in flight:

"Another area where the simulation is lacking is something that you'll probably never be able to put into simulation. That's the inherent fear that pilots have of getting slow or getting close to the ground. That only happens in real life and in simulation if you crashed, you just went to reset and started all over again. So in a simulation, you might try maneuvers that are a little bit out of the ordinary and performancewise, you might try to push the airplane in an area where you normally wouldn't". Therefore, we must understand that the pilot's operation in a simulation may differ from actual flight, and this difference must be considered in the evaluation of the results.

The missing altitude and terrain motion cues are tolerable in air to air combat.

3.2.3 Level Flights at Low Altitude

For a trial of air-to-ship bombing we have modified the visual system of the simulator. First of all we have removed the earth transparency and have compensated by a transparency of water. Second we have removed the gimballed aircraft model and have replaced it with a model of a fast patrol boat. Figure 7 shows a photograph of this gimballed model.

The ship was computer controlled. The impression of sky-earth-horizon was a "typical smooth water with a diffuse horizon" scene. This is a very difficult situation for the pilot. The pilots had to fly attacks on the ship by diving or by level flight at low altitude. The conditions in the simulation cannot be compared with the normal training flight conditions.

Because of missing real flight data under "smooth water with diffuse horizon" conditions the data of air-to-ship simulation have not been verified till now.

The result of this study is the following: For level flights and air-to-ground maneuvers variable details of the ground are necessary for estimating height and distance. The pilots need information on height and distance with that kind of task. Without these variable details the simulation of level flights will not have the same high accuracy in results as air-to-air combat simulation.

4. CONCLUSIONS

Driving a manned simulator means approximation and not duplication of the real world. Deviations from real world are facts the simulator specialists have to live with. For correct working and interpretation of results the differences between simulation and real world must be known and interpreted.

In other words simulation is an imitation of real world and not the real world itself; we simulate and not duplicate the real world. To realise this situation we have investigated the described effects and we have found that these effects, in the particular simulator, are not significant to the results of air-to-air combat simulations.

We have described such effects with the DFS which show some deviations from real world. But we must remark here, that the DFS is a very good aid for air-to-air-combat simulation and it has been proved during many studies of air-to-air-combat. In addition IABG has discovered, in a comparison between air-to-air-combat simulation without motion system and with motion system, that the simulation without motion system has advantages over the simulation with motion system. This is due to the wash-out function of motion systems at frequently alternating high "g" loads during an air-to-air combat simulation. During all studies of validation and air-to-air combat simulations we have seen that the pilots are able to fly correct maneuvers with the DFS. The main remarks of pilots are the following:

- The DFS without motion system and with buffeting and grey-out simulation is sufficient for very good air-to-air combat simulations.
- The impression of the visual system is excellent and the feeling of real flight is existent.
- All the maneuvers of air-to-air combat, including tracking, are possible with sufficient accuracy.
- The described effects are existent, but don't have a noticeable effect in air-to-air combat simulations.
- At this moment motion systems are slow-acting for air-to-air combat. Therefore simulations with motion are worse than without motion.

5. REFERENCES

1. – Lockheed-Report 14475, Test 44 Flt 44 Run/356, 4-5-60, 1960.

2. – *Simulation*, AGARD Conference Proceedings No.79, January 1971.

3. – *Flight Simulation/Guidance Systems Simulation*, AGARD Conference Proceedings No.198, June 1976.

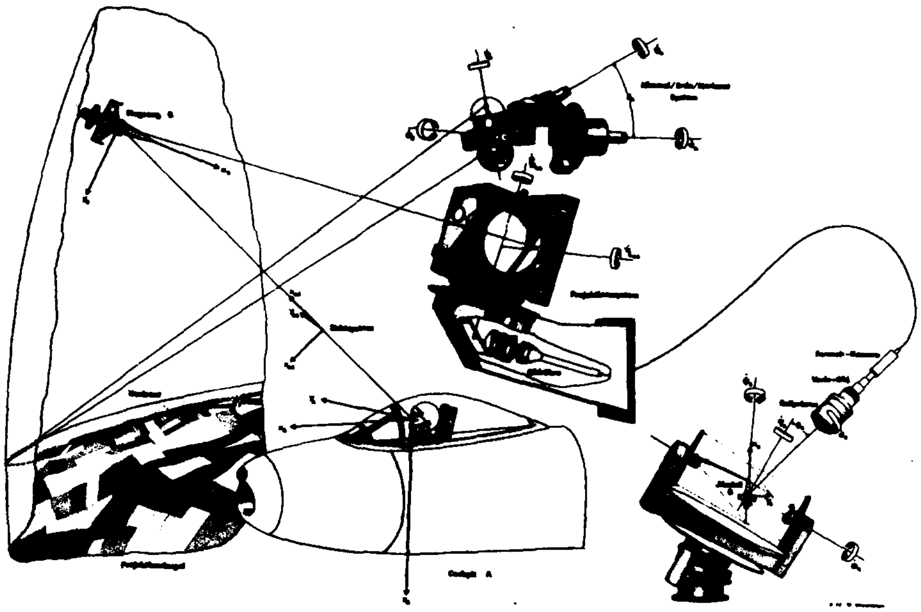


Fig. 1 Dual flight simulator at IABG

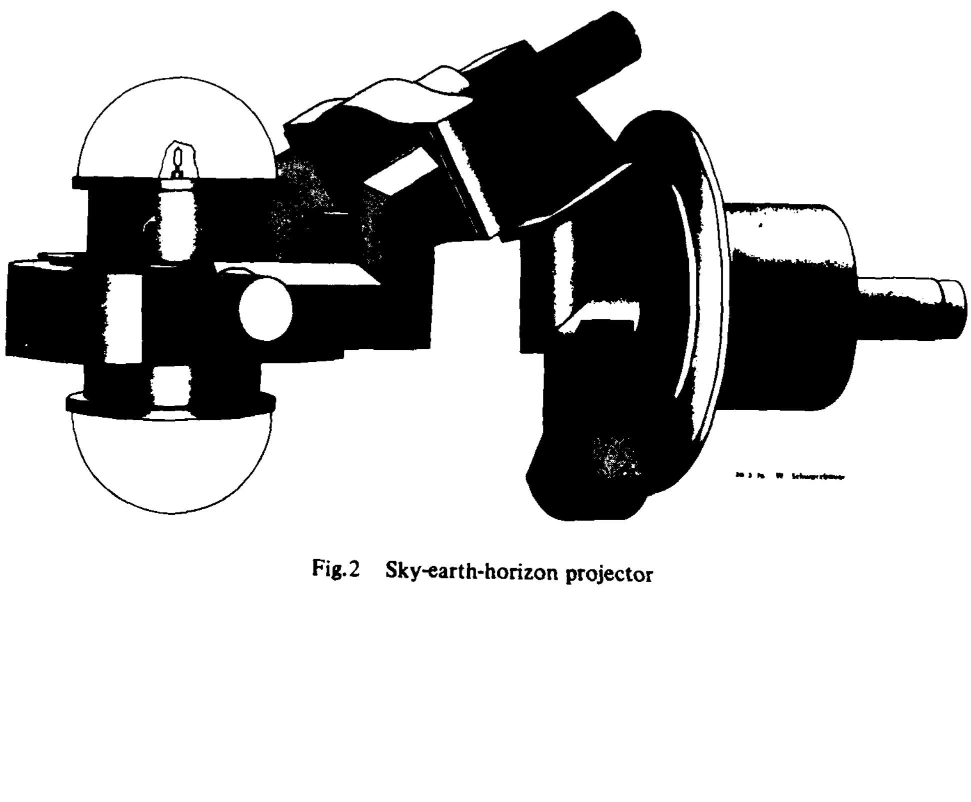
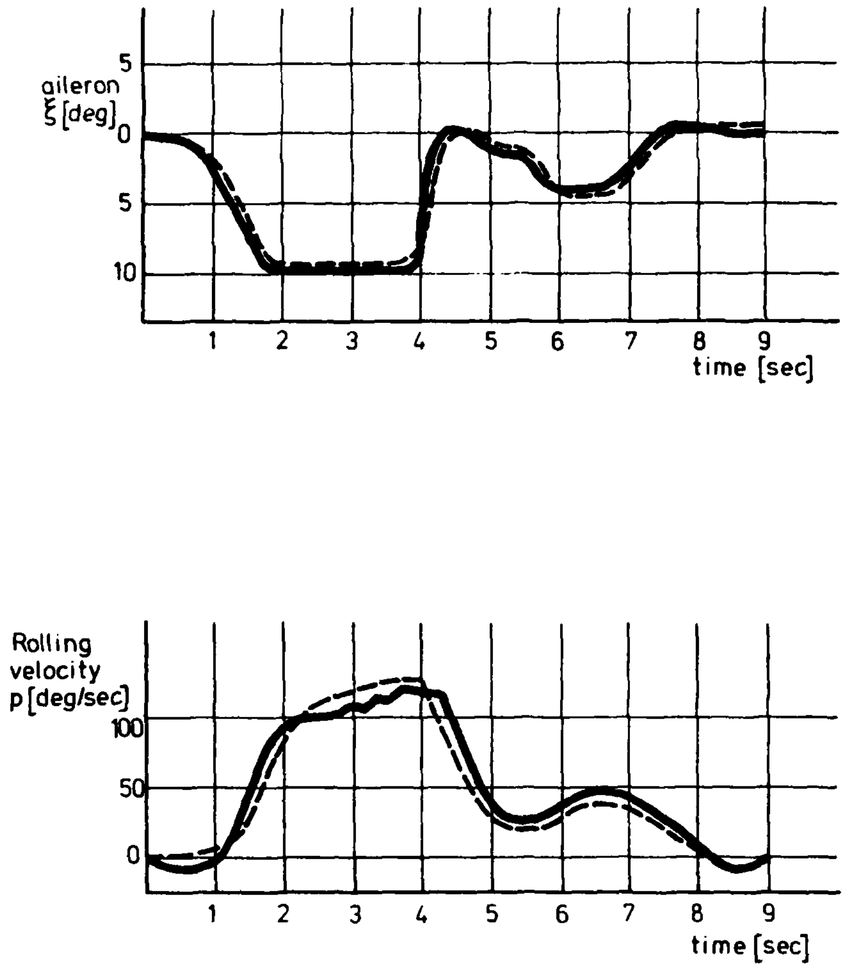


Fig. 2 Sky-earth-horizon projector

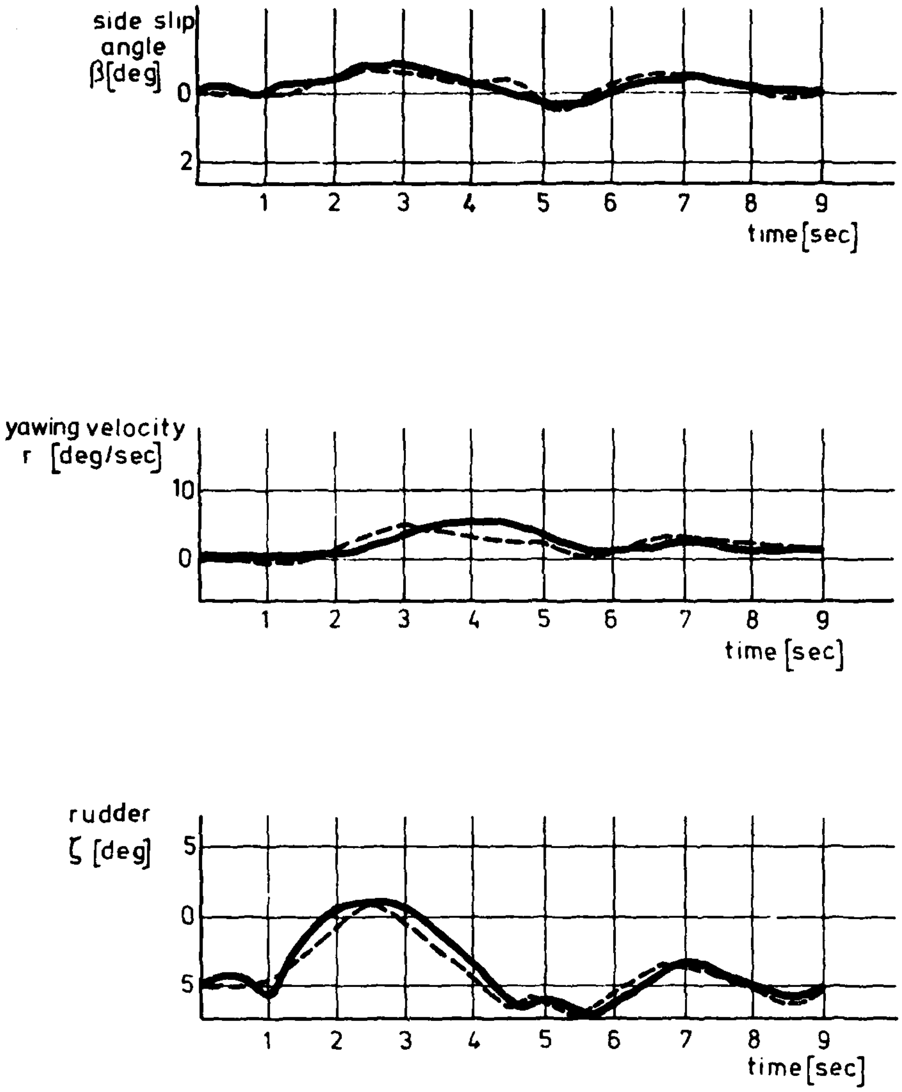


configuration: missiles + wingpylons
total weight: 70 022 N , Height: 12 160m ,
Machnumber: 1.909

——— measurements at real flight [Lockheed Report 14 475 (1960)]

– – – simulated aircraft [Mr. Weickhardt , IABG]

Fig.3 Comparison between flight and simulation

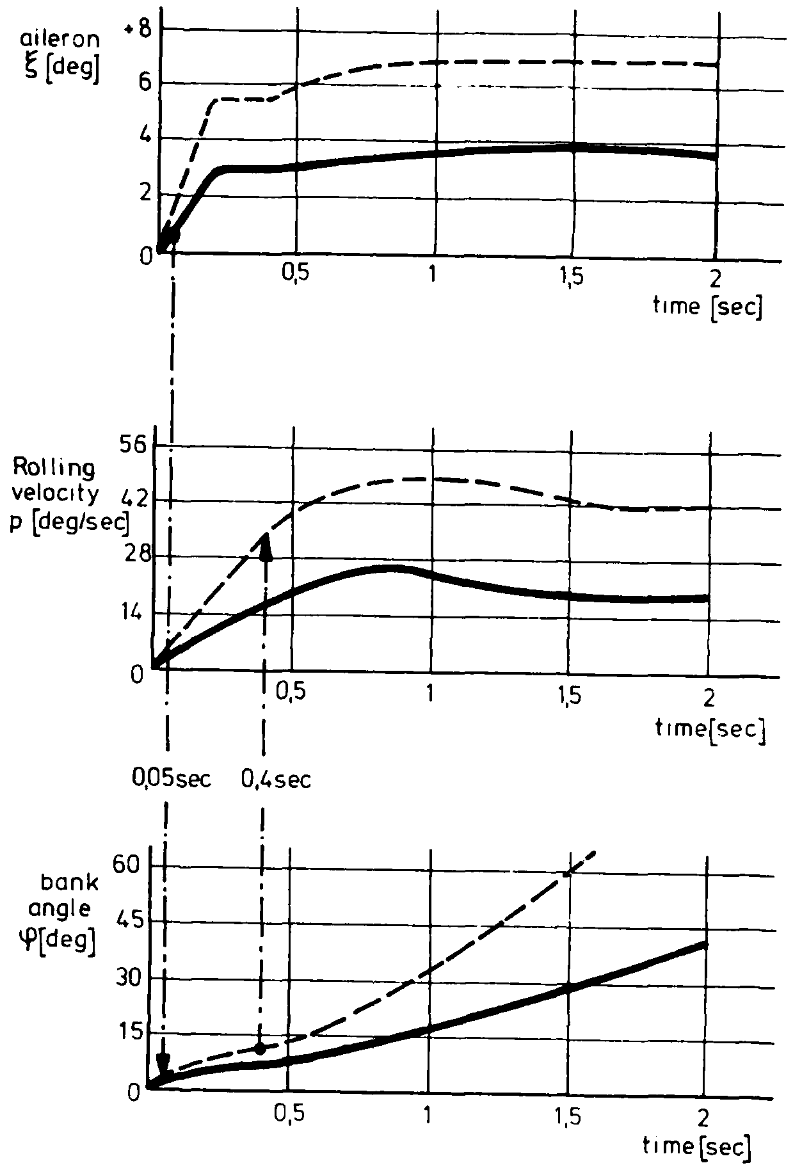


configuration: missiles + wingpylons
total weight: 70 022 N, Height: 12 160 m,
Machnumber: 1.9

▬▬ measurements at real flight [Lockheed Report 14 475 (1960)]

--- simulated aircraft [Mr. Weickhardt, IABG]

Fig.4 Comparison between flight and simulation



configuration: F 104 G
total weight: 79 629 N Height: 3000 m,
Machnumber: 0,5

simulated aircraft at two different roll accelerations
[Mr. Weickhardt, IABG]

Fig.5 Effect by missing roll acceleration

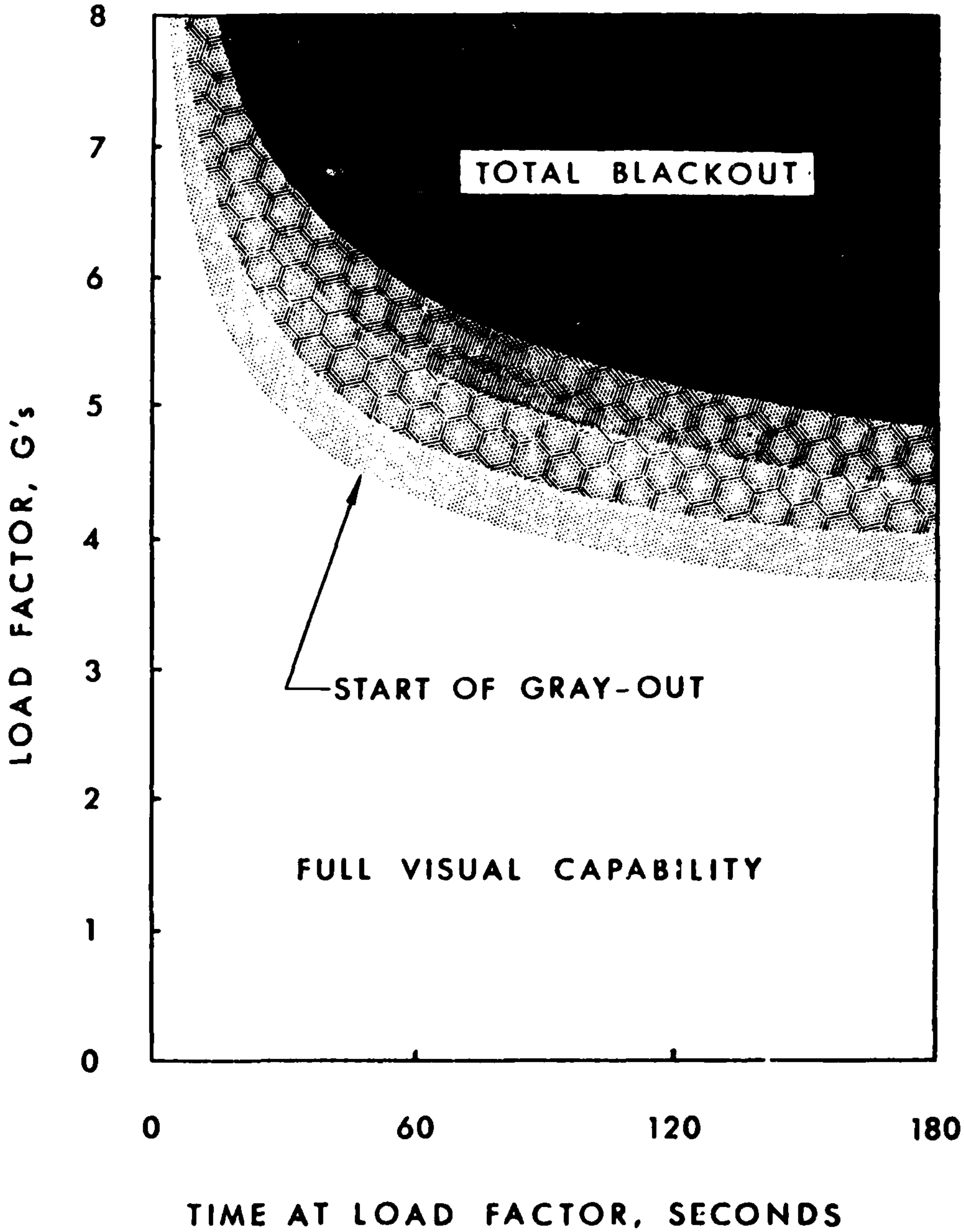


Fig.6 Gray-out as function of $\int g dt$ (Mc.Donnell Douglas report)

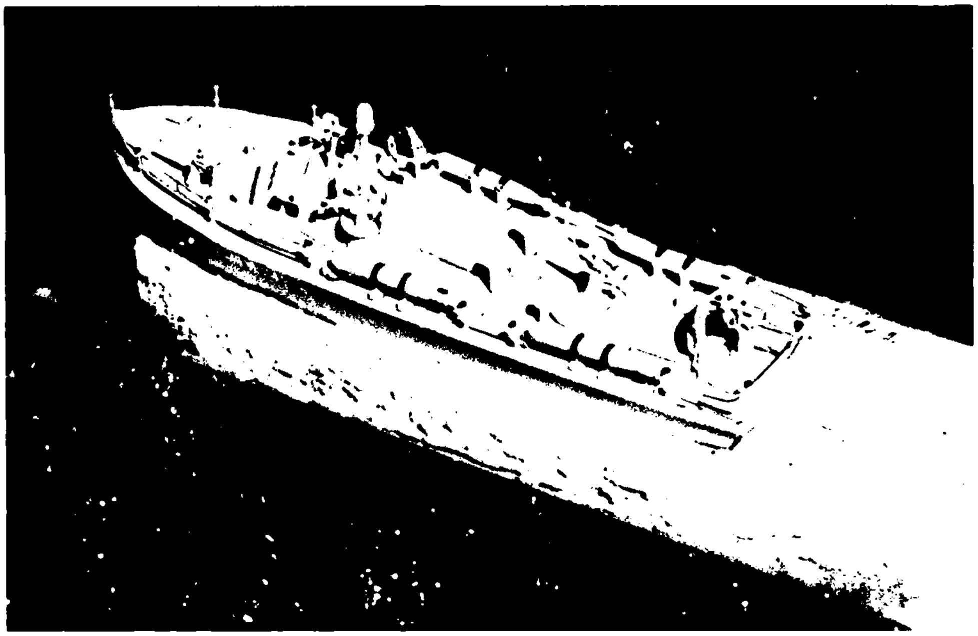


Fig.7 Gimballed model of ship

MANNED AIR COMBAT SIMULATION - A TOOL FOR DESIGN, DEVELOPMENT AND EVALUATION FOR MODERN FIGHTER WEAPON SYSTEMS AND TRAINING OF AIRCREWS

by
R.H. Mathews
Chief, Flight Simulation
Flight Simulation Department
McDonnell Aircraft Company
A Division of McDonnell Douglas Corporation

SUMMARY

Manned air combat simulation has matured into a major element in modern fighter aircraft design and development. The simulation fidelity now available allows meaningful training to be accomplished such that the U.S. Government is now procuring an Air Combat Maneuvering Simulator (ACMS) for fighter tactics training. This paper describes the contributions of manned air combat simulation to the F-15 fighter weapon systems from design concept through successful introduction to squadron service. Specific examples are given of airframe, avionics, and integrated systems simulation support in the design and development process. A comparison of flight and simulation results in several test programs including air combat maneuvering is presented. Additionally, a description is presented of the Air Combat Maneuvering Simulator (ACMS, Device 2E6) being provided to the U.S. Navy for air combat training.

INTRODUCTION

The three types of air combat simulation, shown in Figure 1, can be discussed as follows: digital, manned, and flight test. In digital simulation, air battles are conducted by computer to assess the effect of performance features or tactics. In manned simulation, man is inserted into the loop by seating him in a realistic cockpit, surrounding him with realistic visual, sound and tactile cues, and asking him to test his skill against an adversary projected on a screen. It may seem surprising to consider flight test as a simulation discipline, but it is often referred to as "simulated" air combat. In spite of the fact that it has greater realism and pilot involvement than ground based simulation, it still lacks some of the pilot motivating factors of actual combat. Flight testing also has some interesting limitations relative to manned ground based simulation, which will be discussed later.

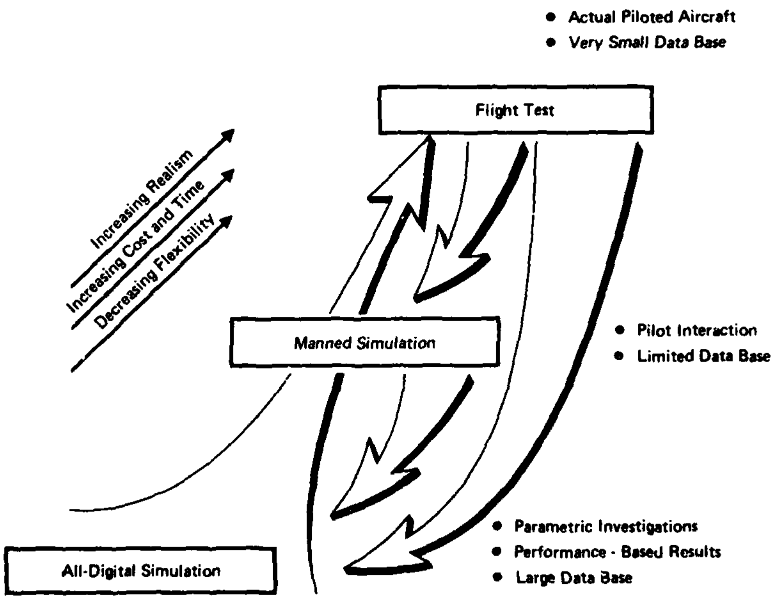


FIGURE 1
DESIGN AND EVALUATION TOOLS

At McDonnell Aircraft Company (MCAIR), these three simulation phases are employed in the design, development and evaluation of new aircraft weapon systems, and in the training of aircrews. As shown in Figure 1, we use a truly integrated approach, in which the more complex and expensive techniques are used to validate and improve the credibility of the simpler, more economical and more flexible approaches. The significant aspect of this integrated effort is the early identification of problem areas and the associated risk reduction of particular importance in today's economic and schedule environment.

As illustrated in Figure 2, manned ground based simulation is an important link in the design, development, evaluation, and training process for advanced fighter systems.

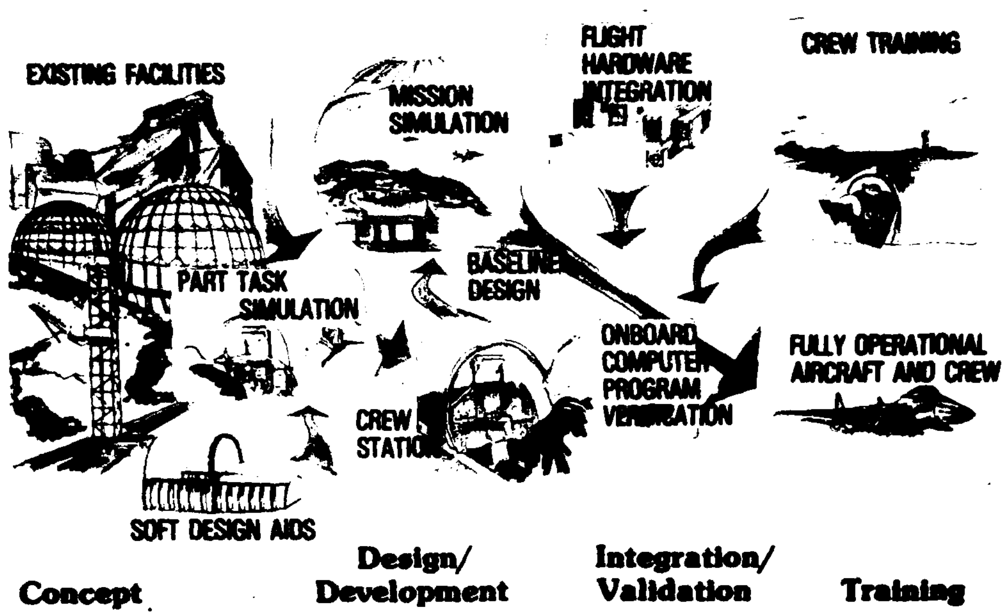


FIGURE 2
MCAIR'S SIMULATION APPROACH

Design

Ground based simulation has an integral part in the design process, even at the conceptual level. Even such design parameters as wing loading and thrust-to-weight ratio can benefit from interactive pilot inputs as to how these possible combinations can be used effectively in a combat environment. All-digital simulation, of course, offers the most cost effective means of evaluating a very large range of values for these types of parameters, and provides a ready tool to define how they affect combat effectiveness. However, interactive pilot inputs, through the manned ground based simulator, are also important, particularly in crew station design.

With the wide assortment of weapons, sensors, display systems and advanced control techniques available to the crew station designer for current and future weapon systems, it is imperative that crew station design begin at least as early as the airframe design. It is in this area that manned ground based simulation can probably contribute the greatest amount of guidance. For the F-15, for example, the design of much of the crew station subsystems, and all of the integration of these subsystems was accomplished with the simulator as a major design tool.

The value of early pilot interaction in the design process is difficult to quantify. It is significant, however, to note that the hardware configuration of the F-15 cockpit of today is essentially unchanged from the simulator cockpit configuration established prior to first flight.

Development

Hardware configuration is the key word in the development phase of manned ground based simulation. With the increasing trend toward digital avionics systems, and the accompanying greater flexibility in the development process, simulation plays an important role. During the F-15 development, much of the avionic suite was integrated into the simulation system. Figure 3 illustrates the manner in which this was accomplished. A valuable use of the simulator was the validation of on-board computer tape "patches" and modifications prior to their flight evaluation. The simulator thus permitted an accelerated flight test schedule, without the loss of a single data-taking flight due to software "bugs". During the course of the on-board computer development, approximately 150 Computer Program "bugs" were identified or corrected through the simulation program. This phase of the F-15 development is described in detail in AIAA Paper No. 77-1531.

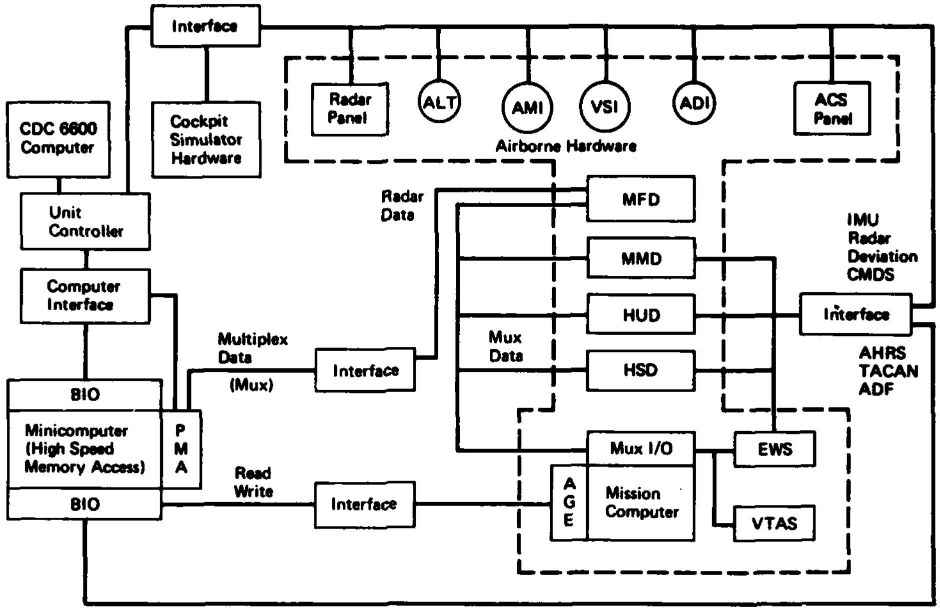
Evaluation

The evaluation phase of the simulation program overlaps the development phase. Technically it commences when the development has evolved to a "baseline" design. This baseline is then evaluated by company and customer pilots in mission scenarios that allow the pilot's full operational freedom of both air vehicle and weapon system. This phase represents the last point in time where changes to the design baseline can be initiated without extremely costly hardware retrofit.

Another major portion of the evaluation phase involves incorporating as many pieces of actual prototype flight hardware into the simulator as practical. As seen in Figure 3, the central computer, ANMI HUD, TEWS display, armament panel, and various flight instruments were all integrated into the F-15 simulator. While standard bench integration tests will verify electrical, and in some cases software compatibility, only a dynamic simulation can completely exercise the equipment. Even more important, all aspects of the software can be tested in a mission environment well before the aircraft flies.

Training

MACS is effective in two distinct training functions. The first is the training of test pilots for the formal flight test program, and later for transitioning aircrews into the aircraft.



BIO	- Binary Input Output	MFD	- Multi-Function Display
PMA	- Priority Memory Access	MMD	- Multi-Mode Display
ALT	- Altitude Indicator	HUD	- Head Up Display
AMI	- Airspeed Mach Indicator	HSD	- Horizontal Situation Display
VSI	- Vertical Speed Indicator	EWS	- Electronic Warning Set
ADI	- Altitude Direction Indicator	VTAS	- Visual Target Acquisition System
ACS	- Armament Control Set	AHRS	- Altitude Heading Reference Set
IMU	- Inertial Measuring Unit	ADF	- Automatic Direction Finder

FIGURE 3
AIRBORNE HARDWARE INTEGRATION CONCEPT

The training for flight testing has a significantly different orientation than traditional training, as the procedures must first be developed and evaluated before they can be learned. Early training is concentrated on development of first flight profiles and contingency procedures, followed by envelope expansion. For example, one of the most critical areas of training for testing is associated with the high angle of attack and spin program. Spin entry and recovery techniques are developed and thoroughly exercised before starting flight test.

Results obtained during F-15 spin testing were gratifying, in that techniques developed in simulation worked exceptionally well in flight. Aircraft attitudes and body rates actually achieved in the spin tests were predicted accurately during the simulation activity.

The simulator was also used for developing and practicing the F-15 time-to-climb profiles. A comparison of simulator predicted and actual times experienced is shown in Figure 4. While the performance at higher altitude (above 15,000M) in the aircraft exceeded the simulator performance due to upper air temperatures, colder than anticipated, the close correlation attests to the fidelity of the simulation model. This fidelity is of course a direct result of the feedback concepts shown in Figure 1.

Altitude (m)	Manned Simulator Time (sec)	Actual Record Set Time (sec)
3,000	28	27.57
6,000	39	39.33
9,000	49	48.86
12,000	59	59.38
15,000	78	77.02
20,000	131	122.94
25,000	175	161.02
30,000	228	207.80

FIGURE 4
F-15 TIME TO CLIMB SIMULATOR vs ACTUAL TIME

Training for operational aircrew follows a more formal syllabus. Normal aircraft operating procedures for start, taxi, takeoff, navigation, and landing are incorporated, but the key element in training fighter aircraft pilots is weapon system utilization.

The Manned Air Combat Simulator (MACS) provides the environment necessary for realistic training in intercept scenarios against single or multiple threats, and reproduces the traditional fighter pilot's world of visual air combat.

The "free play" environment, in which trainees can experiment with new tactics and find their own edge of the envelope against weapon systems not available in flight testing, provides training potential previously unavailable in simulators or not available in actual flight training.

MACS also offers a three-aircraft capability. Training can be conducted in inter-flight coordination by flying two manned friendlies against manned or computer piloted threats. This training capability is now being procured by the U.S. Navy in the Air Combat Maneuvering Simulator (ACMS), Device 2E6. This training system will become operational at the Naval Air Station, Oceana, Virginia in mid-1979. The facility is depicted in Figures 5a and 5b. It features several unique capabilities. First, in the independent mode, the folding partition in the instructor station area permits completely separate simultaneous training missions. Each can stop, start, freeze, replay, and debrief, completely independent of the other.

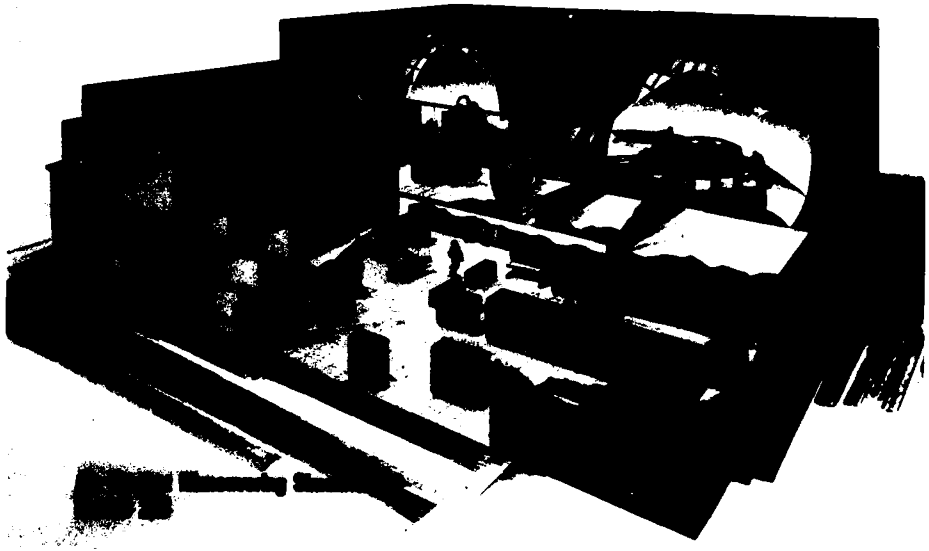


FIGURE 5a
AIR COMBAT MANEUVERING SIMULATOR

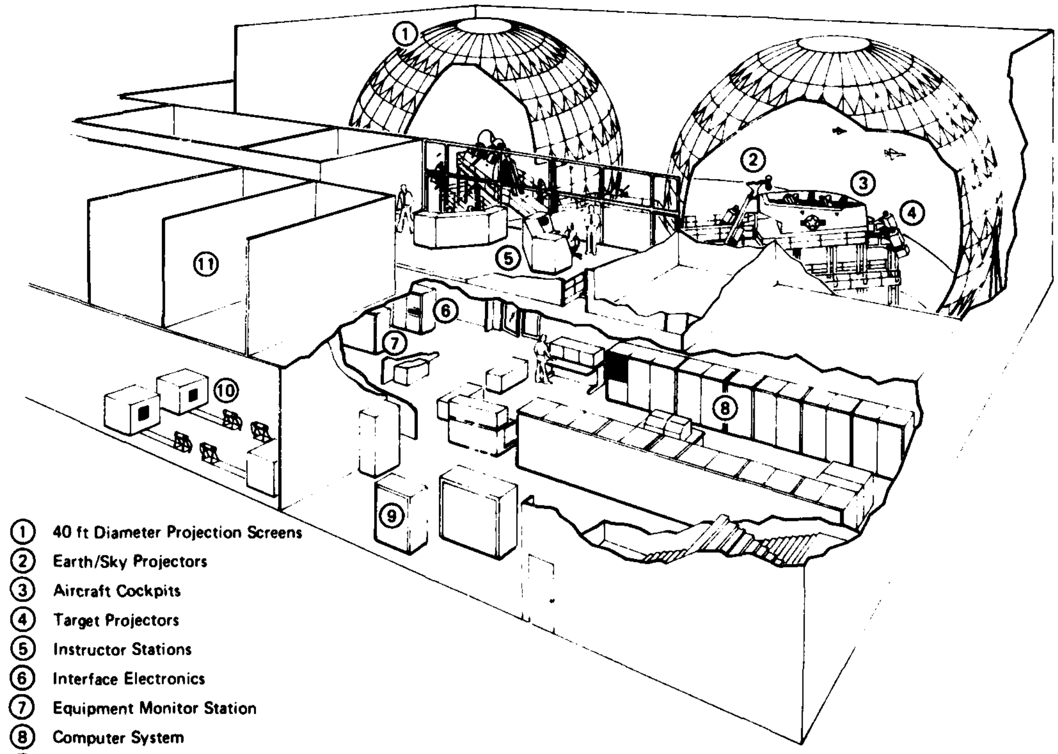


FIGURE 5b
KEY FEATURES

In this sense, the ACMS is essentially two training systems with each having close-in air combat capability in a 2 vs 1 visual environment. In the integrated mode, however, the scenario for both trainee stations is controlled from a single instructor station and the two crews can operate either as a team opposing a common threat or as combatants. In each case; the third visual target is "flown" either from the computer or by the instructor, using stick and throttles located as his control station.

A second significant feature in the ACMS is the capability to change the crew station and attendant software easily and quickly (in less than two hours) to represent any modern single or two place fighter/attack aircraft. This "quick-change" feature in the MACS facility at MCAIR has facilitated the concurrent development of advanced fighter attack system. Its application to the training community offers a significant increase in training capability while minimizing development cost and facility investment.

With ACMS it is possible to quantify combat skill level. Through the instructor's console, displays are designed to produce flexibility in content and simplicity of operation. These displays include:

- Air combat maneuvering situation (Figure 6)
- Out-of-cockpit (Figure 7)
- Instructor flight (Figure 8)

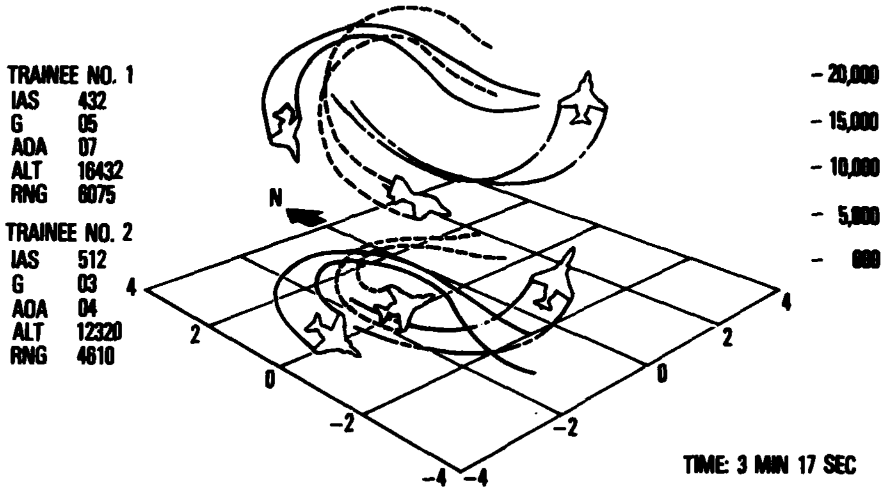


FIGURE 6
AIR COMBAT MANEUVERING SITUATION DISPLAY

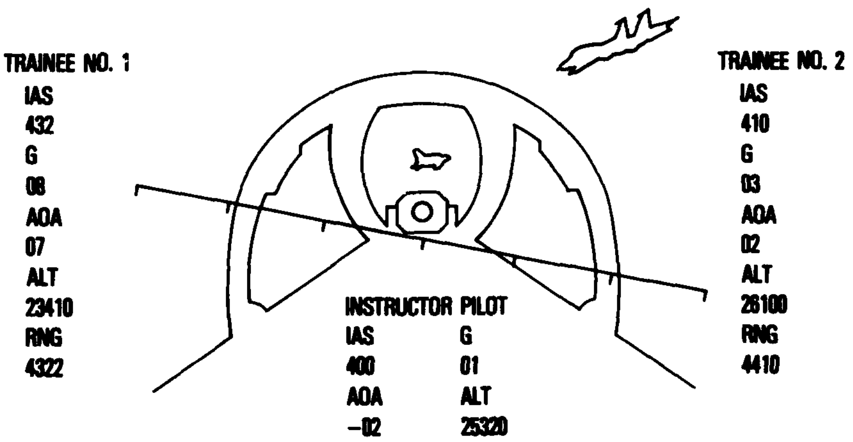


FIGURE 7
OUT-OF-COCKPIT DISPLAY

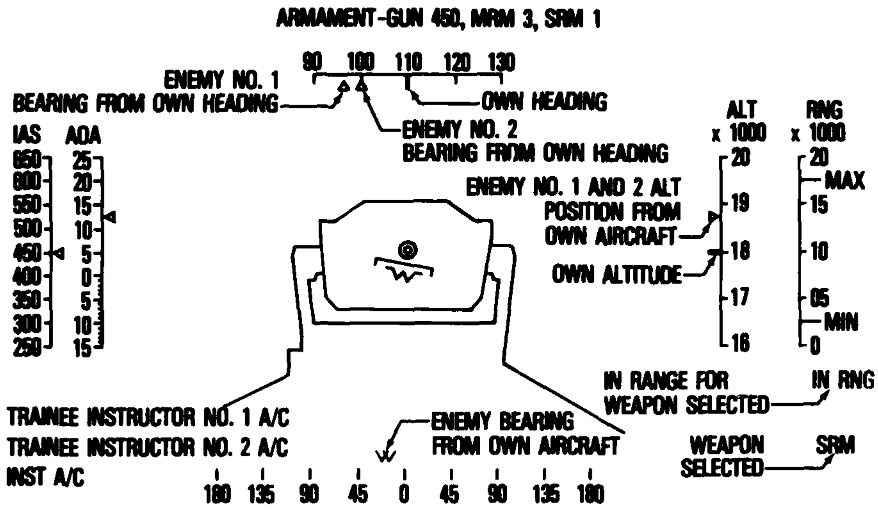


FIGURE 8
INSTRUCTOR FLIGHT DISPLAY

The ACMS instructional features permit the instructor to:

- Standardize the problem or tailor the mission to meet individual student needs
- Initialize specific segments of the flight
- Assist in refinement of training requirements, course material, and instructional strategies
- Review the mission contents in terms of aircraft type, gross weight, armament, target flight profile, etc.
- Review the entire engagement with the student, using either a replay of the engagement in the cockpit or a three dimensional display, with all key parameters, plus voice correlation in real-time
- Duplicate the initial conditions, then explore and evaluate alternate courses of action to improve success rate

CONCLUSION

MACS has progressed from an interesting engineering capability in the late 1960's to a mature design, development, evaluation, and training tool. The use of this capability in each of these areas is expanding rapidly, particularly as weapon systems become more highly integrated. The crew work load involved in weapon and sensor management, particularly in a combat environment, can of course be drastically altered by crew station design and system automation techniques.

The manned ground-based simulator has proven to be an ideal tool for performing trade studies and concept evaluations while greatly reducing the risk factors in the development of new weapon systems. It is important to note that the Manned Air Combat Simulator (MACS) at MCAIR has been used as an additional design tool and not as a replacement for conventional engineering practices. In a similar manner, the combat simulator should be viewed as an additional training tool rather than as a replacement for any part of the total training system. The applications of MACS technology to the training mission are only beginning to be identified and their benefits exploited.

USE OF PILOTED SIMULATION FOR STUDIES OF FIGHTER DEPARTURE/SPIN SUSCEPTIBILITY

William P. Gilbert and Luat T. Nguyen
Aeronautical Engineers
NASA Langley Research Center
Mail Stop 355
Hampton, Virginia 23665
U.S.A.

SUMMARY

The NASA-Langley Research Center has incorporated into its stall/spin research program on military airplanes the use of piloted, fixed-base simulation to complement the existing matrix of unique research testing techniques. The piloted simulations of fighter stall/departure flight dynamics are conducted on the Langley Differential Maneuvering Simulator (DMS). The paper reviews the objectives of the simulation research, presents the rationale underlying the simulation methods and procedures used in the evaluation of airplane characteristics, and discuss in detail the evaluation steps used to assess fighter stall/departure characteristics. Simulation results are presented to illustrate the flight dynamics phenomena dealt with.

The considerable experience accumulated in the conduct of piloted stall/departure simulation indicates that simulation provides a realistic evaluation of an airplane's maneuverability at high angles of attack and an assessment of the departure and spin susceptibility of the airplane. This realism is obtained by providing the pilot a complete simulation of the airplane and control system which can be flown using a realistic cockpit and visual display in simulations of demanding air combat maneuvering tasks. The use of the piloted simulation methods and procedures described in the paper has been found very effective in identifying stability and control problem areas and in developing automatic control concepts to alleviate many of these problems. A good level of correlation between simulated flight dynamics and flight test results has been obtained over the many fighter configurations studied in the simulator.

INTRODUCTION

In the past decade, experience has shown that close-in air combat often occurs and that fighter airplanes required to turn and maneuver effectively (particularly at low airspeeds) must be capable of flying at high angles of attack if they are to be competitive in close-in air combat. Furthermore, experience in air combat and in air combat training has shown that many fighter configurations not designed for flight at high angles of attack experience severe degradations in stability and control characteristics in this region which make them susceptible to inadvertent loss-of-control (departures) and possible entry into spins from which recovery may be impossible. Past losses of airplanes to stall/spin accidents have confirmed the fact that handbook restrictions and artificial warning systems are not suitable substitutes for improved airframe and flight control system design. Therefore, the current research emphasis at Langley is being placed on determining the departure and spin susceptibility of current and advanced fighter configurations and on identifying airframe and control system features which provide good departure and spin resistance, as described in reference 1.

The NASA-Langley stall/spin research program employs a broad and unique matrix of research tools and testing techniques, as illustrated in figure 1 and described in reference 2, in an effort to advance the technology in several areas. While the currently-used research techniques such as static and dynamic wind-tunnel tests, free-flight model tests, and spin-tunnel tests provide considerable information regarding stall/spin characteristics, these methods do not allow for piloted evaluation of airplane spin susceptibility during realistic air combat maneuvering. For this reason Langley has incorporated into the stall/spin research program the use of fixed-base piloted simulation to allow the evaluation of departure and spin susceptibility with a pilot "in the loop" performing air combat maneuvering tasks.

This paper will present and explain the objectives of the piloted stall/departure simulations conducted at Langley, the simulation math models employed to represent the airplane and control system, the simulation hardware used, and the methods and procedures used to assess the departure and spin susceptibility of fighter configurations. Finally, representative simulation results will be presented to illustrate the application of the evaluation methods described and the degree of correlation obtained with flight tests.

SYMBOLS

a_n	normal acceleration, g units
$a_{n,comm}$	pilot-commanded a_n, g units
g	acceleration due to gravity, m/sec^2
h	altitude, m
M	Mach number
p	airplane body axis roll rate, deg/sec
p_{com}	pilot-commanded roll rate, deg/sec

q	airplane body axis pitch rate, deg/sec
R	range, straight-line distance between subject and target airplanes, m
r	airplane body axis yaw rate, deg/sec
t	time, sec
X_I, Y_I, Z_I	orthogonal inertial axes
α	angle of attack, deg
β	angle of sideslip, deg
γ	flight-path angle, deg
δ_a	aileron deflection, positive for left roll, deg
δ_h	horizontal stabilator deflection, positive for airplane nose-down control, deg
δ_r	rudder deflection, positive for left yaw, deg
ε	tracking angle error, angle between evaluation airplane longitudinal body axis and range vector $\bar{R}$ (angle off), deg
θ, ϕ, ψ	Euler angles, deg

STALL/DEPARTURE SIMULATION REQUIREMENTS AND OBJECTIVES

The use of piloted simulation at Langley to investigate stall/departure characteristics has evolved from the initial use of a simple, single-cockpit, limited visual display simulator, shown in figure 2, to the present Differential Maneuvering Simulator (DMS) which will be described later. The first simulation efforts with the simple hardware, described in reference 2, did get a pilot "in the loop" and identified several other important factors to be considered. Results of these studies indicated that in order to get a good evaluation of departure and spin susceptibility, the simulation must present the pilot with a realistic air combat maneuvering environment requiring him to be almost constantly looking outside of the cockpit to acquire and maneuver against an adversary. In addition, there must be provided a good simulation of the cockpit environment in terms of pilot visibility, the display of flight instruments, and the use of a realistic force-feel system for the pilot stick and rudder pedals. As Langley's stall/spin simulation work progressed, it was found necessary to employ the DMS to more completely meet the above mentioned requirements and to cover additional needs for improved hardware and software. Subsequently, much larger, more complete aerodynamic math models have been developed and a complete representation of each airplane's automatic stability and control augmentation system is used.

The general objectives of the stall/departure simulation research today are to comprehensively evaluate the airplane's high-angle-of-attack stability and control characteristics during realistic maneuvering tasks and to define automatic control concepts which provide improved flying qualities and resistance to loss-of-control during high-angle-of-attack maneuvering. More specifically, for a given airplane configuration, the objectives are (1) to determine the controllability and departure resistance during 1-g stalls and accelerated stalls, (2) to determine the departure susceptibility during demanding air combat maneuvers, (3) to identify maneuvers or flight conditions which might overpower the departure resistance characteristics provided by the airframe and control system, and (4) to determine the effects on departure resistance of any proposed airframe modifications.

DESCRIPTION OF SIMULATOR

The Langley Differential Maneuvering Simulator (DMS) is a fixed-base simulator which has the capability of simultaneously simulating two airplanes as they maneuver with respect to one another, including a full, wide-angle visual display for each pilot. A sketch of the general arrangement of the DMS hardware and control console is shown in figure 3. Two 12.2-m (40 ft) diameter projection spheres each enclose a cockpit, an airplane-image projection system, and a Sky-Earth-Sun projection system. A control console located between the spheres is used for interfacing the hardware and the computer and displays critical parameters for monitoring of the hardware operation. Each pilot is provided a projected image of his opponent's airplane, with the relative range and attitude of the target shown by use of a television system controlled by the computer program.

Cockpit and Associated Equipment

A photograph of one of the cockpits and the target visual display is shown in figure 4. A cockpit and an instrument display representative of current fighter aircraft equipment are used together with a fixed gunsight for tracking. Each cockpit is located to position the pilot's eyes near the center of the sphere, which results in a field of view representative of that obtained in current fighter airplanes. Each cockpit is equipped with a conventional center stick, rudder pedals, and a throttle. A hydraulic force feel system provides desired stick and pedal force and dynamic characteristics. Although the cockpits are not provided with attitude motion, each cockpit incorporates a buffet system capable of providing programmable rms buffet accelerations as high as 0.5g with up to three primary structural frequencies simulated.

Visual Display

The visual display in each sphere consists of a target image projected on a Sky-Earth scene. The Sky-Earth scene is generated by two point light sources projecting through two hemispherical transparencies, one transparency of blue sky and clouds and the other of desert terrain features; the scene provides a well-defined horizon band for reference purposes. No provision is made to simulate translational motions with respect to the Sky-Earth scene (such as altitude variation); however, spatial attitude motions are simulated. A flashing light located in the cockpit behind the pilot is used as a cue when an altitude of less than 1524 m (5000 ft) is reached. The target-image generation system uses an airplane model mounted in a four-axis gimbal system and a television camera with a zoom lens to provide an image to the target projector within the sphere. The system can provide a simulated range between airplanes from 90 m (300 ft) to 13,700 m (45,000 ft) with a 10-to-1 brightness contrast between the target and the Sky-Earth background at minimum range.

Additional special effects features of the DMS hardware include simulation of blackout at high normal accelerations, use of an inflatable anti-g garmet for simulation of normal-acceleration loads, and use of sound cues to simulate wind, engine, and weapons noise as well as artificial warning systems. Additional details on the DMS facility are given in reference 3.

Computer Program and Equipment

The DMS is operated with real-time digital simulation techniques and a CYBER 175 computer. The motions of the evaluation airplane are calculated by using equations of motion with a fixed-interval (1/32 sec) numerical integration technique. The equations describing the flight control system and engine dynamics are also programmed in the digital computer and integrated numerically. The equations use nonlinear aerodynamic data as functions of α and/or β in tabular form.

DESCRIPTION OF SIMULATION PROGRAM

The overall simulation program includes the simulator hardware configuration, the computer software program, and the human pilots used to fly the simulator.

Simulation Hardware

A good general description of the DMS hardware was given in the preceeding section of this paper. Since the simulator cockpit is configured as a general purpose fighter cockpit, one generally does not have to insert a new cockpit for each new airplane configuration under study, although the DMS facility is designed to allow such changes with relative ease. Small changes to the cockpit instrument display are often made for a particular airplane. The only major change found necessary in the stall/departure simulations to date was the need to incorporate the option for a forced-actuated, side-stick controller to use in simulations of recent light weight fighters which employ such a controller. A photograph of such an installation is shown in figure 5.

Computer software program

The computer software is written to allow the real-time calculation of the flight dynamics of two complete airplane systems and to generate the parameters necessary to drive the simulation hardware. One of the airplanes represented is the primary, or evaluation, airplane which is the simulated airplane undergoing the stall/departure evaluation. The second airplane represented, set up to drive the second DMS sphere, is used as an adversary or target airplane against which the evaluation pilots fly the primary airplane. The simulations for each of the airplanes are composed of an aerodynamic math model, a mass and geometry package, an engine math model, and the flight control system equations. Information to define the airplane mass and geometry, the engine performance and dynamics, and the flight control system laws is normally obtained from military contractors. The aerodynamic math models are defined using a rather complete set of nonlinear static and dynamic aerodynamics obtained both from contractor tests and from extensive wind tunnel testing conducted in the stall/spin program at Langley. The aerodynamic data are normally provided to cover an angle of attack range from -10° to 90° angle of attack over a sideslip range of up to $\pm 40^{\circ}$; these data are normally for a rigid airframe flying at low subsonic Mach numbers.

The stall/departure aerodynamics employed are known to be inadequate for the calculation of sustained developed spinning conditions and therefore the simulator is not used to study developed spins and recoveries therefrom. Reference 4 presents a discussion of recent Langley experience with the prediction of stall/spin flight motions; and reference 5 presents an indepth discussion of the complex nature of fighter airplane aerodynamics at high angles of attack. Current piloted simulation studies are restricted to study of the airplane stall/departure, and initial spin entry motions where the best correlation with flight tests has been obtained. Particular care is taken in programming the equations of the airplane flight control system to allow flexibility for making control law changes and improvements rapidly during the course of a simulation research program. The airplane equations of motion employed are fully nonlinear, six-degree-of-freedom equations representing a rigid body.

Types of Airplanes and Control Laws

During the stall/departure simulations conducted to date on the DMS, seven different airplane configurations have been studied; five of these are depicted in photographs shown in figure 6. Each of these configurations exhibited a unique set of stall/departure stability and control characteristics. Also, each of these configurations incorporated significantly different automatic control law concepts, particularly relative to the control system influence in the stall/departure region. System complexities range from the simple, limited-authority, rate damper concepts employed in the F-5E to the full-authority, fly-by-wire, maneuver-demand control system used by the YF-16 configuration. Therefore, the simulations have covered a broad range of automatic control concepts, most of which are outlined in figure 7, many of which have been found to be quite effective in preventing loss-of-control during high-angle-of-attack maneuvering.

Simulation Pilots

An extremely important aspect of the simulation programs is the pilots that are used to fly the simulated airplanes, both to evaluate stall/departure susceptibility and to evaluate the apparent correlation between simulation and actual flight test experience. In the course of a simulation study on a particular airplane configuration, the simulation will be flown by NASA research test pilots, by both military and industry test pilots, and by military fleet pilots. Many of the simulations conducted so far in the stall/spin program have provided direct support for full scale airplane development programs, and, in most cases, the simulation was brought into operation before the airplane flight tests began. As a result, there is often no full scale flight test data available for early validation of the simulation. However, the availability of a complete piloted simulation of the airplane's expected stall/departure characteristics prior to initiation of flight testing has been found by the pilots to be very valuable for assessing the probable airplane behavior and identifying potential critical flight conditions. Validation can only be accomplished by having the test pilots engaged in flight testing also fly the simulation to provide comments on the simulation validity. It is for this reason that every effort is made to bring these test pilots in to fly the simulation as early as possible in the airplane program.

However, the bulk of the simulation research flights are conducted by the Langley research test pilots to provide easy access to a constant group of pilots. It has been found to be much more productive to conduct exploratory simulation work using such research test pilots than to attempt to use fleet pilots. Although it is very convenient to conduct most of the simulation study using onsite research pilots, there is no substitute for bringing in both test pilots and fleet pilots during the program to do evaluations of newly-developed control concepts and to validate the simulated airplane behavior against full scale flight test experience. Even direct comparisons of simulated and flight time histories are really no substitute for piloted evaluation, particularly in cases where a phenomenon such as wing rock is involved. Experience has shown that phenomenon such as wing rock can vary in severity considerably between two different airframes of the same airplane design; pilot experience with such variability is invaluable in assessing the validity of simulation.

Form of Simulation Results

In general, the results of the simulator investigations are obtained in the form of pilot comments and time-history records of airplane motions, controls, and tracking for the various tasks and maneuvers performed. In preparing for the simulation of each particular airplane configuration, linearized analyses of dynamic stability characteristics of the combined airplane and control system are conducted to aid in the interpretation of the results and the preliminary prediction of control system effects. During the actual operation of the simulation program, the simulated airplane flight parameters are displayed in real-time for study by the simulation engineer and are recorded on magnetic tape for post-simulation analysis and cross-plotting of results. More recently, a special T.V. camera has been mounted to look over the pilot's shoulder and provide the simulation engineer with a real-time look at the simulated motions; this video information has proven to be quite valuable in interpreting pilot comments during complex maneuvers and correlating the comments with the flight parameter time histories. Movies developed from video tapes taken during simulation flights have been found very useful in the presentation of simulation results to show clearly important airplane dynamics.

EVALUATION CONSIDERATIONS AND PROCEDURES

The evaluation procedures that are currently used in stall/departure simulation at Langley have evolved over the life of several individual simulation programs. The procedures that have now been found most effective reflect considerable care in both the selection of the actual maneuvers to be performed on the simulator and in the specification of the ground rules for the pilot to follow in executing the maneuvers and tasks assigned to him.

Considerations in Evaluation

Most of the evaluations are performed using a NASA research test pilot who is familiar with air combat maneuvers employed with current fighter airplanes; however, as noted earlier, military and contractor test pilots and fleet pilots often fly the simulation during the course of a study. Experience with the simulation of fighter stall/departure characteristics has confirmed that visual tracking tasks which require the pilot to divert attention from the instrument panel are necessary to provide realism in studying the possibility of unintentional loss of control and spin entry. Furthermore, early studies in stall/post-stall simulation showed that mild, well-defined maneuvers can produce misleading results inasmuch as a configuration that behaves fairly well in such slow maneuvers may be violently uncontrollable in the complex and pressing environment of high-g, air combat maneuvering (ACM); therefore, the tasks used should vary in complexity and difficulty. Finally, for purposes of evaluation in comparing the performance of several configurations, the tasks used must be repeatable.

Evaluation Procedures

The following evaluation procedures are used to account for the foregoing considerations. In order to force the evaluation pilot to fly the simulated airplane at high angles of attack, the target airplane is programmed to have the same thrust and performance characteristics as the evaluation airplane; however, the target is given idealized high-angle-of-attack lateral/directional stability and control characteristics. The superior target airplane simulation is then flown by the evaluation pilot through a series of ACM tasks of varying levels of difficulty; simultaneously the target motions are recorded on magnetic tape for playback later to drive the target model as the task for the evaluation airplane. In this manner, repeatable tasks, ranging from simple tracking tasks to complex, high-g ACM tasks are developed for use in the evaluation. The pilot flying the evaluation airplane in a given task is provided with a simple set of ground rules: he is asked to maintain a good offensive position behind the target airplane (small angle off and within gun range) and to then attempt to obtain as much gun-tracking time as possible. This set of pilot ground rules, combined with the fact that the evaluation pilot is pursuing a slightly superior airplane, has consistently provided the simulation engineers with the ability to devise air combat tracking tasks to force high angle-of-attack maneuvering situations to occur.

Normally the simulator evaluation of a particular configuration is conducted in two fairly distinct phases. The first phase of the study involves pilot familiarization with the simulated airplane, evaluation of the "open-loop" departure/spin resistance characteristics of the airplane, and development of the air combat maneuvering (ACM) tasks for use in the second phase of the study. The second phase of the study then involves having the pilot(s) fly the simulated airplane (with various control system and airframe configurations) against the various ACM tasks. Some of the various maneuvers and tasks that are employed during the simulation evaluation of an airplane configuration are outlined in figure 8 and will be described in detail in the following sections.

Airplane Evaluation and Task Development

As mentioned earlier, the first study phase is concerned with pilot familiarization with the simulation, evaluation of the "open-loop" departure/spin resistance characteristics of the airplane, and development of the ACM tasks. The pilot familiarization phase involves allowing the pilot to perform simple air work of his chosing to become familiar with the stability and control and maneuverability of the simulated airframe with its particular flight control system design. For example, several recent simulated airplanes incorporate "maneuver-demand" control laws, where, for example, pitch stick inputs command a blend of normal acceleration and pitch rate and roll stick inputs command roll rate - no stick inputs command a simple aerodynamic surface deflection as is the case for more conventional airplane control systems. The pilot must become familiar with the pecularities of such new control schemes. For example, a roll-rate command system requires the pilot to make a roll stick input if he desires a roll rate. If, instead, the pilot attempts to roll with rudder pedals (as is common on conventional fighter airplanes, particularly at high angles of attack), the roll control system will deflect the ailerons to oppose the generation of roll rate. The resulting control surface deflections constitute crossed-controls - a prospin control combination at high angles of attack. Figure 9 presents a time history of the simulated airplane motions obtained when the pilot attempted to roll with rudders in an airplane using a roll-rate command system. It can be seen from figure 9 that, while the pilot was commanding a right roll, the control system deflected the ailerons to the left to oppose the rolling maneuver, thereby producing a much slower roll than could be obtained if lateral stick were used.

Stall, departure, and spin-resistance.- During the first phase of a study the pilot looks for flight conditions or maneuvers in which the simulated airplane exhibits degraded stability and control characteristics. This involves the evaluation of the stall, departure, and spin resistance characteristics. Flights involve both slow and rapid (accelerated) entries into the stall/post-stall angle of attack region and the assessment of applying various control inputs, individually and in combination. A further assessment of departure/spin resistance is made using several rather extreme maneuvers for stall entry: (1) an inertially-coupled entry, (2) a kinematically-coupled entry, and (3) a vertical stall entry. Although such maneuvers may not be frequently encountered in air combat, they are possible and should therefore be considered for highly maneuverable fighter airplanes.

In the inertially-coupled entry, the pilot applies full back stick while rolling rapidly from a moderate angle of attack condition (a roll and pull maneuver). The combined large roll and yaw rates often cause sufficient inertial coupling into the pitch axis to drive the airplane to large angles of attack. An example of such a maneuver is shown in figure 10 for a fighter configuration which employs active angle of attack limiting to maintain α below about 27°. As can be seen, the coupled maneuver defeated the limiter and drove the simulated airplane into a post-stall gyration. This same type of result has also been obtained in flight on a similar airplane.

The kinematically-coupled entry is attempted by the pilot pulling the airplane into a low-speed, high pitch attitude, high-angle-of-attack condition in a turn and then reversing the bank angle. Such a maneuver is illustrated in figure 11 for the same α-limited airplane as mentioned above. The bank-angle change kinematically translates angle of attack into sideslip and a large sideslip results, followed by an increase in α above the limit due to loss in pitch stability at sideslip. A condition such as this might occur in combat if the pilot attempted a rapid heading change at very low airspeeds during a near-vertical maneuver.

The last maneuver, a vertical entry, is simply accomplished by the pilot putting the airplane into a near vertical climb, allowing the airspeed to drop to near zero, and then pushing the nose over to cause a rapid increase in angle of attack. In this case, an airplane pitch control system is not capable of limiting the angle of attack increase due to the low dynamic pressure and the subsequent lack of control power. Such a maneuver is described by the time history records presented in figure 12. In the case shown in figure 12, the subject airplane was represented as having large, restoring negative pitching moments at the extreme angles of attack encountered, and, therefore the airplane reduced angle of attack readily to an unstalled flight. However, had the configuration exhibited a deep stall trim condition at these extreme angles of attack (which is not unlikely for some CCV configurations), recovery from the post-stall condition could have been greatly delayed, at best, and possibly impossible in the worst case. In summary, these extreme maneuvers can severely tax the capabilities of any automatic control system designed to maintain the airplane within a predetermined flight envelope. It is felt to be important, however, to identify any possible maneuvers which might defeat an automatic limiting concept and lead to loss-of-control.

Roll performance evaluation.- Before moving into the development of complex ACM tasks, normally the pilot is requested to conduct a roll performance task. This involves performing a simple high-g pull-up in a turn to a specified angle of attack followed by a maximum effort bank-angle (or turn) reversal executed near this angle of attack. A three-dimensional sketch of such a task is shown in figure 13. This maneuver is used to assess the useful rolling performance of the simulated airplane at high angles of attack. The maneuver time history, such as the example shown in figure 14, is analyzed to determine the maximum usable roll rate, the level of sideslip generated, and the precision with which the pilot controlled bank angle. Such a maneuver involving a simple, hard turn reversal is believed to be a more realistic maneuver to use in assessing roll rate than one involving rolling the airplane through a full 360°. Use of a roll performance task such as this is very helpful in quantifying improvements obtained from various automatic control system features as is shown in figure 15.

ACM task development.- The last portion of the first study phase is spent developing a series of ACM tasks for use in evaluating the airplane high angle-of-attack maneuverability and departure susceptibility with and without various flight control system features. The early stages of this effort to develop ACM tasks often involves two pilots flying the simulator against each other in one-on-one ACM, where one pilot flies the primary evaluation airplane in one sphere and the other pilot flies the target airplane in the other sphere. An effort is made to identify realistic maneuvering situations that highlight the flight conditions in which the evaluation airplane is most susceptible to loss-of-control. Once the desired maneuvers are identified, the evaluation pilot puts them together into a series to form ACM tasks which are tape recorded as he executes them on the simulator. The tasks may have a duration of up to 200 seconds, although most are shorter.

Usually, several tasks are developed to cover a range of difficulty and complexity. Typically there are three types of tasks: (1) a steady windup turn for steady tracking evaluation (2) a bank-to-bank task (or horizontal S) with gradually increasing angle of attack up to the maximum trim angle of attack to evaluate rapid rolls and target acquisition, and (3) a complex, vigorous ACM task to evaluate the simulated airplane susceptibility to high angle of attack handling qualities problems during aggressive maneuvering. In most of the ACM tasks employed for evaluation, the simulation is initially set up prior to a run with the evaluation airplane positioned 457 m (1500 ft) directly behind the target at the same altitude [approximately 9144 m (30,000 ft)], on the same heading, and at the same subsonic speed as the target (usually between .6 and .8 Mach).

To obtain a steady tracking task a smooth windup turn is flown, with the target airplane angle of attack being increased gradually (to tighten the turn) till it reaches the maximum trim angle of attack possible for the evaluation airplane. This approach of gradually progressing through the high angle of attack region allows the pilot to make a refined assessment of the tracking capability of the simulated airplane over its entire angle of attack envelope. Upon initiation of a simulated flight, the target airplane gradually establishes a banked attitude and slowly increases angle of attack, covering a range of normal acceleration to as high as 7 g's, losing altitude, and finally decelerating to fairly low Mach numbers (as slow as M = .3). The pilot attempts to track the target as accurately as possible while maintaining a reasonably close range and a good trail position.

Usually, the bank-to-bank and the ACM tasks are referred to as maneuvering tasks since they represent a more rapidly changing job for the pilot and require considerably more control activity. The rationale for having both the mild tasks, such as the windup turn, and the maneuvering tasks is that handling qualities deficiencies that may be manageable for the pilot in a mild, slowly-changing task can become completely unmanageable in a pressing, rapidly changing task where the pilot has insufficient time to attempt to compensate for airplane handling deficiencies. The intent is then to find any such situations and attempt to develop control system improvements to alleviate the deficiencies if possible.

An example of a target flying in a bank-to-bank task is shown in figure 16. As noted earlier, such a task allows the pilot to evaluate the ability of the airplane to roll rapidly to acquire the target and then to stabilize for tracking while pulling to high-g loadings. Any significant roll control problems encountered by the pilot in this task will significantly decrease the amount of time-available in a given turn to attempt to do gun tracking. An example of a target flying in a more general ACM task is shown in figure 17. As an aide in visualizing this task, the first half of the task is sketched in figure 17(a). A time history of the target motions is shown in figure 17(b).

Another example of a general ACM task is shown in figure 18 in terms of a time history of the important target airplane flight variables. This latter task was found particularly interesting to fly against in that it requires quite high angles of attack and very low airspeeds, and, at two points (near t = 35 sec and 95 sec), this task requires the execution of near-vertical reversals at airspeeds well below 150 knots. During the simulation in which this task was used, one version of the evaluation airplane being flown against this task experienced prolonged departures from controlled flight at the two critical, low-speed points referred to above. These departures were severe enough to cause the pilot to completely lose his offensive position in the ACM task.

All of the above-described tasks have been found to be very demanding and to require the pursuing airplane to have good handling characteristics at high angles of attack in order to achieve good tracking results and avoid loss of control.

Evaluation of Performance in Tasks

In evaluating the simulated airplane with and without various special high-angle-of-attack control system features, numerous simulation runs are made flying in each of the tracking and ACM tasks for each control system configuration of interest. The pilot is not normally informed of the control configuration or flight task prior to initiating a test run. This procedure tends to minimize any tendency on the pilot's part to anticipate the problems or to be particularly cautious. In particular, during the flights against the recorded ACM tasks, the pilot tries to optimize his offensive position while obtaining as much tracking time as possible.

Sufficient flights are made of the various control configurations in the several tasks to insure that the pilot's "learning curve" is reasonably well established before drawing any conclusions on evaluation results. Some configurations may require close attention to the learning factor since the pilot may be adapting to a new controller, such as a side stick concept, as well as to a new set of automatic control laws. On the basis of the above-described approach to evaluation, the performance of the simulated airplanes in the ACM tasks is believed to be representative of the high-angle-of-attack handling qualities to be expected of the full-scale airplane (recognizing, however limitations imposed by the low Mach number and Reynolds number of the input aerodynamic data).

Evaluation of the performance of the simulated airplane is based on pilot comments, the ability of the pilot to execute the assigned tasks, and analysis of time histories of airplane motions and tracking. In particular, close attention is given to the parameters α, β, ϕ, and ε and the pilot control inputs to determine (1) how well the task was executed, (2) the excursions experience (for instance, in β, tracking error, and range), and (3) the workload of the pilot. Evaluations on the DMS normally consider not only the basic airplane performance but also the effects airplane control system features designed for high angles of attack.

Results of recent studies of wing rock problems at high angles of attack provide a good illustration of the use of the steady tracking task to evaluate high-α handling qualities problems. In the subject case, the fighter configuration under study had been modified to incorporate a stability augmentation system designed to alleviate an airplane wing rock tendency which was easily aggravated by the pilot during precise, closed-loop tracking tasks. Unfortunately, the control systems modification not only failed to suppress the wing-rock problem but inadvertently seriously degraded the airplane departure/spin resistance. After sufficient piloted simulation study and correlation with flight tests, an improved automatic stability and control augmentation system was designed which successfully suppressed the airplane wing rock tendency while providing a high level of departure and spin resistance.

The improvement obtained in steady tracking at moderate to high angles of attack is illustrated in figure 19 which presents time histories of the simulated airplane flying against a wind-up turn tracking task with and without the improved flight control system design. The sideslip, roll rate, and tracking error traces illustrate the effective suppression of wing rock provided by the modified control system design. The successful development of the final system design depended very heavily on use of the piloted simulation to bring a pilot into the loop to insure avoidance of problems with pilot-induced oscillations.

It is often very convenient to summarize the overall tracking performance of each airplane configuration flown in a given ACM task in order to compare the performance differences, for instance, between two control system configurations. This is normally done by post-processing the simulator runs recorded on magnetic tape to calculate the fraction of time during the task for which the pilot was able to obtain a reasonably good level of gun tracking. This tracking time is then presented as a function of angle of attack to show the variation with angle of attack of the pilot's ability to track the target airplane. Presented in figure 20 are two such tracking performance plots. Each plot compares the tracking time obtained with and without high angle-of-attack stability and control augmentation features. Figure 20(a) presents these results obtained in a steady, wind up turn tracking task while figure 20(b) presents similar results obtained in a bank-to-bank tracking task. The large improvement obtained in tracking was provided by the increased damping and controllability provided by the control augmentation added to the airplane.

SELECTED SIMULATION RESULTS AND CORRELATION WITH FLIGHT

An important measure of the value of results produced from piloted simulations such as have been described in this paper is whether or not problems and solutions identified in simulation have also been verified in full scale flight testing. It is not the intent of this paper to present a comprehensive set of detailed simulation results for comparison with flight tests but rather to point out the problem areas where application of the simulation techniques described herein have proved successful and produced results in general agreement with flight test experience. This correlation covers two areas: the correlation between simulated stability and control characteristics and those characteristics seen in flight and the correlation between the piloting problems seen in simulation and those seen in flight tests.

Regarding the first area of the simulated stability and control characteristics, the general flying qualities exhibited by the simulation and the critical maneuvers identified for each configuration studied on the DMS to date have been found to correlate with flight test results. This correlation covers such areas as the sensitivity of a configuration to wing rock, to inertially-coupled departures, and to loss-of-control from such problems as excessive adverse yaw generated by roll control surfaces in the stall. Moreover, automatic control concepts developed in simulation for improving high-α characteristics have been proven out in flight tests. The development of a lateral-stick-to-rudder interconnect concept to alleviate roll-reversals at high angles of attack was one such successful project.

The second area of correlation referred to was that of piloting problems seen in simulation versus flight tests; there are several good examples in this area. One control law that has been studied in recent fighter simulations is the use of the roll-rate command concept for roll control. This concept employs a very high gain system to provide the pilot with very crisp, uniform, well-damped roll performance. Unfortunately, pilots not used to such performance often tend to overcontrol in attempting to anticipate a desired bank angle and stop the roll rate. Such a piloting technique when used with a roll-rate command system produces "roll ratcheting" and pilot induced oscillations. This problem can be made even worse when a force-actuated sidestick controller is in use. This type of problem was seen both in flight and in simulation as pilots adapted to the new control concept. With training, pilots learned to use the system very effectively.

Another control concept, that of rolling the airplane about the flight path at high angles of attack, was also found to cause piloting problems. This concept, known as stability-axis rolling, is designed to minimize sideslip excursions during high-α rolls. However, in rolling this way, the control system both yaws and rolls the airplane in response to a pilot roll control input. It was found that pilots used to rolling about the airplane longitudinal body axis were very disconcerted by the substantial initial yawing motion which they observed in response to what they thought was a pure roll control input. It was found, both in simulation and in flight, that time was required for pilots to adapt to this new control scheme.

One final example of a piloting problem relates to the problems encountered in learning how to fly a fighter outfitted with a force-actuated, side-stick controller such as was shown earlier in figure 5. The controller studied was designed to be rigidly fixed in position and to not move in response to pilot force application; rather than deflect, the controller sensed the longitudinal and lateral forces exerted by the pilot and used these forces as inputs to the flight control system. The problem that arose was that, during extreme maneuvering at low speeds and high α's where high control forces are typical, the pilot often encountered the aft force stop of the stick without realizing it; the same problem occurred to a lesser degree with lateral control force. The pilot had no feel (no stick deflection stop) for when he was at maximum command or the amount by which he was exceeding the maximum.

To demonstrate this problem as it occurred during one of the ACM tasks, time histories of the pilot force inputs are presented in figure 21. The maximum force values are denoted by dashed lines on the plots. It can be seen that the pilot often exceeded the maximum pitch command force and even attempted to modulate pitch control while exceeding the limit. Such modulation had no effect on the airplane response and therefore could appear to the pilot as improper airplane response; the problem was more evident in pitch than in roll control. Similar problems of the pilot not knowing exactly how much control command he was using at a given instant were also encountered in flight. With such a controller, it is most difficult to know when the maximum control command is reached.

CONCLUDING REMARKS

The NASA-Langley stall/spin research program on military configurations has accumulated a considerable amount of experience in conducting piloted simulations to study the stall/departure characteristics of current fighter configurations. Piloted simulation has been found to be an extremely valuable research tool for the analysis of the stall/departure behavior of piloted fighter airplanes for a number of reasons. It is only with such an analysis method that one can obtain a realistic evaluation of an airplane's maneuverability at high angles of attack and an assessment of the departure and spin susceptibility of the configuration. This realism is obtained by providing to the pilot a complete model of the airplane and control system which can be flown in simulations of demanding ACM tasks and maneuvers. The provision of a realistic cockpit environment and high fidelity visual display has been found invaluable in providing the simulation realism needed. The use of the piloted simulation methods and procedures described in this paper has been found very effective in identifying stability and control problem areas and in developing automatic control concepts to alleviate many of these problems.

During the many simulation programs that have been conducted on the DMS facility, several general conclusions have been drawn regarding the requirements for and the potential value of conducting such stall/departure simulation studies. In at least one simulation program conducted, it was possible to obtain a pilot assessment of the realism of simulated stall/departure characteristics on both the fixed-base DMS facility and on a similar simulator which incorporated limited motion cues. The pilot felt that conclusions drawn from work on the fixed-base system were not significantly changed by having [illegible] in the moving base facility representing the same airplane. One important consideration in this conclusion related to the fact that the moving-base facility often provided "false cues" to the pilot as the hardware was attempting to "washout" a sustained motion and reposition itself. It was the pilots feeling that it was better to have no cue at all in lieu of a false cue. Based on this experience and upon the correlation obtained with flight test experience to date, the use of comprehensive fixed-based simulators such as the DMS seem to provide reliable simulation tools for stall/departure studies.

Another conclusion drawn from simulation experience to date has been that it is very dangerous to attempt to make general conclusions regarding airplane stall/departure problems based on a single configuration study and attempt to apply these guidelines across the board to other apparently similar configurations. Subtle differences in a configuration's airframe and control system design have often been found to produce significant differences in the stall/departure characteristics of the configuration. A number of very effective automatic control concepts have been developed for departure and spin prevention; however, experience has shown that the application to a particular airplane configuration requires careful tailoring of the concepts to account for particular characteristics of the study configuration.

In summary, piloted simulation is considered a key tool in the Langley stall/spin research program and will continue to be used to explore the stall/departure behavior of advanced configurations and to develop automatic control concepts to provide improved high-α characteristics for both current and advanced high-performance airplane configurations. The value of fixed-base piloted simulation as a tool for studying airplane stall/departure characteristics has been recognized by many U.S. airframe manufacturers and they are now placing emphasis on conducting such simulations during the airplane development cycle. The military has also come to recognize the great value which high fidelity stall/departure simulations have as pilot training aides.

REFERENCES

1. Chambers, Joseph R.; Gilbert, William P.; and Grafton, Sue B.: Results of Recent NASA Studies on Spin Resistance. Paper presented at AGARD Flight Mechanics Panel Specialist's Meeting on Stall/Spin Problems of Military Aircraft, Brussels, Belgium, November 18-21, 1975.

2. Chambers, Joseph R.; Bowman, James S.; and Malcolm, Gerald N.: Stall/Spin Test Techniques Used by NASA. Paper presented at the AGARD Flight Mechanics Panel Specialist's Meeting on Stall/Spin Problems of Military Aircraft, Brussels, Belgium, November 18-21, 1975.

3. Ashworth, B. R.; and Kahlbaum, William M. Jr.: Description and Performance of the Langley Differential Maneuvering Simulator. NASA TND-7304, 1973.

4. Nguyen, Luat T.; Anglin, Ernie L.; and Gilbert, William P.: Recent Research Related to Prediction of Stall/Spin Characteristics of Fighter Aircraft. Paper presented at the AIAA Third Atmospheric Flight Mechanics Conference, Arlington, TX, June 7-9, 1976.

5. Chambers, Joseph R. and Grafton, Sue B.: Aerodynamic Characteristics of Airplanes at High Angles of Attack. NASA TM 74097, December, 1977.

Figure 1. Scope of Military Stall/Spin Research at Langley

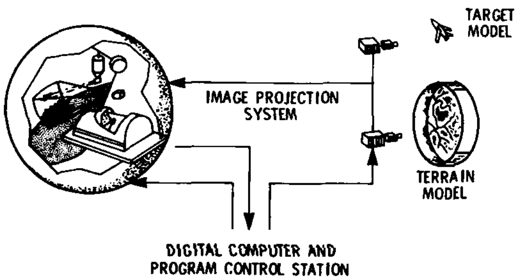


Figure 2. Sketch of Early Stall/Spin Simulation System

Figure 3. Artist's Sketch of DMS Facility

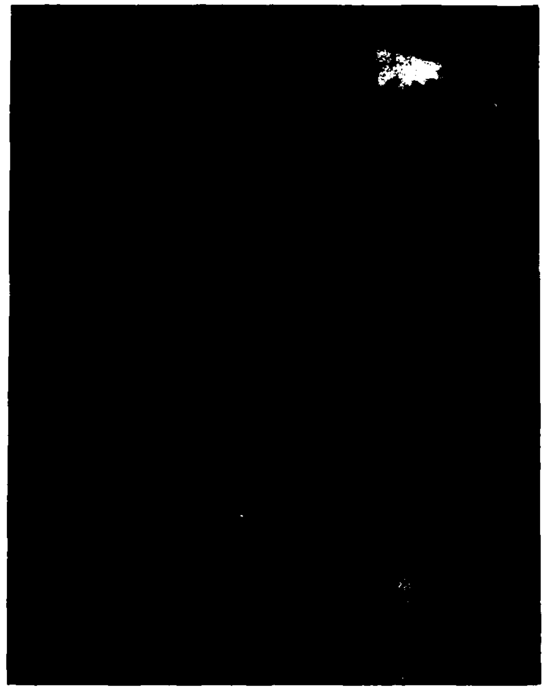


Figure 4. View of DMS Interior

Figure 5. Photograph of Side-Stick Controller Installation

Figure 6. Configurations Studied in Stall/Departure Simulations

- ANGLE OF ATTACK LIMITING
- STABILITY AUGMENTATION
  - STABILITY AXIS YAW DAMPING
  - LATERAL/DIRECTIONAL STATIC STABILITY AUGMENTATION
- CONTROL AUGMENTATION
  - AILERON-TO-RUDDER INTERCONNECT TO COUNTERACT AILERON ADVERSE YAW
  - SCHEDULE CONTROL SURFACE AUTHORITY
  - NORMAL ACCELERATION COMMAND
  - ROLL RATE COMMAND

Figure 7. Departure Prevention Control Concepts

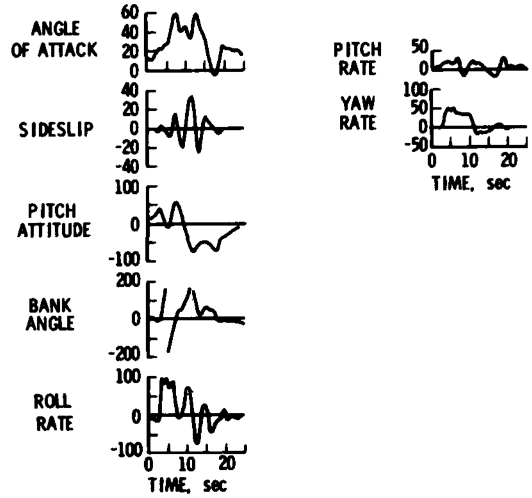


Figure 10. Inertially-Coupled Stall Entry Maneuver

- OPEN-LOOP EVALUATION AND TASK DEVELOPMENT
  - PILOT FAMILIARIZATION
  - ASSESSMENT OF BEHAVIOR IN STALL
    - NORMAL AND ADVERSE CONTROL INPUTS
    - EXTREME MANEUVERS, COUPLED AND LOWSPEED
  - COMPOSITION/TAPING OF TRACKING TASKS
- FLIGHT AGAINST TRACKING TASKS
  - GROUND RULES
    - MAINTAIN OFFENSIVE POSITION
    - TRACK WHEN POSSIBLE
  - TYPES OF TASK
    - STEADY TURNS
    - TURN REVERSALS
    - COMPLEX ACM

Figure 8. Outline of Evaluation Maneuvers and Tasks

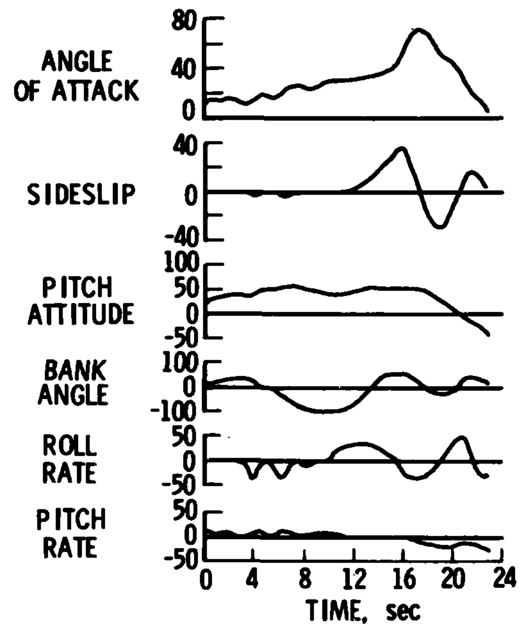


Figure 11. Kinematically-Coupled Stall Entry Maneuver

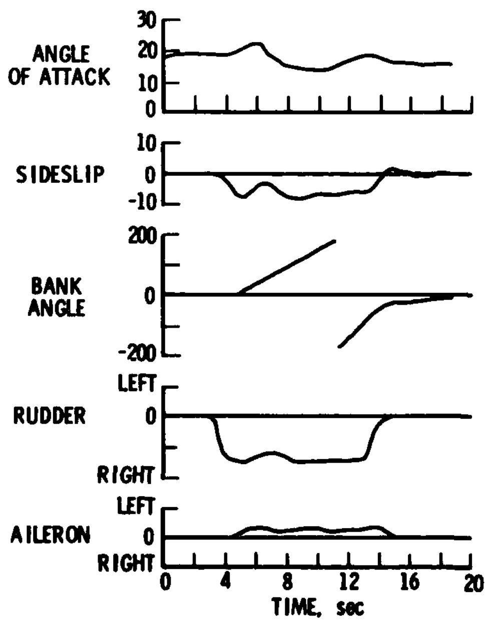


Figure 9. Rudder Roll in Airplane Having Roll-Rate Command System

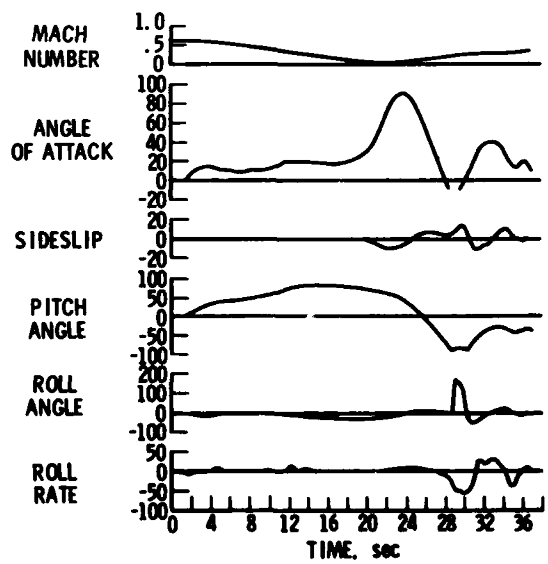


Figure 12. Vertical Stall Entry Maneuver

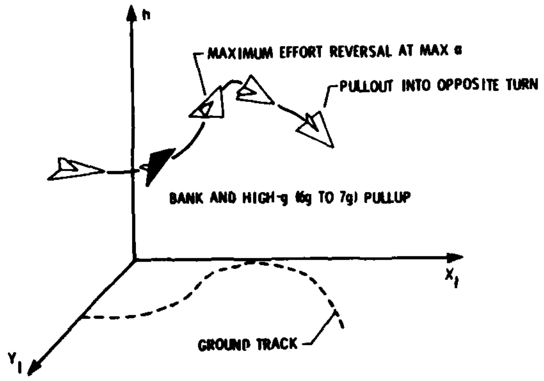
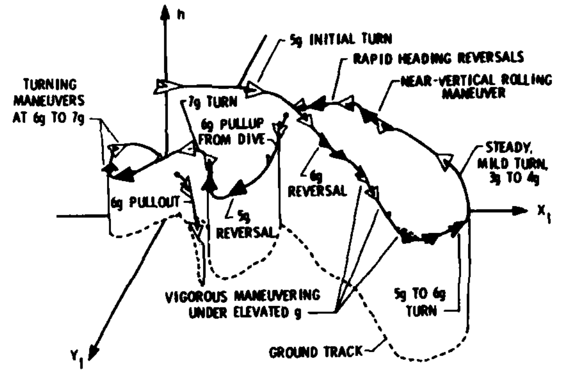


Figure 13. Sketch of Roll Performance Task



(a) Sketch of First Half of Task

Figure 17. Description of General ACM Tracking Task

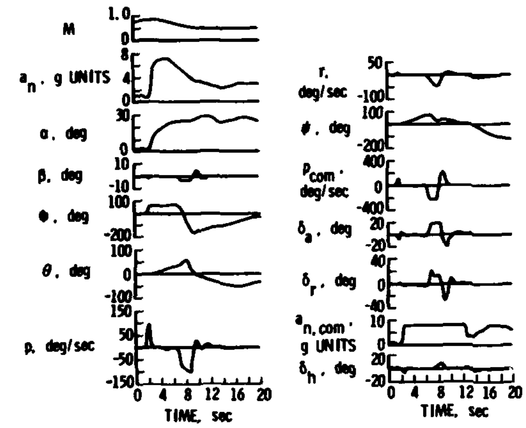
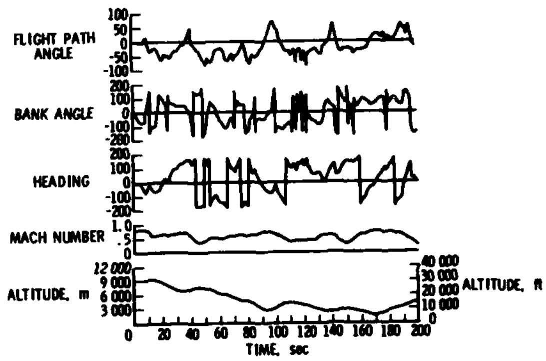


Figure 14. Time History of Turn-Reversal Used to Assess Roll Performance



(b) Time History of Target Motions In General ACM Task

Figure 17. - Concluded

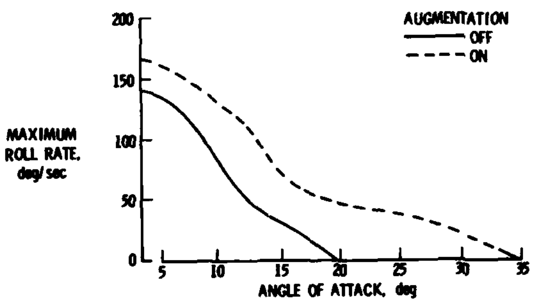


Figure 15. Roll Performance Improvement Provided By Augmentation

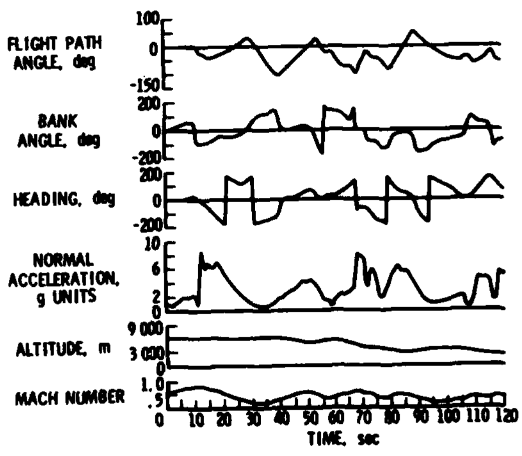


Figure 18. Time History of Target Motions in Low-Speed ACM Task

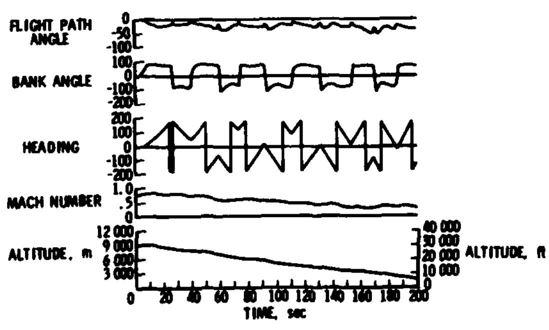


Figure 16. Time History of Target Airplane Flying Turn-Reversal Task

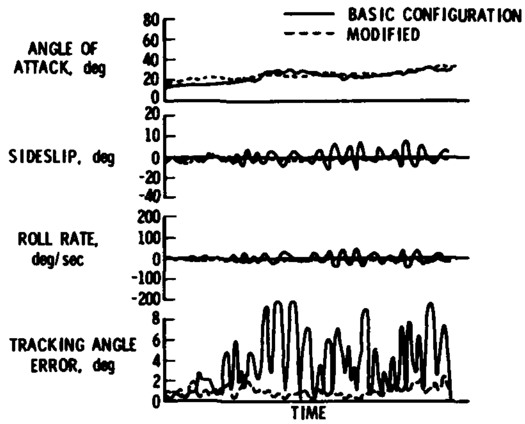
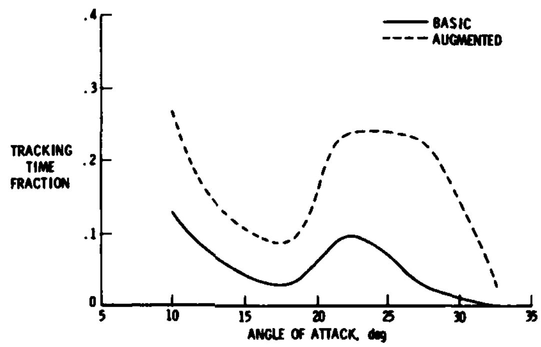
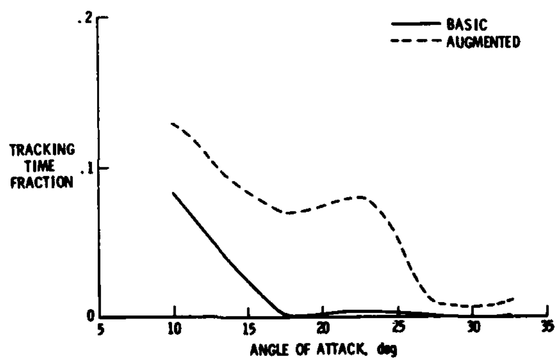


Figure 19. Illustration of Wing Rock Suppression Obtained by Proper Control System Design



(a) *Steady, Windup Turn Task*

Figure 20. Tracking Performance in ACM Tasks



(b) Turn-Reversal Tracking Task

Figure 20. - Concluded

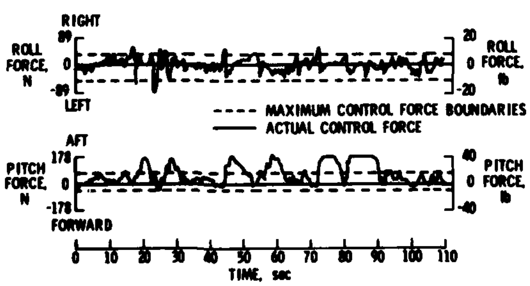


Figure 21. Time History of Pilot Control Forces Applied to Side-Stick in ACM Task

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-CP-249	ISBN 92-835-0222-1	UNCLASSIFIED

5. Originator	Advisory Group for Aerospace Research and Development North Atlantic Treaty Organization 7 rue Ancelle, 92200 Neuilly sur Seine, France
6. Title	PILOTED AIRCRAFT ENVIRONMENT SIMULATION TECHNIQUES
7. Presented at	at the Flight Mechanics Panel Specialists' Meeting on Piloted Aircraft Environment Simulation Techniques held in Brussels, Belgium, 24–27 April 1978.

8. Author(s)	9. Date
Various	October 1978

10. Author's Address	11. Pages
Various	316

12. Distribution Statement	This document is distributed in accordance with AGARD policies and regulations, which are outlined on the Outside Back Covers of all AGARD publications.

13. Keywords/Descriptors

Flight simulation	Human factors engineering	Aerial warfare
Environment simulation	Pilots (personnel)	Aircraft seats
Aircraft	Atmospheric models	

14. Abstract

These proceedings consist of the papers presented at the FMP Specialists' Meeting on "Piloted Aircraft Environment Simulation Techniques". An extensive coverage of the subject is presented. The areas examined range from requirements and user experience, through simulation of the atmosphere – including atmospheric models – to assessments of a wide range of visual systems. Also covered are motion systems, 'g' seats and air combat simulators. A comprehensive Technical Evaluation of the meeting appears in AGARD Advisory Report No.126.

AGARD Conference Proceedings No.249
Advisory Group for Aerospace Research and Development, NATO
PILOTED AIRCRAFT ENVIRONMENT SIMULATION TECHNIQUES
Published October 1978
316 pages

These proceedings consist of the papers presented at the FMP Specialists' Meeting on Piloted Aircraft Environment Simulation Techniques. An extensive coverage of the subject is presented. The areas examined range from requirements and user experience, through simulation of the atmosphere – including atmospheric models – to assessment of a wide range of visual systems. Also covered are motion systems, 'g' seats and air combat

P.T.O.

AGARD-CP-249

Flight simulation
Environment simulation
Aircraft
Human factors engineering
Pilots (personnel)
Atmospheric models
Aerial warfare
Aircraft seats

AGARD Conference Proceedings No.249
Advisory Group for Aerospace Research and Development, NATO
PILOTED AIRCRAFT ENVIRONMENT SIMULATION TECHNIQUES
Published October 1978
316 pages

These proceedings consist of the papers presented at the FMP Specialists' Meeting on Piloted Aircraft Environment Simulation Techniques. An extensive coverage of the subject is presented. The areas examined range from requirements and user experience, through simulation of the atmosphere – including atmospheric models – to assessment of a wide range of visual systems. Also covered are motion systems, 'g' seats and air combat

P.T.O.

AGARD-CP-249

Flight simulation
Environment simulation
Aircraft
Human factors engineering
Pilots (personnel)
Atmospheric models
Aerial warfare
Aircarft seats

AGARD Conference Proceedings No.249
Advisory Group for Aerospace Research and Development, NATO
PILOTED AIRCRAFT ENVIRONMENT SIMULATION TECHNIQUES
Published October 1978
316 pages

These proceedings consist of the papers presented at the FMP Specialists' Meeting on Piloted Aircraft Environment Simulation Techniques. An extensive coverage of the subject is presented. The areas examined range from requirements and user experience, through simulation of the atmosphere – including atmospheric models – to assessment of a wide range of visual systems. Also covered are motion systems, 'g' seats and air combat

P.T.O.

AGARD-CP-249

Flight simulation
Environment simulation
Aircraft
Human factors engineering
Pilots (personnel)
Atmospheric models
Aerial warfare
Aircraft seats

AGARD Conference Proceedings No.249
Advisory Group for Aerospace Research and Development, NATO
PILOTED AIRCRAFT ENVIRONMENT SIMULATION TECHNIQUES
Published October 1978
316 pages

These proceedings consist of the papers presented at the FMP Specialists' Meeting on Piloted Aircraft Environment Simulation Techniques. An extensive coverage of the subject is presented. The areas examined range from requirements and user experience, through simulation of the atmosphere – including atmospheric models – to assessment of a wide range of visual systems. Also covered are motion systems, 'g' seats and air combat

P.T.O.

AGARD-CP-249

Flight simulation
Environment simulation
Aircraft
Human factors engineering
Pilots (personnel)
Atmospheric models
Aerial warfare
Aircraft seats