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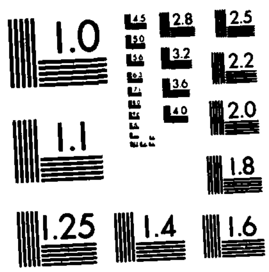

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AGARD REPORT No.746

Workshop on Design Loads for Advanced Fighters

(1)

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Report No.746

WORKSHOP ON DESIGN LOADS FOR ADVANCED FIGHTERS

Papers presented at the 64th Meeting of the Structures and Materials Panel of AGARD in Madrid, Spain on 27 April—1 May 1987.

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- Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);
- 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;
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SUMMARY

Workshop on Design Loads for Advanced Fighters.

The AGARD Structures and Materials Panel held a Workshop at Madrid, Spain in the Spring of 1987 to discuss problems associated with defining Design Loads for Advanced Fighters. This publication includes the majority of the presentations made in the course of this Workshop, together with the Recorder's Report.

RESUME

Réunion de travail concernant les charges au stade du projet des chasseurs avancés.

Le Panel des structures et matériaux de l'AGARD a organisé une réunion de travail à Madrid en 1987 au printemps afin de traiter les problèmes rencontrés lors de la détermination des charges au stade du projet des chasseurs avancés. La présente publication comporte la plupart des présentations faites au cours de la réunion, ainsi que le compte-rendu du rapporteur.

PREFACE

The design of modern fighter aircraft is becoming an increasingly complex process, and the establishment of design criteria is an extremely important element in that process. The Structures and Materials Panel of AGARD have noted with concern that the existing design manoeuvre load regulations in the NATO nations a) are not uniform in content and b) do not generally reflect the actual service experience of the aircraft.

The Sub-Committee on Design Loads for Advanced Fighters have therefore held the Workshop reported herein in the attempt to focus attention on these problems, and to direct the knowledge of invited experts toward the solution of these problems. The Workshop was organised as follows:

SESSION I — REVIEW OF MANOEUVRE DESIGN LOAD REGULATIONS

SESSION II — OPERATIONAL MANOEUVRE PARAMETERS VERSUS SPECIFIED DESIGN PARAMETERS

SESSION III — THE INFLUENCE OF ADVANCED FLIGHT CONTROL SYSTEMS ON DESIGN LOADS

On behalf of the Structures and Materials Panel, I would like to thank the authors and session chairmen whose participation has contributed so greatly to the success of the Workshop. In particular, I especially wish to thank the Aerospace Medical Panel and the Flight Mechanics Panel for the valuable contributions to the Workshop provided by these Panels.

R.F.O'Connell
Workshop Chairman
Chairman, Sub-Committee on Design Loads
for Advanced Fighters

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THE DEVELOPMENT OF MANOEUVRE LOAD CRITERIA FOR AGILE AIRCRAFT

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SUMMARY

Design manoeuvre load regulations in the Nato nations have evolved from crude assumptions of single control surface movement to relatively complicated series of pilot inputs in all three axes. These inputs need to be standardized to permit the assessment of structural loads with reasonable effort, but with the advent of active control technology the hiatus between standardized control inputs for load assessment and actual pilot practice with agile aircraft is rapidly increasing.
A solution of this delemma may be to design flight control systems such that they provide "carefree handling", that is a system which even for the wildest pilot inputs does not lead to structural damage. But this solution has also disadvantages: a) structural designers lose the wealth of experience contained in previous design practice and with it their basis for initial dimensioning of the airframe. This affects a large portion of the aircraft mass and later re-design may be impossible. b) Structural safety becomes crucially dependent on the functioning of black boxes and their connections. As long as we have no technically feasible direct load sensing and controlling system, a compromise is proposed: Use the best combination of the old criteria for initial design but allow for a long development period flight control system adjustements of load critical functions to fully exploit the manoeuvre capability of the aircraft without structural damage. This will require a flexible system of operational clearances where the user can not have a complete definition of the manoeuvre capabilities at the start of a programme.

1. Introduction

The flight manoeuvre loads are major design criteria for agile aircraft (aerobatic, trainer, fighter aircraft), because large portions of their airframe are sized by these loads. They also belong traditionally to the most elusive engineering criteria and so far engineers never succeeded in precisely predicting what pilots will eventually do with their machines. One extreme solution to this problem would be to put so much strength into the structure that the aerodynamic and pilot tolerance capabilities can be fully exploited by manoeuvering without failure. This is more or less the case with aerobatic aircraft, but modern fighters would grow far too heavy by this rule.

So the history of manoeuvre load criteria reflects a continuous struggle to find a reasonable compromise between criteria which do not unduly penalize total aircraft performance by overweight and a tolerable number of accidents caused by structural failure.

To keep things lucid in this overview, I shall try to generalize or simplify the problems but retain the essential interrelations. Fig. 1 serves to illustrate this:

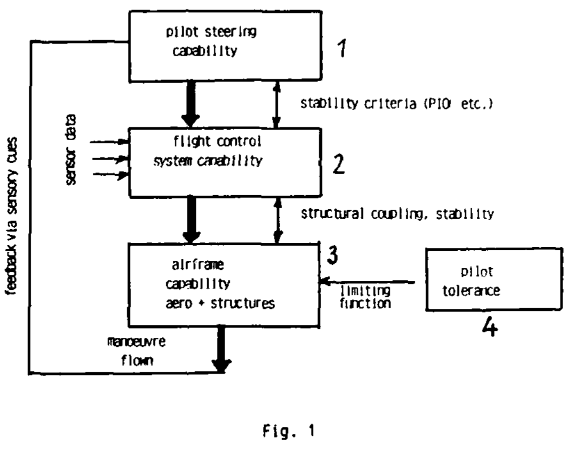

Fig. 1

Box 1 contains the pilot's sensomotoric capabilities, that is, his production of time, force and frequency dependent inputs into the aircraft controls.
Box 2 resembles the complete flight control system function from the sensors down to powered actuators. It has to satisfy not only aircraft stability but also man-machine stability criteria among others.
Box 3 stands for the airframe with its aerodynamic and structural capabilities to produce and withstand manoeuvre loads.
Box 4 contains the physiological limitations of the pilot - his tolerance of high g, angular acceleration etc.
Box 4 acts as a single limiting fuction on box 3 and can be treated independently, but all other boxes are strongly coupled with multiple feedback paths.

In the course of an aircraft development programme, box 4 is given a priori (see next paper in this session) and apart from special training effects, box 1 is also given at the start in average form.
Box 3 is frozen relatively early by definition of the aircraft configuration and so is the architecture of box 2. But then for a long period of simulation and flight testing the functions of 2 are optimised, not only for the clean aircraft but for a variety of external stores. To a lesser degree corrections are also possible in this period for box 3. This optimisation process concerns both handling qualities and manoeuvre loads, but the approaches are different. The handling specialist has to analyse the whole

spectrum of possible flight manoeuvres with main emphasis on stability and achievement of performance. Design load investigations are a search for maxima and an experienced loads analyst can narrow down the vast spectrum of possible flight cases to relativly few which become load critical. However, this process is becoming increasingly difficult with modern active control systems and the control system departments have to live with a new burden - the responsibility for causing exotic loads.

As a basis for return to safe ground when the following discussions of advanced manoeuvre systems should lead too far astray, the next chapter gives a summary of the present status of manoeuvre load regulations for agile aircraft.

2. Status of Present Criteria

The easiest way of obtaining manoeuvre loads is to assume abrupt control surface movement to the stops, limited only by pilot or actuator force, and to derive the resulting airloads without aircraft motion analysis. This cheap method is still in use for certification of some civil aircraft but all the military regulations now require sequences of pilot control inputs to initiate load critical manoeuvres. The following regulations will be summarized here:

(A) MIL-A-008861 A (USAF) 1971 for the US Air Force

(B) MIL-A-8861 B (AS) 1986 for the US Navy

(C) DEF-STAN 00-970 1983 for the UK

(D) AIR 2004 E 1979 for France.

The US situation at the moment is curious. (A) used to be the main US specification for flight loads over many years. It has been replaced for the Air Force in 1985 by MIL-A-87221 (USAF), but this new specification is only a frame without the essential quantitative material and as such no great help for the designer. The US Navy on the other hand, who traditionally used to have their own and different specification, have now adopted the old USAF Spec. (A) and updated and amplified it for application to modern control system technology, including direct force control, thrust vectoring etc. Thus (B) seems to be the most up-to-date specification available now. Although modern fighter tactics use combined control inputs in several axes, for a starting basis we prefer to treat them separately as pitching, rolling and yawing manoeuvres.

2.1 Pitching manoeurves

US Air Force

Fig. 2 shows the longitudinal control inputs for a checked manoeuvre required in (A) to rapidly achieve high load factors. Table 1 gives the corresponding boundary conditions. Case (a) requires to pull maximum positive g by a triangular control input; if the maximum is not achievable by this, then the pilot shall pull to the stops and hold for such time that max. g is attained. Case (b) is similar to (a) but control displacement and holding time t_3 shall be just sufficient to achieve max. g at the end of the checking movement. Case (c) is similar to (b) but with control movement not only back to zero but 1/2 of the positive amplitude into the negative direction.

These theoretical manoeuvres are certainly not exactly what pilots will do with modern fighters, but as long as we cannot use the vast amount of combat simulation results as an all-embracing envelope for flight loads, they provide at least a design basis - and they have historically produced reasonable manoeuvre loads, particularly tail loads.

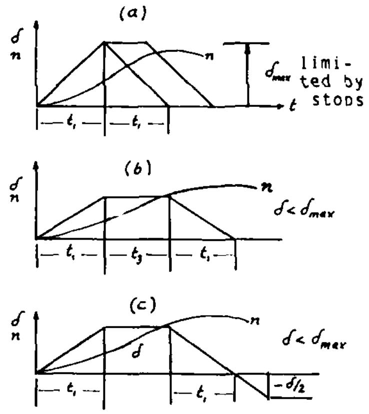

Fig. 2 Stick Inputs for pitching cases of 8861 A

Table 1 Symmetrical manoeuvre parameters of 8861 A

aircraft class	limit load factor: basic design mass, max		basic design mass, min at V_H	all masses, min at V_L	max design mass, max	max design mass, min at V_L	t_1 s
A, F, T	subsonic	8,0	-3,0	-1,0	4,0	-2,0	0,2
A, F, T	supersonic	6,5	-3,0	-1,0	4,0	-2,0	0,2
O		6	-3,0	-1,0	3,0	-1,0	0,2
U		4	-2,0	0	2,5	-1,0	0,3

US Navy

(B) has adopted these 3 cases with slightly changed boundary conditions, see Table 2.

Table 2 Symmetrical manoeuvre parameters of 8861 B

aircraft class	limit load factor					t_1 s
	basic design mass		all masses	max design mass		
	max	min at V_H	min at V_L	max	min at V_H	
F, A	7,5	-3,0	-1,0	5,5	-2,0	0,2
T	7,5	-3,0	-1,0	4,0	-2,0	0,2
O	6,0	-3,0	0	3,0	-1,0	0,3
U	4,0	-2,0	0	2,5	-1,0	0,3

but it has two additional new cases:

(d) maximum control authority in the negative direction shall be applied until maximum stabilizer or wing load has been attained. This can mean more than $-\delta/2$ in case (c).

(e) is a special case for "computer control, fly-by-wire, active control, stability augmentation, direct lift control, or other types of control system where the pilot control inputs do not directly establish control surface position" which we shall call here generically ACT systems. This case requires that aircraft strength shall also be sufficient to cover modifications of cases (a) to (c) caused by ACT systems partially failed (transients, changed gains etc.), a requirement which is easier stated than proven.

UK

In the UK pitching manoeuvres have traditionally been covered by aeroplane response calculations after the Czaykowski method which assumed an exponential function for elevator movement and no checking. This was an expedient way to obtain tail loads but the new UK specification (C) advises that pilot control inputs should be used now. It does not specify any details of these.

France

The French specification (D) is very similar to case (a) of (A), with two differences: it has other load factors, see Table 3, and it allows a slower stick return to neutral in time t_2; for servo controls $t_1 = t_2$ shall be derived from maximum control surface rate under zero load. It does not require checking into the negative region as (A) and (B) do. (see Fig. 3)

Table 3 Symmetrical manoeuvre parameters of AIR 2004 E

aircraft class	limit load factor		t_1 s	t_2 s
	max	min		
III	n_1 *	-0,4 n_1	0,2	0,3
II	4	-1,6	0,2	0,3
I	2,5	-1,0	0,3	0,3

* n_1 defined in the aircraft specification

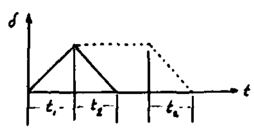

Fig. 3 Control Inputs of AIR 2004 E

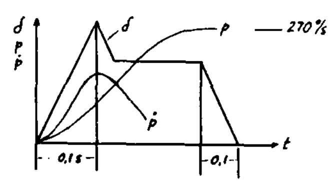

Fig. 4 Stick Input for rolling cases of 8861 A

2.2 Rolling manoeuvres (with pitching)

US Air Force

The rolling cases of (A) assume rapid control inputs and reversal (checked manoeuvres), see Fig. 4. With 267 N force the stick shall be moved sideways in 0,1 s, held until the specified bank angle is attained and then reverted to neutral in 0,1 s. If a roll rate greater than 270°/s would result, control position may be lessened to just achieve this value, but the roll rates shall never be lower than those necessary to achieve the time to bank criteria in the handling qualities specification (T_{360} = 2,8 s gives $p_{max} \approx$ 150 °/s).

a) Fast 180° rolls are required starting from level flight with -1 to +1 g

b) Fast 360° rolls are required starting from n = 1

c) Rolling pull out is required to start from steady level turns with load factors from 1 to 0,8 n_1 (for a typical 8 g aeroplane this is 1 to 6,4 g).

By the application of rapid lateral control (Fig. 4) the aircraft shall be rolled through twice the initial bank angle. In our typical example this would be a bank change of 162°. Longitudinal control may be used to prevent exeeding 0,8 n_1 during the manoeuvre.

US Navy

The US Navy has in (B) adopted the rolling criteria of (A) but with significant additions: for ACT aircraft the pilot force is replaced by "maximum control authority". The reference to roll performance requirements is removed - probably because this criterion used to be less stringent than the 270 °/s in most cases. Important is the explicit reference to external store configurations; the rolling cases of (A) have often been met in the clean configuration only. But most important is the addition of a new case for ACT aircraft. It states that the aircraft shall be designed for maximum abrupt pilot inputs in all three axes. But it also states that these inputs shall in no case lead to higher rates and load factors than the conventional cases.

This paragraph is remarkable in several respects. It describes a control system which would digest the wildest pilots inputs into control outputs which are tailored to just achieve the old load maxima. It shows clearly the dilemma of the rulemaker in the face of rapid technical development. This is the dream of the now much advertised carefree (foolproof) handling system. In reality control systems are primarily optimised for actual manoeuvre performance and not for achievement of some theoretical load cases. On the positive side this criterion recognizes the need to retain some reference to proven manoeuvre design load practice.

Another addition in (B) is the requirement that the structure shall also be designed to withstand the demonstration requirements of MIL-D-87088 (AS), which apparently is not obvious.

UK

In the UK a wider envelope of initial conditions is required for the rolling cases, including a negative g roll reversal: -1,5 to 7,2 g. For the maximum roll rate several limits are given: at least 1 1/3 of p_{max} from the roll performance criteria in the handling specification which amounts to about 200 °/s; 200 °/s for ground attack and 250 °/s for aerial combat manoeuvres. The control input time history is roughly as in (A).

France

The French specification also requires negative initial conditions for the rolling cases: -1,6 to 6,4 g. (D) has control inputs similar to (A), but with t_1 = 0,2 and t_3 = 0,3 or maximum servo capability. The roll limits are more severe: a full 360° roll and $p_{max} \approx$ 300 °/s. (C) and (D) may reflect the experience that US pilots tend to avoid negative g manoeuvres in contrast to their European collegue.

Table 4 summarizes the rolling parameters for a typical 8 g aeroplane.

Table 4 Comparison of rolling parameters (8g aeroplane)

(A) 8861 A	(B) 8861 B	(C) DEF STAN 970	(D) AIR 2004 E
180° roll -1 to +1g 360° roll at 1g rolling pull out from 1 to 6,4g t_1 = t_3 = 0,1s p_{max} = 270°/s	same as A plus ACS foolproofness with maximum control authority plus demonstrationrequirements	rolling pull out from -1,5 to 7,2g p_{max} = 1,33 p handling $\approx$ 200°/s ground attack 200°/s aerial combat 250°/s no t_1, but maximum servo capability	360° roll, p_{max} = 300°/s rolling pull out from -1,6 to 6,4g t_1 = 0,2 t_2 = 0,3s or max servo capability under zero load and t_1 = t_2

2.3 Yawing Manoeuvres

US Air Force

Apart from the usual engine failure cases, (A) specifies low and high speed rudder reversal.

Fig. 5 a) shows the rudder input for manoeuvres from straight and level flight. At low speed 1334 N pedal force are required, at high speed 800 N.

Fig. 5 b) shows the rudder input for the reversal case: from maximum steady sideslip a fast recovery to zero yaw shall be made.

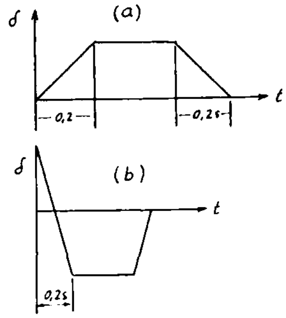

Fig. 5 Rudder Inputs of 8861 A

US Navy

(B) has adopted these design cases and amplified them with three new ones:

a) for aircraft with direct side force control, strength shall be provided for abrupt application of control authority up to a maximum side load factor of $n_y = 3$.

b) for aircraft with lateral thrust vectoring capability, all manoeuvres specified in the handling and stability criteria shall also be covered in the loads analysis.

c) there is a general phrase that evasive manoeuvres such als jinking, missile break etc. shall be considered in the loads analysis.

UK

(C) requires a rudder kick with 667 N pedal force or maximum output of the control system at all speeds. It also requires the traditional British fishtail manoeuvre: starting from straight level flight, the rudder is moved sinusoidally for 1 1/2 periods of the Dutch Roll frequency with an amplitude corresponding to 445 N pedal force or 2/3 of the actuator maximum.

France

(D) has a rudder reversal case very similar to Fig. 5 b) and a rudder kick without reversal, but both slightly slower than (A) due to $t_1 = 0.3$ s.

Spinning is somewhat marginal for our theme of pilot controlled manoeuvres but it deserves mentioning that it can cause rather high loads. (B) has now increased the yawing velocity of agile aircraft with fuselage mounted engines from the 200 °/s in (A) to 286 °/s. This is a severe requirement for long fuselages.

The following figures show typical load critical manoeuvres resulting from application of the current US Mil.-Specs. to an aircraft with moderate amount of ACT (Tornado).

Fig. 6 gives time histories of response quantities in a rapid pitching manoeuvre with the control input specified in Fig. 2, case (a). Displacement δ_{max} and holding time are just sufficient to achieve $n_{z\ max}$.

Fig. 7 is a time history of response quantities resulting from the control input of case (c) in Fig. 2, which is critical for taileron bending moment BM.

Fig. 8 corresponds to the rolling pull out manoeuvre described in para 2.2 with initial load factor 0,8 n_1. This is another critical case for taileron loads.

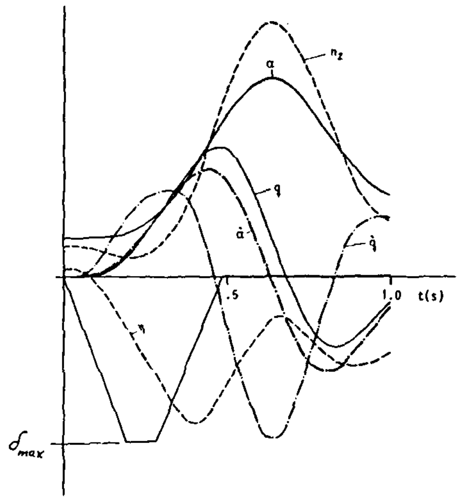

Fig. 6 Tornado rapid pitch, case (a)
0,9 M, 1000 ft, full CSAS

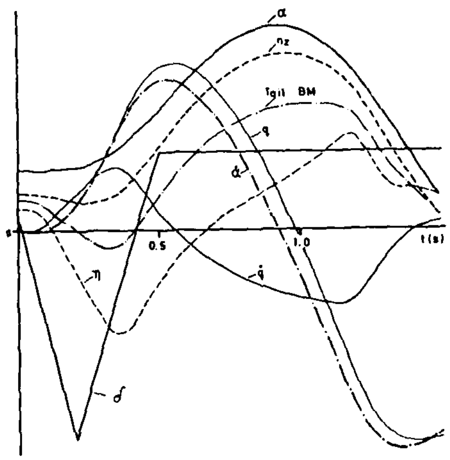

Fig. 7 Tornado rapid pitch, case (c)
0,92 M, 22500 ft, full CSAS

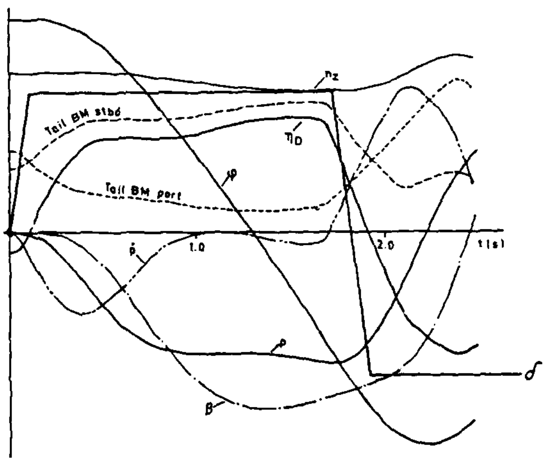

Fig. 8 Tornado rolling pull out
0,92 M, 19100 ft, full CSAS

3. The influence of piloting technique

Having set the scene of present structural manoeuvre criteria, the next step is to review how realistic they are in a changed tactical environment with different piloting techniques. Mohrman has given a good account of these changes in [1] , describing engagement rolls, turn reversal with push down to incrase roll rate, jinking manoeuvres etc.. From the fact that these manoeuvres are only weakly corelated with the specification manoeuvres one might be tempted to conclude that the old specifications should be abandoned altogether in favour of realistic simulation of combat manoeuvres. Before deciding on this radical cut however, several arguments need to be considered.

Even for the oldfashioned aircraft without ACT the specified control inputs were never fully representative of actual pilot handling. They came closest for a control system with a solid stick directly connected to tail surfaces without sophisticated tabs, but they were only engineering simplifications of nature - like a (1 - cos) gust which does exist nowhere but used to produce reasonable loads.

Pilots are quite inventive in finding new techniques for combat manoeuvering - in fact this is part of the selection process (survival of the fittest). For this reason and due to changed tactical scenarios, most aircraft later in their service life are used differently from the way projected at the design stage. If a sophisticated simulated combat manoeuvre is used to derive critical design loads this case may be overtaken by evolution after a few years in service. ACT gives the possibility of late ajustments of the limiting functions, ideally by software changes only, but this is equally true for an aircraft designed to the old criteria.

Perhaps the major difference between the old criteria and the new piloting techniques lies in the longer sequences of combined manoeuvres and not so much in the short elementary inputs (stick to the stops, maximum pilot force).

If so, it would be easier to adapt an aircraft designed to the old criteria to changed operational practice than one with sizing load cases derived from specific complex simulated manoeuvres.

An important difference to the old criteria exists in the absolute level of manoeuvre loads. Improved g-suits,increased aircraft performance and improved control systems with load limitation - all these factors have led pilots to pull limit loads more often and for longer duration. There is also indication for an increased application of negative g in jinking manoeuvres. This general tendency goes so far that high performance aircraft are now more frequently crashed due to pilot incapacitation (GLC).

The increased overall load level certainly necessitates adjustment of the old fatique strength criteria (e.g. MIL-8866); whether it also requires expansion of the design g-envelope, is debatable. Following the rationale which has been the basis of our airworthiness criteria for many years now, it would be sound engineering practice to increase design strength if the overall load level has statistically increased. Other people argue however, that the load limiting capability of ACT does not only justify staying with the old design loads, but even reducing the factor of safety.

Whilst designers are confronted with a very real increase in the overall level of the symmetrical load cases, the situation is more obscure with the unsymmetrical loads. Due to various scheduled interconnects between rudder, taileron, aileron or spoilers, the pilot now is rarely aware of the effect his commands have on the aircraft control surfaces. The only real limitation of unsymmetrical manoeuvres is probably the pilot's tolerance to lateral acceleration which is far less than in the vertical direction. Turning to Fig. 1 again, this control function is executed via the feedback path between boxes 3 and 1.

At this point it is well to remember that the results of any ground based simulation are severely limited by the absence of realistic motion cues to the pilot - nevertheless these simulations have become an indispensable development tool.

4. The influence of advanced control systems

The cockpit environment has drastically changed in recent years with the rapid development of flight control systems. For many decades pilots had to move large controls against inertia and air forces to keep their machines under control. Most of the aircraft in service now have still control movement but artificial feel to provide some indication of the flight conditions. Now sidestick controllers are being introduced which are force sensitive and require almost no motion. Although man is basically a motion sensitive animal, pilots seem to have adapted to this type of control. But from our viewpoint of aircraft loads, we should keep in mind that many natural limitations which used to prevent the pilot from commanding critical flight situations, do not exist with ACT-aircraft. The conventional type of control is essentially a low pass filter; with sidestick controllers many high frequency inputs, some of them unintentional, can make the FCS nervous.

Several loading cases in the existing criteria are based on maximum pilot forces. The attempt in (B) to replace this for ACT-aircraft by "maximum pilot authority" is not convincing. What is this pilot authority? The phrase "maximum deflection of motivators" in (C) does not resolve the problem either. This is just another case where we have lost an engineering yardstick which used to work well in the past.

More important than changes at the input side are changes in the main FCS functions. Traditionally, flight control systems have been optimised for handling qualities, with a few loads related functions like roll rate limitation incorporated separately. So the problem was to provide maximum manoeuverability with sufficient flight stability to prevent loss of control. This task requires high authority and strong control outputs. Now ACT systems have a new basic function, load limitation, which requires low authority and mild control outputs. Thus FCS optimisation has become a much more demanding task to unite two conflicting targets.

The FCS-certification effort has also increased drastically with automatic load limitation since the FCS is now a direct component of the proof of structural integrity. Where it was previously ficient to show that consecutive failures in the FCS led to degraded handling but still preserved a minimum get-you-home capability, the load limiting function of the FCS is directly safety critical and must therefore satisfy more severe criteria for failure rates, redundancy etc.. To a degree this is reflected in (B) by the requirement that the loading cases shall also include different failure states of the FCS. The associated problems are severe and can only be touched upon: sensor redundancy, -disparity, software qualification, load distribution and a.o.

It is clear that proof of airworthiness of ACT aircraft would be incomplete with consideration of the deterministic loads cases only; the ACT part needs to be treated statistically and this can be a cumbersome journey through the woods of failure trees. Quantitative guidance can be taken from [2] . The overall failure rates given there are still applicable to new designs.

Let us return now to the "carefree handling" concept which appears to offer great possibilities for loads control and which Air Staffs are all too ready to specify because it would reduce pilots workload significantly and free them for tactical tasks. In our context of manoeuvre loads such a control system ideally would limit all flight loads to the design values so that neither pilot nor designer need to worry about exceeding the structural capability of the airframe. This requires a large number of reliable inputs - air data, flight path coordinates, but also continuous complete knowledge of the aircraft mass status, including external stores partially released. (Speed limits would probably still have to be observed by the pilot).

The central problem of such a system however, is the fact that good handling qualities and reliable load limitation have conflicting tendencies in the FCS optimisation. So at best, a compromise can be achieved where due to the load limiting functions the handling envelopes are reduced, particularly in the upper left hand corner.

Load distribution is another complicating factor: on ACT aircraft the same flight condition can often be achieved with a variety of aircraft configurations, depending on foreplane position, manoeuvre flap scheduling and perhaps vectored thrust. Assessment of those cases is even more difficult because airload distribution is already a great problem on modern agile aircraft due to non - linearities, elastic structure, fuselage lift, dynamic lift etc. (see also [1]).

It appears unlikely that we shall see comprehensive carefree handling control systems in operational use which would also effect complete load limitation. More realistic is the selection of a few single parameters such als symmetric g, roll rate and perhaps sideslip which are controlled automatically. After all, who wants a formula 1 racing car with a carefree handling control system ?

One of the great benefits of ACT is its flexibility. Where previously adjustment of the handling characteristics during development was very limited to changes of springs, bobweights and control surface tabs, it is now possible to tailor handling qualities over a wide range during flight testing without large hardware changes. Also greater changes in operational usage can be accomodated later on by ACT. This has consequences for the loads; they are subject to larger changes during the aircraft life. On the other hand development of modern aircraft takes so long that the basic configuration must be frozen long before the final loads situation is known with confidence.

In consequence, the certification process needs to be changed too. It is futile from the start trying to find structural manoeuvre load criteria which cover all eventualities. What we can do is to keep our feet on proven ground initially, that is to use the updated conventional criteria for the basic design. Then, for a long period of simulation and flight testing, adjustments are made whenever weak areas are discovered. This requires an integrated approach by the FCS and loads departments. The certification process must recognize this by not aiming at the usual final operational clearance, but over many years providing preliminary clearances which reflect the temporary state of knowledge about tested manoeuvre loads and the related build standard of the FCS.

In summary, the manoeuvre loads part of aircraft design has evolved from a relatively clean-cut, predetermined analysis to a long iterative process which gradually utilizes flight test information to expand the flight envelopes; a process which is also much more demanding because it involves the reliability of the FCS in proving structural integrity.

Conclusions:

We have no consistent set of airworthiness criteria which fully covers manoeuvre loads of agile aircraft.

Attempts to update the existing criteria to embrace the vast possibilities of ACT are only partially successful.

Proof of airworthiness of aircraft with ACT has become more demanding since the load influencing functions of the FCS are directly safety critical and must be analysed for failure to the same quantitative criteria as the structure itself.

The existing criteria can and should still be used for initial design to define the airframe.

Certification needs to become adaptive to reflect a long period of testing and FCS changes.

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Acknowledgement

The Tornado data has been supplied by the loads department of MBB Munich.

FIGHTER DESIGN FOR HUMAN LOAD LIMITS

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INTRODUCTION

The Current Fighter Acceleration Environment

Recent studies (1) have shown that current first line fighters (F-15, F-16) are being flown at very high levels of sustained acceleration with onset rates sufficiently high to provoke the unique physiological dangers inherent in rapid onset acceleration exposures. The loss of nine aircraft through G- induced loss of consciousness has been acknowledged as a result of this type of acceleration environment. Approximate maneuvering G levels versus engagement duration are shown in Fig. 1.

Limitations on G Tolerance

Man's tolerance of sustained acceleration is limited by the characteristics of the cardiovascular system and by current acceleration protection equipment. The ability of the cardiovascular system to produce sufficient arterial blood pressure to counteract the inertial effects on it produced by sustained acceleration is the basis of the limitation. Tolerance varies according to the physiological axis involved. The Z axis (head to foot) is the most vulnerable since the longest hydrostatic column of the circulatory system lies in this axis; the column of blood between the aortic valve and the brain.

In the average individual, this hydrostatic column is 350mm in height, corresponding to a pressure of approximately 25mm Hg. Consequently, for each additional multiple of gravity, the heart and circulatory system must raise the blood pressure by 25mm Hg/G in order to maintain perfusion to the retinas and brain. Unprotected man can sustain up to approximately +5Gz if the acceleration stress is gradually applied. If it is rapidly applied the average tolerance is around +4Gz.

Using upright seats, current anti-G suits/valves are capable of adding an additional 1 to 1.5G to unprotected tolerance. In order to be able to fly at +9Gz, then, a pilot must increase his blood pressure by 75 to 100mm Hg by performing a straining maneuver in which all major skeletal muscles are isometrically tensed while grunting against a closed, or partially closed glottis. This is an extremely fatiguing procedure and becomes less effective as an engagement wears on.

As noted above, tolerance to rapidly applied acceleration is less than that in slow onset exposures because cardiovascular reflexes, which mobilize in approximately 10 seconds, cannot contribute to tolerance. Unless a pilot is well trained, well equipped, and prepared for the stress a very high onset rate exposure can result in exhaustion of the brain blood oxygen reserve with resultant abrupt loss of consciousness without warning. The effect of onset rate on time to loss of consciousness is shown in Fig. 2 (2).

Airframe designers are beginning to discuss new kinds of maneuvers involving rapid pitch movements followed by rapid roll motions around the velocity vector axis. The area of practical aerodynamics is, as yet, too new to allow precise definition of the acceleration stresses involved. It is clear that such maneuvers will blur the distinction between what is referred to as sustained acceleration (duration more than one second) and impact acceleration with very brief durations. In Figs. 3 and 4 are shown the high, medium, and low probabilities of tissue damage attendant to abrupt accelerations in the X and Z physiological axes (3).

Techniques for Enhancement of Human Load Limits

CURRENT EFFORTS

Anti-G Suits - The anti-G suit affords acceleration protection to the extent of about 1G. Current suits are little changed from those flown during the World War-II era and do not provide all of the protection that could be provided. It is known that an arterial occlusion suit using thigh and arm cuffs can provide between 2 and 3G of protection albeit at considerable cost in discomfort. Current efforts are being conducted on a suit using an inextensible Nomex panel over the buttocks in order to increase the return of blood to the central circulation (4). In another development, a sequentially inflating suit controlled by a microprocessor is currently being tested (5), and an advanced suit making use of reticulated foam is being developed at the USAF School of Aerospace Medicine with the objective of enhancing the transfer of suit pressure to underlying tissue.

Anti-G Valves - The conventional anti-G valve is an inertially operated regulating valve that pressurizes the anti-G suit in accordance with a fixed pressure versus G inflation schedule defined by the characteristics of the valve. In order to avoid objectionable sensitivity, for example to buffeting, such valves incorporate a certain degree of damping and a deadband with the result that such valves are not as responsive as they should be in the presence of rapid onset aircraft maneuvers. Current research on advanced concept valves is devoted to the development of a variety of rate and magnitude sensitive electronic valves (6,7,8) and the development of a flight control adaptive electronic valve (9,10) interfacing with the digital data buss in aircraft so equipped (10, 11). Research with human subjects has shown that higher average pressures and a more rapid mode of action provide enhanced acceleration protection(7,12). An additional advantage of a valve of this type is its anticipatory potential which could be based on control stick movements which would result in commands to the G protection system ahead of the airframe response.

Positive Pressure Breathing (PPB) - Positive pressure breathing raises intrathoracic pressure in the same manner as does the breathing portion of the straining maneuver described above. By doing so, it reduces the fatigue associated with straining, especially if combined with a chest counterpressure garment, and accordingly enhances endurance at high sustained G. At the present time PPB systems using chest counter-pressure are being tested at pressures regulated at 12mm Hg/G (above +4Gz). In combination with steeply reclined seats, such a system has been shown to make tolerance to +9Gz relatively easy, and it is believed that +11Gz is attainable. In Fig. 5 is seen an integrated system utilizing PPB which is being developed under the Human Systems Division's Tactical Life Support System effort.

Loss of Consciousness Monitoring System (LOCOMS) - A variety of such systems are under development in the aerospace community based on the approach of using altitude as a criterion for the initiation of a recovery maneuver. At the Armstrong Aerospace Medical Research Laboratory a system (13) is under development making use of non-invasive sensors in order to form an assessment of the likelihood of pilot incapacitation. These sensors will observe such factors as head lolling, breathing patterns, grip on stick and throttle, estimates of eye level blood pressure, status of arterial pulses in the head, and anti-G suit function. All of these will be assessed in the context of the current and antecedent acceleration state of the aircraft by an artificial intelligence system. It is posited that combining such a system, referred to informally as "Guardian", with a system incorporating aircraft state variables will lead to a low false alarm rate and high reliability.

Semi-Reclined Seats - Current exploitation of the advantages to be had from radically reclining the pilot has not been very effective. The F-16 uses a 30o seat back angle which confers, at best, a fraction of a G of protection. It is reported that the French RAFALE uses a 38-40o seat which is an improvement, but not a significant one, as will be discussed below.

Future Potentials

Pilot Positioning - Man can tolerate very high levels of acceleration if he is positioned so that the acceleration vector is more or less normal to the hydrostatic column of blood between the aortic valve and the brain. In a radically supinated position accelerations as high as 15-16Gz have been tolerated, the limiting factor being chest pain and difficulty in breathing. In order to realize the benefits of supination, it will be necessary to recline the seat back pan and torso/head to angles between 45o and 55o in order to achieve significant acceleration tolerance benefits, taking into account the likely angles of attack (which add to the seat back angle). Such seats will require completely rethinking the design of the fighter cockpit and will impact control and display issues as well as ejection and vision; especially aftward vision. New visual systems now under development may relieve the vision problem.

A crouching posture is also a possibility for the enhancement of acceleration tolerance. Since, anatomically, the retinas are about 14o forward of the aortic valve, the conventional seat (reclined about 13o to 15o in the aft direction) places the hydrostatic column in more or less exact alignment with the Z axis acceleration vector. Tilting the pilot forward into a crouched position is a process that begins with an immediate 14o advantage from the physiological standpoint.

A prone position cockpit design carries with it many of the same problems identified for the reclined seat cockpit, not the least of which are the issues of supporting the head in the facial area and aftward vision. Nevertheless, a prone cockpit confers even more of the advantages described above for a crouched position and, with careful design and developments in new visual systems, could be a worthwhile concept for acceleration protection (14).

Unconventional Flight Maneuvering Environments - Aircraft with six degree of freedom (6DOF) flight maneuvering capabilities have been investigated in the AFTI/F-16 program. The biodynamic effects of sustained and oscillating lateral acceleration (±Gy) have been defined by the Armstrong Aerospace Medical Research Laboratory (15). In this research it was demonstrated that pilot performance of a complex psychomotor tracking task was severely degraded at levels above ±1.5Gy unless the pilot was provided with fixed, lateral shoulder supports. Given adequate restraint it was shown that performance was virtually unaffected up to ±2Gy (Figs. 6,7,8,9). Muscular and performance effects on man at ±3Gy were also studied (16) and it was found that simple, single axis psychomotor task performance is possible at that level with shoulder restraints. On the basis of earlier work (17) it is known that lateral acceleration at levels above ±4Gy will assuredly require head restraints in order to avoid severe disorientation and injury.

Supermaneuverability - This is a new concept arising out of studies conducted by Messerschmitt-Boelkow-Blohm in which unconventional maneuvers involving very rapid pitch-up motions are combined with roll motion about the velocity vector. This type of flight maneuver will require new approaches to seating and restraints as well as research concerning human tolerance to the rapid angular motions combined with sustained acceleration that may occur in this type of maneuvering. As yet, none of the flight parameters have been defined sufficiently to enable a realistic estimate of the problems that may be encountered.

Man/Maneuver Matching - It is possible that future maneuver algorithms could be matched to human physiology while expanding the usable portion of the performance envelope. It is well known that unprotected man can tolerate virtually any level of sustained acceleration, from the cardiovascular standpoint, as long as the duration is limited to approximately three seconds. It should not be inferred from this that such maneuvering could be done with impunity, since the antecedent G history of the aircraft would have an effect on the remaining reserves of the man. Nevertheless, with adequate supporting research, it may well be possible to design an advanced flight control system that would make use of acceleration physiology for expanding the performance envelope.

Supercockpit - An exploratory effort is now underway at the Armstrong Aerospace Medical Research Laboratory to develop a supercockpit (21) incorporating synthetic 360o vision systems using helmet mounted displays depicting the entire physical surround and battle status in computer generated symbology. Voice control, eye-pointing/activation of controls and other advanced techniques are also included. Systems such as Supercockpit may, in the not too distant future, provide the solutions to some of the problems inherent in the use of postural protection measures.

Crew Selection - Human tolerance to sustained acceleration varies widely between individuals, showing the normal Gaussian distribution typical of many natural phenomena. As the performance capabilities of future fighter designs escalate, it may become necessary to give more attention to the concept of selecting fighter pilot candidates for their inherent acceleration tolerance (19, 20). Considering some of the unusual configurations that may be used in future fighter cockpits it may well develop that additional attention will also have to be directed toward crew anthropometry.

RECOMMENDATIONS

As long as materials and propulsion limited the performance of the fighter aircraft to a point well within the limits of human endurance it was reasonable to design aircraft with little regard to those limits. That period is now history, and attention must now be directed to the optimum mix of man and machine capabilities.

If oncoming generations of fighters are to realize their full potential, the designers of those aircraft must accommodate their designs to the realities of human capabilities. These realities will dictate new concepts in protection, radically different cockpit configurations and arrangements of display and controls, and pilot restraint systems suitable for the unique maneuvering capabilities that now appear possible.

For the design community to do otherwise will result in needless loss of life and material, and a needless loss in performance capabilities that might otherwise be within reach.

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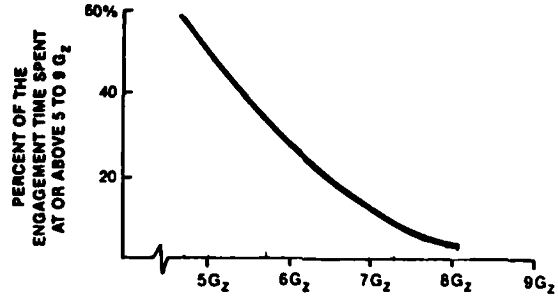


FIG 1 The current maneuvering environment

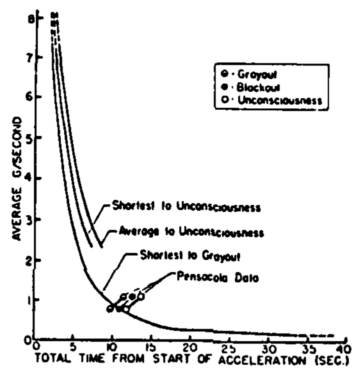


FIG 2 Influence of onset rate of charge of acceleration on time to loss of consciousness

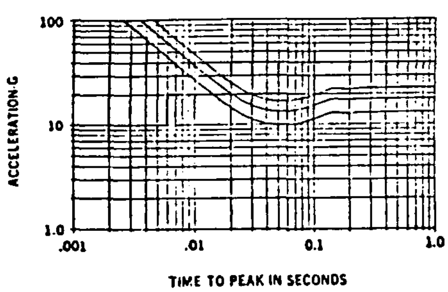


Figure 3. Injury Risk Levels for +Z Axis Half-Sine Acceleration Pulses.

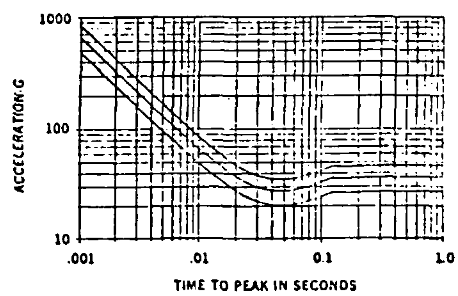


Figure 4. Injury Risk Levels for -X Axis Half-Sine Acceleration Pulses.

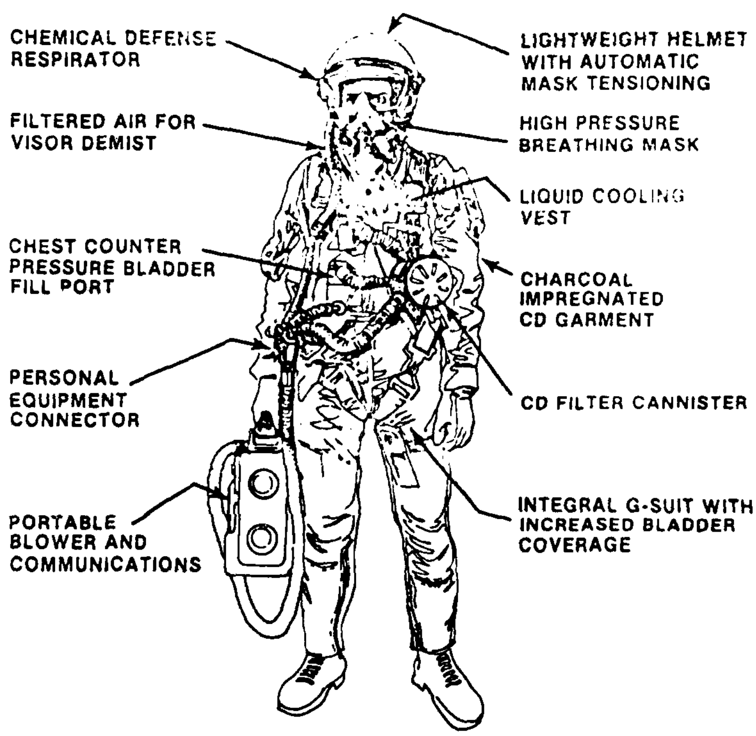
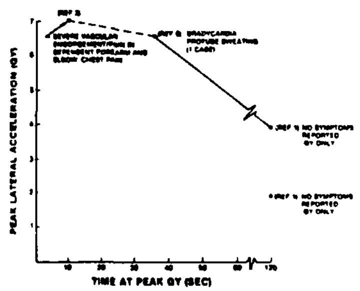
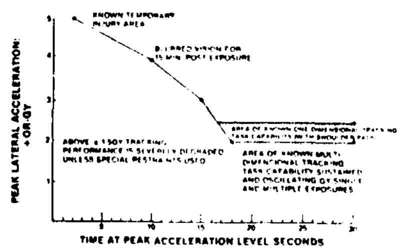


FIG 5. The integrated Tactical Life Support System developed by the Human Systems Division of the USAF



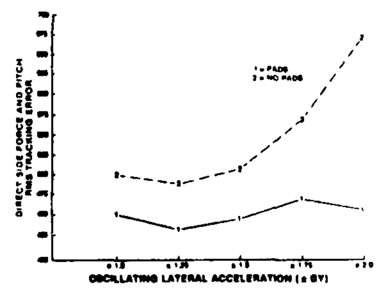
HUMAN TOLERANCE TO LATERAL ACCELERATION (± GY)-FULLY RECUMBENT, FULLY SUPPORTED MALE SUBJECTS

FIG 6



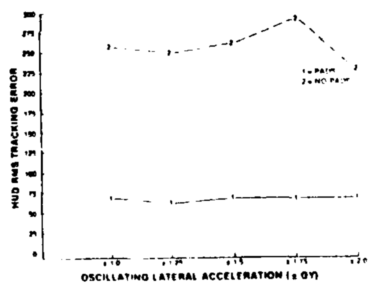
TOLERANCE TO SUSTAINED LATERAL ACCELERATION (+ GY) FOR MALE SUBJECTS WITHOUT SPECIAL HIP AND SHOULDER RESTRAINTS, SINGLE EXPOSURES, EXCEPT AS NOTED ONSET RATES FROM 0.4 TO 0.5 G/SEC

FIG 7



CLOSED LOOP TRACKING ERROR WITH AND WITHOUT SHOULDER PADS (ACTIVE YAW AND PITCH TASK)

FIG 8



CLOSED LOOP TRACKING ERROR WITH AND WITHOUT SHOULDER PADS (HEAD UP DISPLAY TASK)

FIG 9

CHANGES IN USAF STRUCTURAL LOADS REQUIREMENTS

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ABSTRACT

The new General Specification for Aircraft Structures, MIL-A-87221 (USAF), does not establish the traditional, fixed requirements, but instead it presents the current tailored approach to establishing structural loads requirements. In most cases the previous specifications set arbitrary load levels and conditions to be used in aircraft design. These requirements were based on historical experience, without consideration of future potential needs or capabilities brought about by technology advances. Instead, the new philosophy requires that loading conditions be established rationally for each weapon system based on anticipated usage. Also, compliance with each condition must be verified by analysis, model test, or full scale measurement.

INTRODUCTION

During the late 1970s, several conditions came together that caused the US Air Force to develop new aircraft structural specifications. While the USAF has always had a policy of reviewing, revising, and upgrading existing specifications, there were factors favoring a new approach. The contracting and legal authorities believed that the existing system of many layers of specifications needed to be simplified. Also, rapidly advancing structural technologies, coupled with new realms of performance and control capabilities, demanded that the structural specifications address much wider range of conditions while using an ever widening mix of technologies. The new military specification for aircraft structures, MIL-A-87221 (USAF), is a major deviation from past requirement practices. It establishes weapon system uniquely tailored structural performance and verification requirements for airframes based on an in-depth consideration of operational needs and anticipated usage. In the past, specifications set arbitrary conditions, levels, and values to be used in the design of broad categories of aircraft.

Various sources have alleged that design requirements have not kept pace with current usage practices; especially in the area of flight combat maneuvers. These allegations ignore the new requirement philosophy and are wrong for several reasons. The specification, MIL-A-87221 (USAF), does not preclude the consideration of any type of loading situation. The new specification actually requires the consideration of any loading condition that can be identified for either analysis, model testing, or full scale measurement. Therefore, if a loading oondition is overlooked, the fault is not with MIL-A-87221 since it is not a set of rigid, pre-determined requirements.

Thus, this new approach does place a greater reliance on the designer's insight and ability to correctly anticipate the actual service loads. The term designer represents a broad spectrum of individuals associated with the USAF, System Contractor, and not just from the System Project Office which manages system development for the USAF. Anyone attempting to use the specification must understand that this one document covers all types of aircraft; from light observation, to the largest transport, to the fastest fighters, to any of the most advanced flight vehicles. Therefore, any application of this new specification must be tailored to the specific type of aircraft under design. It should also be understood that no two aircraft designs, even of the same general type, will have the same, identical, anticipated usage. Therefore, not only must the detail design specification be tailored to a specific type or category of aircraft, but it must also reflect the specific anticipated usage of the aircraft being designed and performance capabilities brought about by technology improvements in aerodynamics, control system integration, materials, and human factors.

STRUCTURAL LOADING CONDITIONS

The general organization of MIL-A-87221 is shown in figure 1. Structural loading requirements are developed through the application of section 3.4 of the appendix. The verification of these requirements is established by the use of section 4.4, also of the appendix. This procedure when incorporated into the new specification gives the user the best features of both a checklist approach and total design freedom. The loading requirement section 3.4, is divided into flight and ground conditions as shown in figure 2. The flight and ground conditions are divided into subsections as shown in figures 2a and 2b respectively. Each of the many subsections contain varous specific load sources which the designer can either accept or modify as appropriate. During aircraft design, particular care must be exercised in defining both the structural loading conditions and the associate distributions used to design the airframe, which in turn directly influences the performance and reliability of the aircraft. No single section of the specification can be addressed independently. All requirements pertaining to all technologies must be considered as one unified entity. Both flight and ground operating conditions must be based on the anticipated usage, unique to a specific aircraft design effort. These conditions reflect the operational usage from which design loads shall evolve.

Even though this new approach gives the designer considerable flexibility, the designer is not abandoned to establishing all requirements without guidance or assistance. In both the requirement and verification sections, numerous possibilities are presented for consideration. The applicability or non-applicability of each suggested requirement or verification can be indicated by inserting either "APP" or "N/A" in a blank provided with each one. For those that are considered applicable, either the requirement or verification procedure is then fully defined. Additionally, unique requirements can be added as a direct product of the tailoring process.

FLIGHT LOADING CONDITIONS

The flight conditions (subsection of 3.4) consists of thirteen categories, from the standard symmetrical maneuvers, to missile evasion, to the all inclusive "Other" category which is the one that both frees the designer from rigid requirements and simultaneously burdens him with the need to better define anticipated usage. The maneuver load category suggests a minimum of five sub-categories for consideration. There is, of course, the usual symmetric maneuver envelope, figure 3. However, due to current usage, various maneuvers such as extreme yaw, jinking, or missile lock evasion are suggested for design consideration. Any maneuver which is possible for an anticipated aircraft and its usage, must be considered for design purposes.

Other changes can be found in the area of turbulence analysis. Historically, gust loading conditions have been analysed by a discrete approach. However, the current procedure is to employ an exceedance distribution calculation. In order to establish the exceedance distribution, various parameters are needed. Fortunately, the new specification does suggest values for these terms; figure 4 is an example from the specification. Also, historically, maneuver and gust loadings were considered independent and non-concurrent of each other except for aircraft engaged in low altitude missions. However, MIL-A-87221 actually suggests the designer rationally consider various conditions where gust and maneuver loads are combined because they concurrently affect the aircraft.

A very different type of load condition occurs during in-flight refueling. While some services use the probe and drogue system, a few others use the flying boom approach; a few use both types of in-flight refueling systems. This specification provides guidance in both these areas to establish appropriate design conditions.

Since the very beginning of aircraft pressurization, specifications have addressed its loading effects. However, this new specification addresses pressurization in a more inclusive manner then in the past. Usually, pressurization concerns have been focused on cockpits or crew compartments. In contrast, the new specification addresses all portions of the aircraft structure subject to a pressure differential. The requirements to consider pressurization even apply to such areas as fuel tanks, avionics bays, or photographic compartments. The broad application of this section of the specification requires constant and capable vigilance by the designer to include all pertinent structure.

Since this specification does not presume to directly address all possible loading phenomena, a special category is reserved for any unique situations. This category is called "Other" and is available so the designer can completely define all anticipated aircraft flight loading conditions. The important aspect of this category is that the designer is free to include any flight loading condition derived from operational requirements that can be appropriately defined for analysis.

GROUND LOADING CONDITIONS

While aircraft ground operations are not as glamorous as flight performance, they can be the source of significant loading conditions. Unlike flight conditions, there have been very few changes to ground operating conditions in recent years. In some cases the loading levels have been decreased due to improved civil engineering capabilities; improved runways, taxiways, ramps, etc. Ground loading conditions include all ground operations (taxi, landing, braking, etc.) and maintenance operations (towing, jacking, hoisting, etc.).

Ground Operations

Since the earliest days of aircraft, ground operations have changed very little. Most of these changes have been in the area of load magnitude, not in the type or source of load. Before takeoff, an aircraft normally needs to taxi, turn, pivot, and brake. Various combinations of these operations must be considered in order to fully analyse realistic gorund operations. The resultant loads are highly dependent on the operating conditions, which are in turn dependent on the aircraft type and anticipated mission.

Takeoff and Landing

Usually takeoffs and landings are performed on hard, smooth surfaces which are of more than adequate length. However, in some situations the surface is not of adequate length, hardness, or smoothness. Therefore, takeoff specifications must either anticipate all possible situations or allow the designer to establish specific takeoff and landing requirements for each system. For example, consideration is given to rough semi-prepared and unprepared surfaces. Even rocket and catapult assisted launch is included in the specification. However, the designer is free to consider devices such as ski-jumps, if they are appropriate to the aircraft and missions involved. Since takeoffs are addressed; so too are landings. Various surfaces, arrestment devices and deceleration procedures are included for consideration as possible load producing conditions. The designer and eventual user must work together to correctly establish landing requirements, since they can vary greatly depending on the final usage of the aircraft.

Towing

Since the beginning of aviation, it has been necessary to tow aircraft. While the designer is free to define his own towing conditions and associated loads, he must also verify the legitimacy of these conditions. In this category the new specification comes close to the previous Air Force criteria specifications by providing the values given in figures 5 and 6. One should remember that these towing conditions are very much a result of years of empirical experience. Justifying and verifying new towing load conditions could be a very difficult task.

Crashes

Unfortunately not all flights are successful; some end in crashes. Different types of aircraft require various types of design considerations for crash loads, depending on their inherent dangers due to mission and general configuration. For example, fighters pose crash problems with respect to seats, fuel tanks, or cockpit equipment, but definitely not litters or bunks. However, the design of a transport would most assuredly involve crash load considerations for cargo, litters, bunks, or even temporary fuel tanks in the cargo compartment. The new specification suggests various combinations of on-board equipment. These suggested values, figure 7, are very similar to the historic ones which in the past were firm requirements. Today a designer can use factors other than the suggested ones, as long as the alternate load factors can be substantiated.

Maintenance

Even daily maintenance actions can impose various loading conditions on aircraft. Many maintenance operations require towing, jacking, or hoisting which subject the aircraft to abnormal and unusual loading combinations that must be considered during aircraft design. General data is supplied for these conditions, figure 8. However, following the tailoring philosophy in MIL-A-87221 (USAF), the designer is free to define any level of maintenance induced loadings which can be substantiated.

CONCLUSIONS

The new specification, MIL-A-87221, will allow design requirements to be more closely tailored to the anticipated use of the aircraft. In this way the final product will be more efficient, with less wasted, unneeded, and unused capabilities. This will lead, in turn, to reduce costs of ownership for Air Force weapon systems. This specification has been applied to the definition of requirements for the Advanced Tactical Fighter. This process is now taking place.

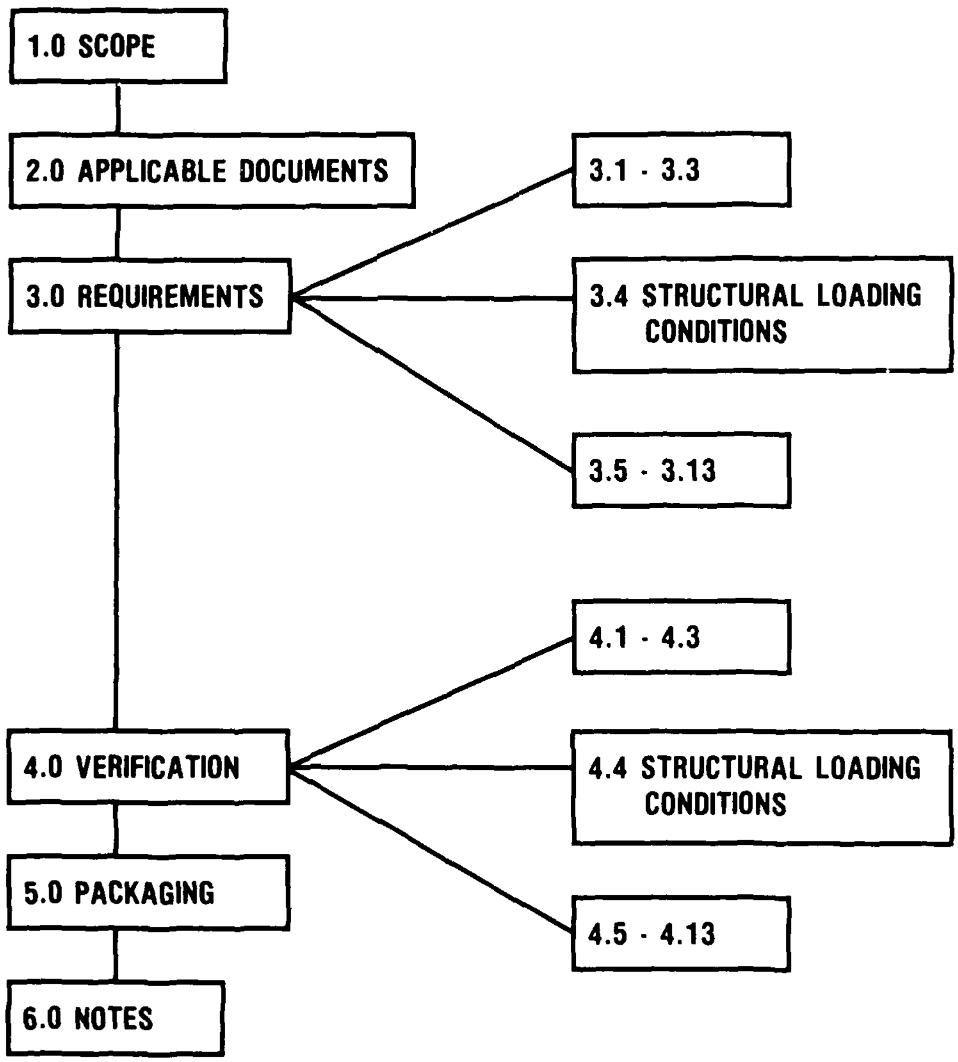


FIG. 1 ORGANIZATION OF MIL-A-87221 (USAF)

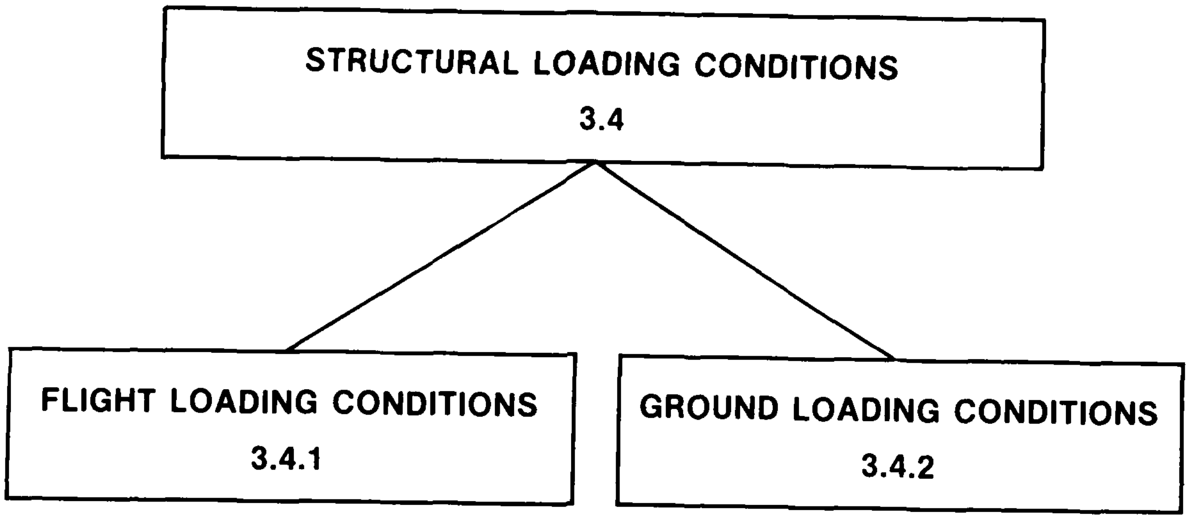


FIG. 2 ORGANIZATION OF "STRUCTURAL LOADING CONDITIONS"

FLIGHT LOADING CONDITIONS

3.4.1

3.4.1.1	SYMMETRIC MANEUVERS
3.4.1.2	ASYMMETRIC MANEUVERS
3.4.1.3	DIRECTIONAL MANEUVERS
3.4.1.4	EVASIVE MANEUVERS
3.4.1.5	OTHER MANEUVERS
3.4.1.6	TURBULENCE
3.4.1.7	AERIAL REFUELING
3.4.1.8	AERIAL DELIVERY
3.4.1.9	SPEEDS AND LIFT CONTROL
3.4.1.10	BRAKING WHEELS IN AIR
3.4.1.11	EXTENSION AND RETRACTION OF LANDING GEAR
3.4.1.12	PRESSURIZATION
3.4.1.13	OTHER FLIGHT LOADING CONDITIONS

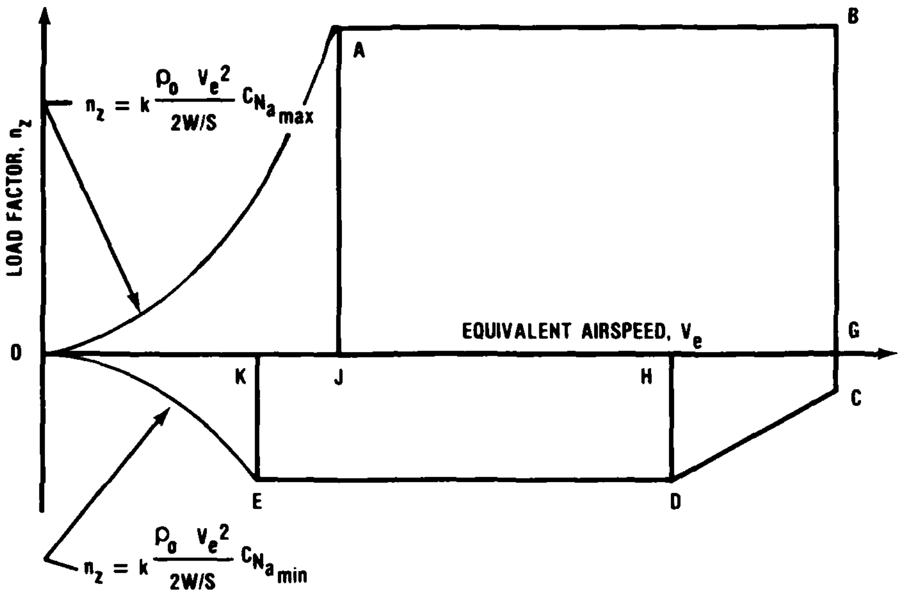
FIG. 2A FLIGHT LOADING CONDITIONS

GROUND LOADING CONDITIONS

3.4.2

- 3.4.2.1 TAXI
- 3.4.2.2 TURNS
- 3.4.2.3 PIVOTS
- 3.4.2.4 BRAKING
- 3.4.2.5 TAKEOFF
- 3.4.2.6 LANDINGS
- 3.4.2.7 SKI EQUIPPED AIR VEHICLES
- 3.4.2.8 MAINTENANCE
- 3.4.2.9 GROUND WINDS
- 3.4.2.10 CRASHES
- 3.4.2.11 OTHER GROUND LOADING CONDITIONS

FIG. 2B GROUND LOADING CONDITIONS



NOTES:

1. JA = GB = VALUE SPECIFIED IN PARAGRAPH 3.2.9
2. GC = VALUE SPECIFIED IN PARAGRAPH 3.2.9
3. HD = KE = VALUE SPECIFIED IN PARAGRAPH 3.2.9
4. OH = V_H AS SPECIFIED IN PARAGRAPH 3.2.7
5. OG = V_D OR V_L AS SPECIFIED IN PARAGRAPH 3.2.7

FIG. 3 V - n DIAGRAM FOR SYMMETRICAL FLIGHT AS PRESENTED IN MIL-A-87221 (USAF)

ALTITUDE (FT)	MISSION SEGMENT	DIRECTION 1/	P_1	b_1 (FT/SEC)	P_2	b_2 (FT/SEC)	L (FT) 2/
0 - 1,000	LOW LEVEL CONTOUR	VERTICAL	1.00	2.70	10^{-5}	10.65	500
0 - 1,000	LOW LEVEL CONTOUR	LATERAL	1.00	3.10	10^{-5}	14.06	500
0 - 1,000	CLIMB, CRUISE, DESCENT	VERT & LAT	1.00	2.51	.005	5.04	500
1,000 - 2,500	CLIMB, CRUISE, DESCENT	VERT & LAT	.42	3.02	.0033	5.94	1750
2,500 - 5,000	CLIMB, CRUISE, DESCENT	VERT & LAT	.30	3.42	.0020	8.17	2500
5,000 - 10,000	CLIMB, CRUISE, DESCENT	VERT & LAT	.15	3.59	.00095	9.22	2500
10,000 - 20,000	CLIMB, CRUISE, DESCENT	VERT & LAT	.062	3.27	.00028	10.52	2500
20,000 - 30,000	CLIMB, CRUISE, DESCENT	VERT & LAT	.025	3.15	.00011	11.88	2500
30,000 - 40,000	CLIMB, CRUISE, DESCENT	VERT & LAT	.011	2.93	.000095	9.84	2500
40,000 - 50,000	CLIMB, CRUISE, DESCENT	VERT & LAT	.0046	3.28	.000115	8.81	2500
50,000 - 60,000	CLIMB, CRUISE, DESCENT	VERT & LAT	.0020	3.82	.000078	7.04	2500
60,000 - 70,000	CLIMB, CRUISE, DESCENT	VERT & LAT	.00088	2.93	.000057	4.33	2500
70,000 - 80,000	CLIMB, CRUISE, DESCENT	VERT & LAT	.00038	2.80	.000044	1.80	2500
ABOVE 80,000	CLIMB, CRUISE, DESCENT	VERT & LAT	.00025	2.50	0	0	2500

NOTES: 1/ PARMETER VALUES LABELED VERT & LAT ARE TO BE USED EQUALLY IN BOTH THE VERTICAL AND LATERAL DIRECTIONS.

2/ FOR ALTITUDES BELOW 2,500 FT, THE SCALE OF TURBULENCE, L, CAN BE ASSUMED TO VARY DIRECTLY WITH ALTITUDE.

FIG. 4 SAMPLE OF TURBULENCE FIELD PARAMETERS

<table>
<tr><th rowspan="2">CONDITION</th><th colspan="2">TOWING LOAD</th><th rowspan="2">ROTATION OF AUXILIARY WHEEL RELATIVE TO NORMAL POSITION</th><th rowspan="2">TOW POINT</th></tr>
<tr><th>DIRECTION FROM FORWARD, DEGREES</th><th>MAGNITUDE</th></tr>
<tr><td>1</td><td>0</td><td rowspan="4">0.75 T</td><td rowspan="4"></td><td rowspan="4">AT OR NEAR EACH MAIN GEAR</td></tr>
<tr><td>2</td><td>±30</td></tr>
<tr><td>3</td><td>180</td></tr>
<tr><td>4</td><td>±150</td></tr>
<tr><td>5</td><td>0</td><td rowspan="2">T</td><td rowspan="2">0</td><td rowspan="8">AT AUXILIARY GEAR OR NEAR PLANE OF SYMMETRY</td></tr>
<tr><td>6</td><td>180</td></tr>
<tr><td>7</td><td>0</td><td rowspan="2">T</td><td rowspan="2">180</td></tr>
<tr><td>8</td><td>180</td></tr>
<tr><td>9</td><td>MAXIMUM ANGLE</td><td rowspan="2">0.5 T</td><td rowspan="2">MAXIMUM ANGLE</td></tr>
<tr><td>10</td><td>MAXIMUM ANGLE PLUS 180</td></tr>
<tr><td>11</td><td>MAXIMUM ANGLE</td><td rowspan="2">0.5 T</td><td rowspan="2">MAXIMUM ANGLE PLUS 180</td></tr>
<tr><td>12</td><td>MAXIMUM ANGLE PLUS 180</td></tr>
</table>

FIG. 5 SUGGESTED TOWING CONDITION

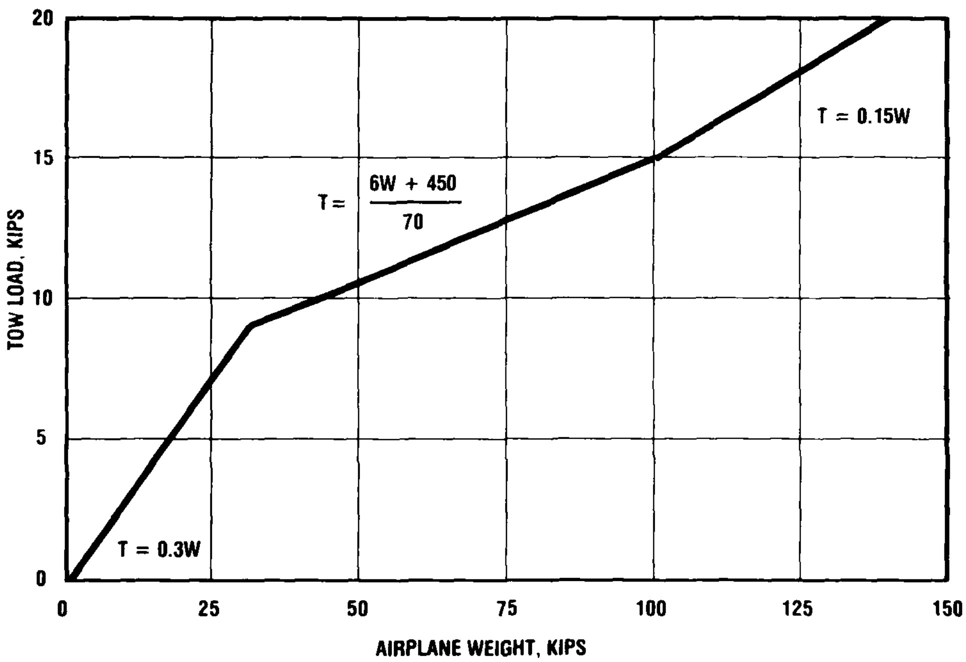


FIG. 6 SUGGESTED RELATIONSHIP BETWEEN AIRCRAFT WEIGHT AND TOW LOAD

BASIC MISSION SYMBOLS	LOAD FACTORS				APPLICABLE ITEMS
	LONGITUDINAL		VERTICAL	LATERAL (LEFT AND RIGHT)	
	FORWARD	AFT			
ALL AIRPLANES EXCEPT CARGO (C)	40	20	10 UP 20 DOWN	14	APPLICABLE TO ALL ITEMS
	20	10	10 UP 20 DOWN	10	APPLICABLE TO ALL ITEMS EXCEPT STOWABLE TROOP SEATS
CARGO (C)	10	5	5 UP 10 DOWN	10	APPLICABLE TO STOWABLE TROOP SEATS

FIG. 7 SAMPLE SEAT CRASH LOAD FACTORS SHOWN IN MIL-A-87221 (USAF)

COMPONENT	LANDING GEAR 3-POINT ATTITUDE	OTHER JACK POINTS LEVEL ATTITUDE
VERTICAL	1.35 F	2.0 F
HORIZONTAL	0.4 F	0.5 F
F IS THE STATIC VERTICAL REACTION AT THE JACK POINT.		

FIG. 8 SAMPLE JACKING LOADS GIVEN IN MIL-A-87221 (USAF)

STRUCTURAL DESIGN REQUIREMENTS FOR AIRCRAFT INCORPORATING ACTIVE CONTROL TECHNOLOGY

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SUMMARY

This paper considers the special structural design and certification requirements that are needed for military aircraft incorporating Active Control Technology (ACT). UK requirements are introduced which cover static strength, fatigue performance aeroelasticity, and the need to assess the influence of modifications to ACT software. The requirements draw attention to the essential role of flight load measurements undertaken during both development and operational flying in the process of structural substantiation.

INTRODUCTION

During 1984, using knowledge gained from the Experimental Aircraft Programme (EAP) and looking ahead to the *European Fighter Aircraft (EFA) Programme*, the UK Joint Airworthiness Committee (JAC) began revising Defence Standard 00-970 Design and Airworthiness Requirements for Service Aeroplanes to include specific requirements for aircraft incorporating Active Control Technology. Accordingly the JAC formed Sub-Committee No 83 (SC 83) to undertake the drafting of a new Defence Standard 00-970 Chapter entitled Active Control Systems (ACS). Chapter 208 as it became, includes requirements for all aspects of ACS. Indeed the coverage is so broad that specialist working groups were formed to draft the requirements for software and structures. The Structures Working Group of which the authors were Secretary and Chairman respectively, comprised representatives from industry, MOD (Procurement Executive), MOD (Air Force Department) and the Civil Aviation Authority.

Since Chapter 208 was drafted Mil-A-8861B has been revised to include some specific design cases for aircraft equipped with Direct Lift Control (DLC) and Direct Side Force Control (DSFC). However, the revision does not cover the structural implications of ACS in as great a depth as Chapter 208, and the two sets of requirements should be regarded as complementary.

This paper discusses the means of specifying acceptable safety levels for ACS and describes the rationale underlying the Defence Standard 00-970 requirements for static *strength, fatigue performance*, aeroelasticity, loads measurement and mandatory cases for structural resubstantiation.

ACCEPTABLE LEVEL OF SAFETY

The Structures Working Group initially investigated whether it would be possible to specify, in probabilistic terms, an acceptable level of safety for an aircraft utilising an ACS. Specifically, consideration was given to whether the aircraft as a whole should be set a safety target in terms of the number of flying hours before catastrophic failure due to all causes, and whether to achieve this overall target the ACS and its components should be allocated higher individual targets. This did not prove possible for two fundamental reasons. Firstly, the Software Working Party was adamant that it is impossible to quantify software reliability because software integrity is largely dependent on the scope of software testing that is undertaken. Secondly, no suitable data could be found on the frequency of occurrence of aircraft loads. Existing operational 'g' data are not collated against aircraft mass and therefore cannot provide limit load exceedance data; furthermore, even if such data were available for conventional aircraft it would be of doubtful relevance to ACS aircraft. Also data on gusts were largely collected by commercial transport aircraft and contain manoeuvre effects. Some gust data for military aircraft has been collected but most programmes have not utilised aircraft which can fly close to Mach 1 at sea-level.

The Structures Working Group, therefore, adopted a policy of equivalent safety that is: an aircraft incorporating an ACS should be as safe as a similar aircraft designed to fulfil the same role without an ACS. Consequently, the aim of structures-related material in Chapter 208 is to identify instances in the aircraft design and *development process where special procedures must be adopted or new factors considered* to ensure that an ACS aircraft is as safe as its conventional counterpart.

STATIC DESIGN

INADEQUACY OF EXISTING DESIGN CASES FOR MANOEUVRES

Compared with a conventional aircraft the ACS aircraft can perform unconventional uncoupled manoeuvres. Examples of such manoeuvres are shown in Figure 1. Figures 1a to 1c show manoeuvres utilising some degree of DLC, while Figures 1d to 1e show manoeuvres which utilise DSFC. Figure 1a demonstrates the vertical translation mode in which, for example, symmetric wing flaperon/tail deflection makes the aircraft change altitude without altering fuselage axis inclination. With the body level the flight path can be inclined, typically, 5° or 10°. Figure 1b demonstrates control of normal acceleration at a constant Angle of Attack (AOA) which is achieved by the blending of direct lift and pitch rate. This gives precision flight path control, quicker dive recovery and increased manoeuvre factor at constant AOA, Figure 1c demonstrates pitch-pointing showing how it is possible to alter fuselage pitch without substantially changing V or flight path. Figure 1d shows lateral translation in which lateral velocity can be varied at constant heading to enable the pilot to take out drift on landing or errors in air-to-ground firing. Figure 1e shows variable yaw control which blends DSFC with the standard rotational mode to achieve wings level turning without sideslip or roll. This enables tracking of laterally moving targets. Figure 1f shows yaw pointing which uses foreplane, rudder and roll control to change yaw angle while keeping flight path constant to achieve near instant aiming control.

In ACS control systems there is a computer between the pilot's control and the motivators. This computer modifies the pilot's control demands according to certain response quantities. Thus it is not possible to relate motivator deflections to the pilot's control forces and/or deflections. Consequently, critical design loads may no longer occur at the corners of pilot input v time histories and a comprehensive examination of loads during transient response is required to identify critical design cases. Figure 6 illustrates such a situation by comparing typical pitch responses, with and without the stability augmentation system engaged, to a rapid pilot input which is then held on.

Present Defence Standard 00-970 requirements for static strength assume that the aircraft will perform conventional manoeuvres, eg that changes in aircraft trajectory will be associated with rotations (variation in pitch for climbing and diving, variation in bank for turning). Design cases for symmetrical manoeuvres are specified by a requirement to sustain the loads due to all combinations of forward speed (V) and normal acceleration (n) which fall within the boundaries of a V-n diagram. Design cases for asymmetric manoeuvres are specified in terms of motivator deflections, maximum motivator Power Control Unit (PCU) power output, pilot's control forces and, for combined pitch and roll manoeuvres, specified combinations of roll motivator deflections and n. These requirements are not sufficient to define all the critical design cases for aircraft equipped with ACS as: firstly, the requirements do not consider unconventional uncoupled manoeuvres; secondly, it is not possible to relate motivator deflections to pilot's control forces; finally, the requirements do not demand an investigation of loads throughout transient responses.

ADDITIONAL DESIGN CASES FOR ACS AIRCRAFT

It is not possible to complement the existing requirements by specifying specific additional design cases as they are difficult to identify because they are too multitudinous. Different types of aircraft will utilise ACS for different applications; for example, some will seek to achieve enhanced agility and weapon platform stability while others will aim to alleviate loading actions to permit reductions in structural weight, size or stiffness. Similar aims will be achieved by different types of aircraft using different motivators; for example, a DSFC manoeuvre may be achieved by several different combinations of differential foreplane, aileron, elevon, differential tailplane and rudder deflections. Furthermore, each aircraft type will have unique software features in the form of system architectures and control laws. Therefore, the designer must be alerted to the difficulties of identifying critical ACS design cases and told where special procedures must be adopted or new factors considered to ensure the structural integrity of ACS aircraft.

FAILURES/DEGRADATIONS

As ACS software reliability cannot be quantified it is impossible to predict the system failures and degradations, and consequently the corresponding loads, that will be experienced by operational aircraft. Therefore, structural airworthiness must be ensured by requiring that the aircraft has sufficient strength to sustain the loads due to all system failures, degradations or transients which can be envisaged and from which it is reasonable to expect the aircraft to recover. In addition, the structure should have some capability of sustaining loads which could occur following birdstrike damage, battle damage etc. Thus the structure must also be capable of sustaining those loading conditions which would exist following the occurrence of combinations of structural damage and system degradations from which recovery is feasible.

The designer should also consider whether the pilot could reduce the severity of the loads which are likely to occur during flight with a degraded ACS by, for example, limiting maximum speed and/or 'g' or, jettisoning stores or fuel. If the designer does choose to require the pilot to implement a limitation following an ACS malfunction then the cardinal principle should be that the average service pilot should be capable of observing the limitation. Thus the pilot must be provided with a timely and unambiguous warning of the ACS malfunction so that he has time to prevent a catastrophic situation from developing. Furthermore, the operating margin equivalent to the difference between the maximum load predicted to occur following the implementation of the limitation and the limit load capability of the degraded aircraft should depend on the ease with which the pilot may observe the limitation.

LOADING GRADIENTS

Traditionally the design and operation of a conventional aircraft has not resulted in a knowledge of the loading gradients (the variation in structural load with input function) in the region between Design Limit Load (DLL) and Design Ultimate Load (DUL). Examples of typical input functions would be gust velocity in the case of a gust, or achieved aircraft response (rate of pitch etc) in the case of a manoeuvre. The loading gradients between DLL and DUL of conventional aircraft are not known for three reasons. Firstly, the ultimate factor of safety has catered for unknowns due to: inexactitudes in the evaluation of aerodynamic loads and stress analysis, exceedances of DLL, and differences between operational usage and that assumed during design. Secondly, loads greater than DLL have not been investigated during development flying. Finally, existing Royal Air Force fatigue monitoring procedures do not link recorded 'g' counts with aircraft mass and thus cannot provide data on the frequency of DLL exceedances.

The loads sustained by an ACS aircraft are dependent on more variables than the loads experienced by a conventional aircraft; consequently, it is possible that an ACS aircraft may experience more frequent exceedances of DLL. Influences which could cause DLL exceedances are:

a. The probability that an ACS aircraft will engage in more high 'g' manoeuvring than a conventional aircraft and consequently have greater opportunity to exceed DLL or encounter critical combinations of gust and manoeuvre loads.

b. The inability to quantify software reliability.

c. System failures and degradations.

d. System non-linearities such as C_p shifts, non-elasticities, kinetic heating effects, CG shift, inertia coupling, inaccuracies in control laws, system dwells, control deflection limits and PCU rate limits.

e. System authority limits such as those which can occur when a particular motivator has more than one function and cannot perform both functions simultaneously, eg a gust load alleviation system may not be able to provide full load alleviation during intensive manoeuvring or severe turbulence.

f. System approximations such as the fact that a 'g' limiting system cannot be classed as a load limiting system because it can only limit one of the components of load in a feature.

Figures 2a and 2b show the effect load gradient can have on the operating margin equivalent to a load increment from DLL to DUL. As an example both figures show examples where the ACS provides a constant % load alleviation upto DLL but saturates above DLL. In both figures the load gradients for ACS serviceable and ACS unserviceable are identical between DLL and DUL; however, below DLL the gradients in Figure 2b are more severe than those in Figure 2a.

In the example shown in Figure 2a there is a reduction in available operating margin following an ACS failure; however, this operating margin might be acceptable if:

a. The variation in input function was such that there would be a small probability of the margin being exceeded during flight in the degraded condition.

b. An operating limitation could be applied which would effectively increase the margin by reducing the values of the largest loads which would be encountered during flight in the degraded condition.

In the example shown in Figure 2b there is a negative operating margin following an ACS failure. A negative operating margin would be unacceptable and a redesign would be necessary unless it was possible to restore an acceptable operating margin by applying a suitable operating limitation during flight with a degraded ACS.

Figure 3 shows the effect load gradient can have on the ease with which DLL may be approached in flight at high 'g'. Two cases are shown and it is obvious that the steeper the loading gradient the smaller the operating margin equivalent to an increment in load from that equivalent to Service Release Conditions to DLL.

Obviously, the examples given in Figures 2, and 3 are hypothetical; however, they do illustrate the influence which loading gradient has on the ease with which DLL and subsequently DUL may be approached and exceeded. They are especially relevant to the structural integrity of an ACS aircraft as it has already been shown that critical design cases are very difficult to determine. Therefore, Chapter 208 requires that the designer shall determine the loading gradients for significant structural items of the ACS aircraft and show that they are not so severe that a small increment in input function could produce such a large increment in load that there would be a high probability, if Service Release conditions were slightly exceeded, of DUL being approached or exceeded.

COMBINATIONS OF GUSTS AND MANOEUVRES

Figure 4 shows typical 'g' spectra for conventional and ACS combat aircraft designed for a similar role. The plots have been compiled using a mixture of operational and design data for several aircraft types and show the number of counts of or above a particular 'g' level which occur every 1000 flying hours. The differences in the shape of the spectra show that the ACS aircraft performs more high 'g' manoeuvres than its conventional counterpart.

Existing ESDU gust data presents gust frequency as a function of altitude and distance flown. Therefore, for similar sorties ACS and conventional aircraft should experience similar gust spectra. However, the ACS aircraft is more likely to encounter critical combinations of gust velocity and manoeuvre 'g' because it will experience the more severe manoeuvre spectra.

A statistical analysis using ESDU gust data and the 'g' spectrum of one of the ACS aircraft used to compile Figure 4 has been carried out and the results are plotted in Figure 5. The probability of occurrence of a particular combination of manoeuvre 'g' and gust velocity is dependent on the durations of the manoeuvre and the gust. No such duration data exists and, consequently, Figure 5 is a carpet plot of frequency of occurrence of manoeuvre/gust combinations versus manoeuvre and gust durations.

Defence Standard 00-970 does not contain a combined manoeuvre/gust requirement; however, MIL-A-008861B requires the aeroplane to sustain a 25 fps (7.62 m/s) gust associated with a manoeuvre of 0.6 x maximum n (for a 9 g aeroplane this is 5.4 g). This MIL requirement does not specify the duration of the 25 fps gust; however, a [illegible] duration has been assumed and the MIL requirement is superimposed, for a 9 g aeroplane, on Figure 5. The figure shows that depending on the durations of the manoeuvre and gust the MIL specified condition will be encountered once every 20-140 flying hrs. The figure also shows that to first order the following combinations of manoeuvres and gusts can be expected to occur during a typical combat aeroplane's life of 6000 hrs:

a. 9 g with 25 fps (7.62 m/s)

b. 8 g with 35 fps (10.67 m/s)

c. 7 g with 45 fps (13.72 m/s)

d. 6 g with 50 fps (15.23 m/s)

e. 5 g with 55 fps (16.77 m/s)

Although the analysis results must be regarded tentatively because of the lack of real duration data and the inadequacies in the gust data noted in para 4, they do indicate that the existing MIL requirement may not be sufficiently severe. Therefore, the designer must conduct a rational analysis to determine critical combinations of gust and manoeuvre loads.

FATIGUE DESIGN

The pilot of an ACS aircraft may be encouraged to fly many high 'g' manoeuvres because his ACS may be a carefree manoeuvring or load limiting facility. Thus as shown in Figure 4 the manoeuvre spectrum of the ACS aircraft will be a different shape to that of the conventional aircaft, and will contain more frequent occurrences of the higher 'g' levels. Consequently, the designer must pay special attention to the derivation of the fatigue spectrum of the ACS aircraft.

Compared with a conventional aircraft the ACS aircraft will exhibit increased control activity, particularly small amplitude high frequency motions, and the designer must pay special attention to the fatigue design of motivators, actuators and associated support structure and linkages. Vibrations caused by virtually continuous motivator movement may cause significant fatigue loads on ACS components. Therefore, such vibratory loads should be considered when the fatigue load spectrum of an ACS component is derived. In addition, it may be very important to carry out a fatigue test of a complete ACS system.

AEROELASTIC DESIGN

The Structures Working Group recognised that some credit, as regards reduction of critical loads, must be given for active flutter suppression systems, provided that a positive flutter margin still existed when the ACS was degraded. Therefore, Chapter 208 requires that an aircraft with a fully serviceable ACS system must comply with existing design requirements in that it should have a flutter margin of 0.15 of the Design Diving Speed (V_D) at any point in the flight envelope for any mass/stores configuration. In addition, Chapter 208 requires that an aircraft with a degraded ACS should be flutter free to V_D. Chapter 208 also advises that it may be acceptable for the aircraft with the degraded ACS to be flutter free to a speed less than V_D if this may be accomplished by a jettison of external stores or by a reduction in airspeed provided that the pilot can be given sufficient warning to enable him to perform the necessary actions, and that jettison of stores is acceptable in peacetime.

LOADS MEASUREMENT

The difficulties in the identification of design loads for ACS aircraft have already been stated. Consequently, it is very important that ACS aircraft are fitted with load measurement systems to confirm design loads and design 'g' spectra. Chapter 208 envisages that the standard of loads-measurement equipment fitted, to prototype and development aircraft should be different to that fitted to operational aircraft.

Prototype and development aircraft must be fitted with comprehensive instrumentation to enable fatigue and static loads to be measured and critical loading actions to be defined. The data so obtained must be analysed to assess the validity of design loads and to determine whether any additional critical loading actions could occur if the relative phasing of manoeuvre and gust loads was altered.

In-Service aircraft must be fitted with a fatigue monitoring system to enable defined critical fatigue loads to be measured and assessed so that fatigue consumption can be quantified, and design 'g' spectra confirmed by determining operational usage. In addition, a representative sample of in-Service aircraft must be fitted with a comprehensive load measurement system, which although not necessarily as complex as that fitted to prototype and development aircraft, must be sufficient to enable defined critical static and fatigue loads to be monitored and to allow any new critical loading actions to be identified. The data from the latter group of aircraft will allow the validity of the fatigue monitoring system fitted to all aircraft to be assessed, and should also identify cases where a structural re-substantiation is required to confirm that the structure has sufficient strength to sustain a newly identified loading action.

STRUCTURAL RE-SUBSTANTIATIONS

A re-substantiation of the structure of an ACS aircraft will be required whenever new critical loading actions are identified by in-flight measurements or whenever an ACS software or hardware modification has a possible influence on structural loads. In the simplest case the re-substantiation would involve a check to verify that the critical load fell within the strength envelope of the aircraft. In more complicated cases the re-substantiation would be accomplished by calculation and/or testing. An example of an ACS software modification influencing structural loads would be an ACS PCH rate change to overcome a deficiency in aircraft roll rate. In such an instance in-flight load measurements would be required to re-assess loads to determine whether structural strength must be re-assessed.

Instances when a re-substantiation is required may occur during aircraft development or when the aircraft is in service. In both cases an appropriate flying limitation to ensure loads do not exceed 80% DLL should be applied until the re-substantiation is complete.

CONCLUSION

It is not possible to set a safety level for an ACS aircraft in probabilistic terms and, therefore, a philosophy of equivalent safety must be adopted to ensure that the ACS aircraft is as safe as its conventional counterpart. Def Stan 00-970 achieves this aim by identifying those facets of the aircraft design and development process which require special attention to ensure the structural integrity of the ACS aircraft.

The designer is alerted to the difficulties in the identification of critical static loading cases and he is required: firstly, to take account of the effects of ACS failures, degradations and transients; secondly, to assess the influence of loading gradients on the ease with which DUL may be approached or exceeded if the structure experiences loads which are greater than design loads; thirdly, to conduct a rational analysis to determine the probability of occurrence of particular combinations of manoeuvre 'g' and gust velocity. As the ACS aircraft is likely to undertake more high 'g' manoeuvres and require more control activity than its conventional counterpart the designer is advised that he should pay special attention to the derivation of fatigue spectra and the fatigue design of motivators, actuators and associated supporting structure. Furthermore, the designer is advised that an ACS aircraft with a serviceable ACS should have a flutter margin of 0.15 V_D and that an aircraft with a degraded ACS should be flutter free to V_D.

Due to the difficulties in identifying critical static and fatigue loads it is especially important that load measuring systems are fitted to ACS aircraft. Prototype and development aircraft must be fitted with instrumentation to define critical static and fatigue loads. All operational aircraft must be fitted with fatigue monitoring systems to quantify fatigue consumption and determine fatigue spectra; in addition, some operational aircraft must be fitted with a comprehensive load measuring system so that the fatigue monitoring system fitted to all aircraft can be validated and any new critical loading actions identified.

A resubstantiation of the structure is required whenever new critical loading actions are identified or whenever ACS software or hardware modifications are made which have a possible influence on structural loads.

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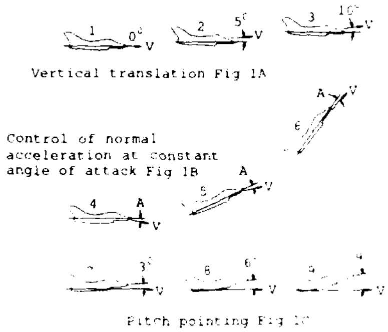
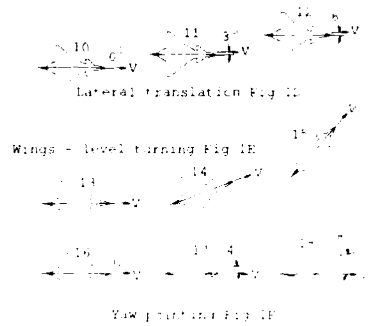


Symmetric manoeuvres unique to acs aircraft



Asymmetric manoeuvres unique to acs aircraft

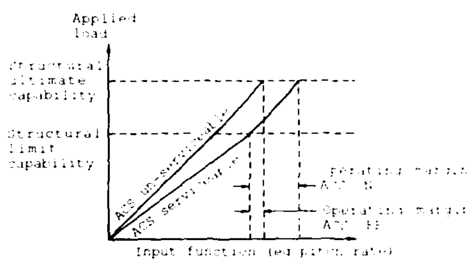


fig 2a Variation in operating margin with load gradient

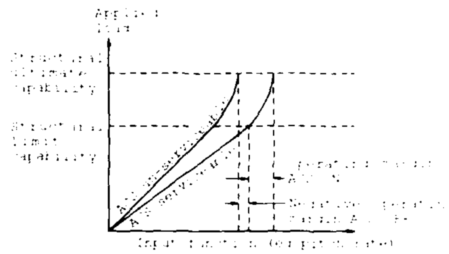


fig 2b Variation in operating margin with load gradient

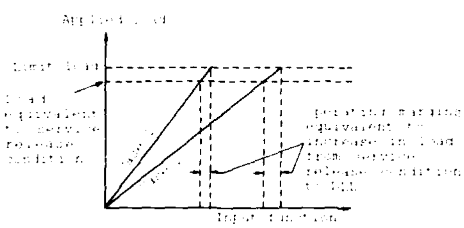


Fig 3 Effect of loading gradient on ease of exceedance of DLL following exceedance of service release

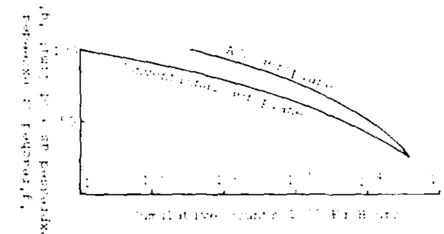


Fig 4 Typical normalised 'g' spectra for conventional and ACS aeroplanes

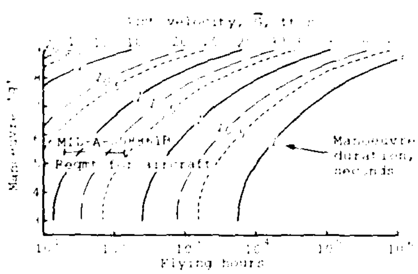


fig 5 frequency of occurrence of gust and manoeuvre combinations for gusts of 0.5 s duration

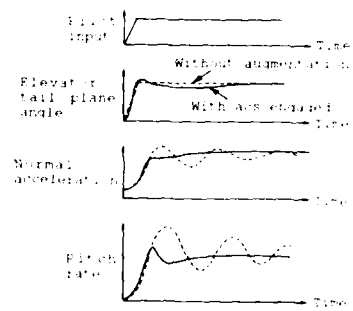


Fig 6 Response to rapid symmetric stick movement

AD-P005 766

THE RELATIONSHIP BETWEEN OPERATIONAL FLIGHT MANOEUVRE PARAMETERS AND DESIGN PARAMETERS

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SUMMARY

The philosophy of the relevant design requirements and the essential load parameters for the manoeuvre load conditions, including the determination of the control displacements corresponding to the design requirements, is reviewed. As far as the operational load parameters are concerned, numerous data have been recorded for the normal load factor but only a few for other main load parameters, e.g. lateral load factor, roll rate etc. These data usually are evaluated as cumulative frequency distributions. The envelope of such normal load factor spectra shows a large scatter depending on the aircraft and its usage.

For future design work, an approach to the evaluation of operational manoeuvres is presented. In this analysis, the maximum values of the main load parameters needed, i.e. normal and lateral load factor, roll rate and bank angle, can be determined. The extreme operational loads on the structural components have been derived by applying a manoeuvre model and compared with the design values.

1. INTRODUCTION

The regulations give the time history of the control surface deflections and numerically define several essential load parameters for determination of the load level. With the introduction of the fly-by-wire and/or active control technology, recent specifications do no longer define the control surface deflections but the cockpit control displacements, the other load criteria being retained. The application of these cockpit control displacements cannot be considered as adequate for the design load determination.

In practice, manoeuvres, especially combat manoeuvres are flown in accordance with given, practised rules that lead to a specified motion of the aircraft. In Germany, an evaluation of combat manoeuvres is being made with the aim of deriving operational loads by analyzing measured parameters. For the manoeuvres evaluated, a normalization of the relevant parameters of motion is feasible, and the results could be verified in a manoeuvre model. Taking into account extreme operational load parameters in the manoeuvre model, the extreme operational loads can be ascertained.

2. DESIGN REQUIREMENTS

2.1 Design parameters specified in regulations

Aircraft structures are designed in accordance with the relevant regulations and based on a philosophy defining the load level so as to cover all loads expected in service. The design loads are largely independent of the manoeuvres actually performed in operation.

The design load conditions are determined by the main load parameters as limit values for:

- symmetrical manoeuvres as load factor (nz)
- unsymmetrical manoeuvres as roll rate (p) and bank angle (Φ) combined with a specified load factor (nz)

as shown in Table 1 and 2.

REQUIREMENT Basic Mission Symbol Category III	SYMMETRICAL FLIGHT LIMIT LOAD FACTOR					Time for abrupt control displacement t_1/t_2, second
	Basic Flight Design Weight		All Weights	Max. Design Weight		
	Max	Min at V_H	Min at V_L	Max	Min at V_H	
MIL-A-008861 A						
A, F, TF (Subsonic)	8.0*	-3.0	-1.0	4.0	-2.0	0.2
A, F, TF (Supersonic)	6.5	-3.0	-1.0	4.0	-2.0	0.2
O, T	6.0	-3.0	-1.0	3.0	-1.0	0.2
AIR 2004/E Category	n_1 corresponding to A/C Specification					0.2/0.3

* as required by Performance and Design Requirements (PDR)

Table 1 SYMMETRICAL DESIGN PARAMETERS FOR FIGHTER

REQUIREMENT Unsymmetrical Manoeuvre	Initial Load Factor Max.	Min.	Roll Rate [°/s]	Bank Angle [°]	Time for abrupt control displacement
MIL-A-008861A					
ROLLING PULL OUT	$0.8n_{z(max)}$	1.0	≤270	2x value corresp. to n_z	0.1
ROLL 180	1.0	-1.0	≤270	180	0.1
ROLL 360	1.0	1.0	≤270	360	0.1
YAWING	1.0	1.0	-	≤5	0.2
AIR 2004/E					
ROLL 360	$0.8n_1$	$0.2n_1$	≤300	360	0.2/0.3
YAWING	1.0	1.0	-	≤5	0.2/0.3

Table 2 UNSYMMETRICAL DESIGN PARAMETERS FOR FIGHTER

2.2 Procedures specified for design load determination

The structural loads are determined by response calculations of the aircraft for defined cockpit control displacements, and thus the manoeuvre loads for the whole flight envelope are calculated. The cockpit control displacements are defined as time history for

- pitching manoeuvres
- rolling manoeuvres
- yawing manoeuvres

stated in MIL-A-008861A as shown in Fig. 1 and in AIR 2004/E as shown in Fig. 2

In accordance with the former regulations MIL-A-8861 and AIR 2004/D the control surface deflection is specified and its time history has to be determined so as to produce the most critical load conditions. Application of these control surface movements permits to determine the most critical loads acting on the main structural components. This means, this procedure, as far as the control surface deflection time histories are concerned, includes distinct load criteria that provide a load level which cannot be exceeded by any other control surface movements.

The introduction of the fly-by-wire and/or active-control technology makes this philosophy inadequate, *though*. The latest regulations MIL-A-008861 A and AIR 2004/E do no longer specify the control surface deflections but the cockpit control displacements, whereas the other load criteria are retained. That means, the time history of the control surface deflection results firstly from the cockpit command and secondly from the parameters fed back. If there is no similarity between the time history of the cockpit control and of the control surface deflection, the task of determining the critical cockpit control displacement time history and thus the extre⸗ loads on the main structural components is very complex. [4]

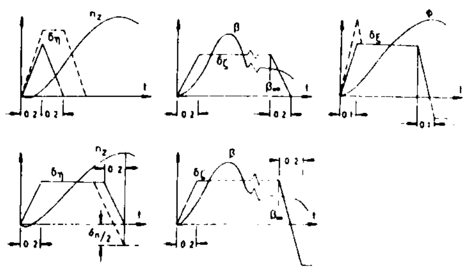

Fig. 1 COCKPIT CONTROL DISPLACEMENT MIL-A-008861A

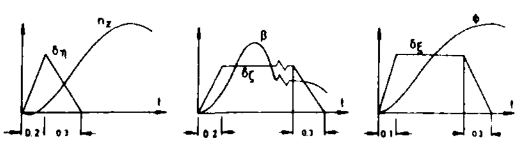

Fig. 2 COCKPIT CONTROL DISPLACEMENT AIR 2004/E

3. OPERATIONAL PARAMETERS

3.1 Spectra of main load parameters

It has become common practice to fit accelerometer systems (fatigue meter) to fixed wing aircraft to obtain service data on fatigue loading actions associated with symmetric manoeuvres and normal gusts. The following operational parameters usually are recorded and comp led:

- number of flights and/or flight hours
- configuration and mass of the aircraft
- vertical acceleration at the C.G. of the aircraft

A lot of such data are available but the evaluation procedures are different with respect to the separation of the data by duties, missions, manoeuvres etc. The vertical acceleration at the C.G. is the only main load parameter available and is analysed in different ways.

These data are usually evaluated as cumulative frequency distributions of incremental load factors. For some aircraft operated in the U.S. the spectra of normal load factors are available, covering the following aircraft F102, F106, F4, F14, F15 and F16. The envelope of all these spectra is shown in Fig. 3 normalized for 1000 flight hours. The scatter is very large, especially for the positive load factors. The exceedances of 6 g varying from 2 to 20.000 times per 1000 flight hours, or once per flight hour the values between 3.0 and 8.3 g are exceeded. In Fig. 4 the envelope of the normal load factor spectra for aircraft flown in Germany F104, F4-F, G.91 and Alpha Jet are shown. The scatter band is smaller and limited by 6 g. The exceedance of 6 g varies from 1 to 500 times per 1000 flight hours, or once per flight hour the values between 2.4 and 5.3 g are exceeded.

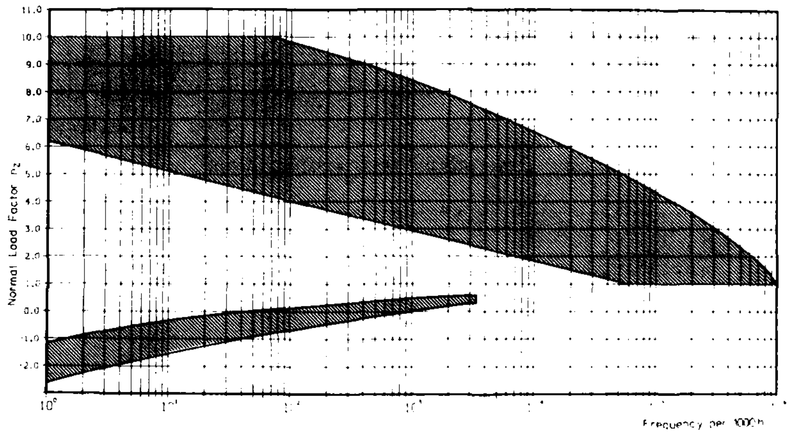

Fig. 3 ENVELOPE OF NORMAL LOAD FACTOR SPECTRA FOR DIFFERENT A/C IN THE US

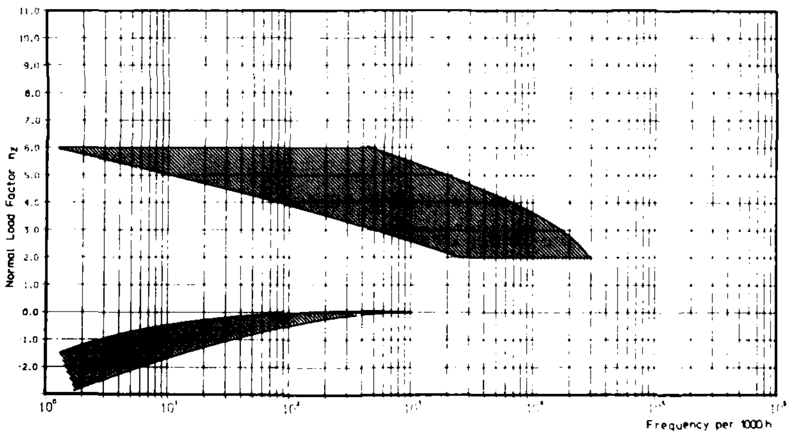

Fig. 4 ENVELOPE OF NORMAL LOAD FACTOR SPECTRA FOR DIFFERENT A/C IN GERMANY

The spectra of normal load factors for different missions for the F16 are shown in Fig. 5 including a comparison with the corresponding spectra of MIL-A-87221. For the air-to-air mission, F16 operation has been considerably more severe and for air-to-ground operation slightly higher than stated in the MIL-Specification. In Fig. 6 the same comparison is shown for the G.91 aircraft. All of the data measured are covered by the MIL-spectra. For comparison, the FALSTAFF-spectrum is plotted. The positive load factors are in good agreement with the air-to-ground mission of the G.91 aircraft and the negative values with the air-to-air mission given in MIL-A-87221. With respect to the large scatter in the load factor spectra it is proposed for the derivation of design parameters to concentrate the evaluation on the discrete event of a single manoeuvre.

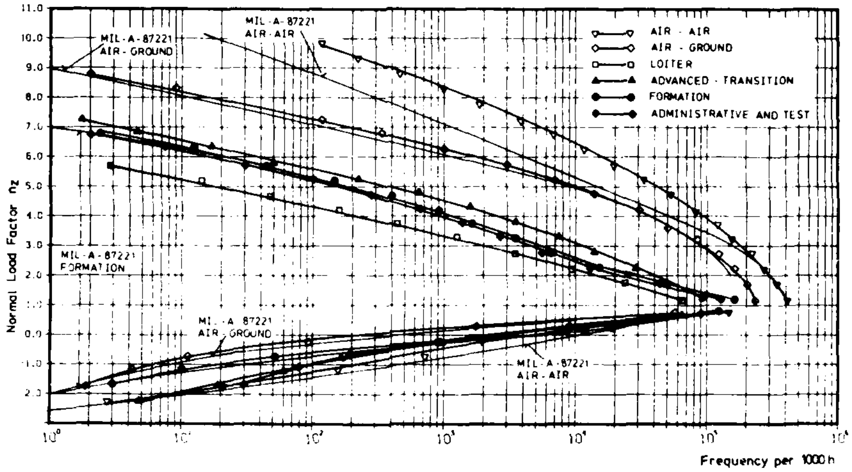

Fig. 5 SPECTRA OF NORMAL LOAD FACTORS FOR DIFFERENT MISSIONS OF F16

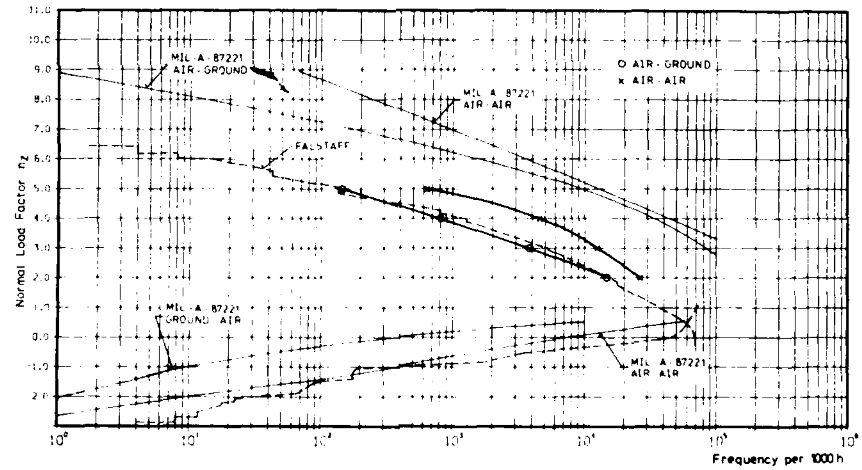

Fig. 6 SPECTRA OF NORMAL LOAD FACTORS FOR DIFFERENT MISSIONS OF G.91

3.2 An approach to evaluate operational design parameters

In Germany an evaluation of combat-NATO-manoeuvres is beeing made with the aim of deriving operational loads by applying measured parameters in operational flights. [12] These parameters include the time history of the aircraft response and the control deflections for each manoeuvre type. The flights have been performed and completed at the test centre of the German Air Force on two aircraft (F4-F, Alpha Jet) and on a third aircraft (Tornado) the tests are still under way. Within the scope of this evaluation, an attempt is made to find a way for a load analysis from operational manoeuvres in addition to the applicable design regulations. Additionally a few manoeuvres of the European Fighter (J 90) have been performed by simulation and evaluated.

The present state of the evaluation has led to the following results:

- for the manoeuvres evaluated a normalization of the response parameters in time and amplitude for each type of manoeuvre is feasible.

- the correlation (phasing) of the load relevant parameters of motion has been verified applying the manoeuvre model to the manoeuvre types evaluated.

- the extreme operational loads are determinable using the boundary conditions as determined by extreme value distributions derived from measurements in service.

In table 3 the operational manoeuvres evaluated from flights for F4-F, Alpha Jet, Tornado and from simulation for J90 are presented. For these manoeuvres the frequency distribution of the maximum values for the main load parameters have been ascertained and plotted.

- normal load factor nz in Fig. 7
- lateral load factor ny in Fig. 8
- roll rate p in Fig. 9
- angle of bank Φ in Fig. 10

TYPE OF MANOEUVRE	MANOEUVRES EVALUATED			
	A.-JET	F-4F	Tornado	J-90*
Break	5	1	3	-
Barrel roll over top	4	3	2	2
Barrel roll underneath	4	3	2	2
High -g- roll	4	4	2	-
High -g- turn	4	7	2	2
Scissor	4	2	2	-
Slice	4	-	2	-
Full aileron reversal	-	10	-	2
Rolling entry and pull out	4	7	-	2

* Simulation

Table 3 OPERATIONAL MANOEUVRES EVALUATED FOR DIFFERENT AIRCRAFT

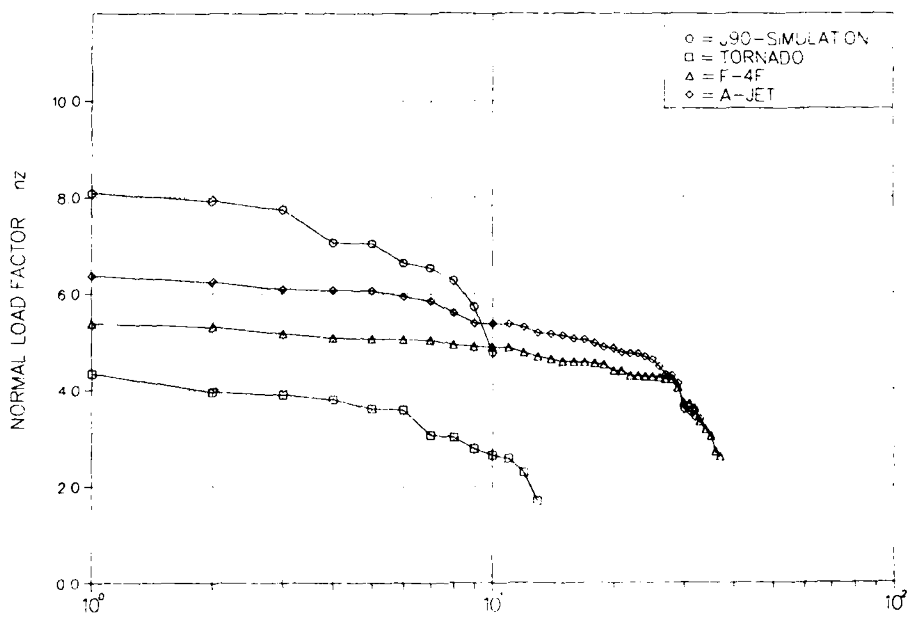

Fig. 7 FREQUENCY OF EXTREME VALUES

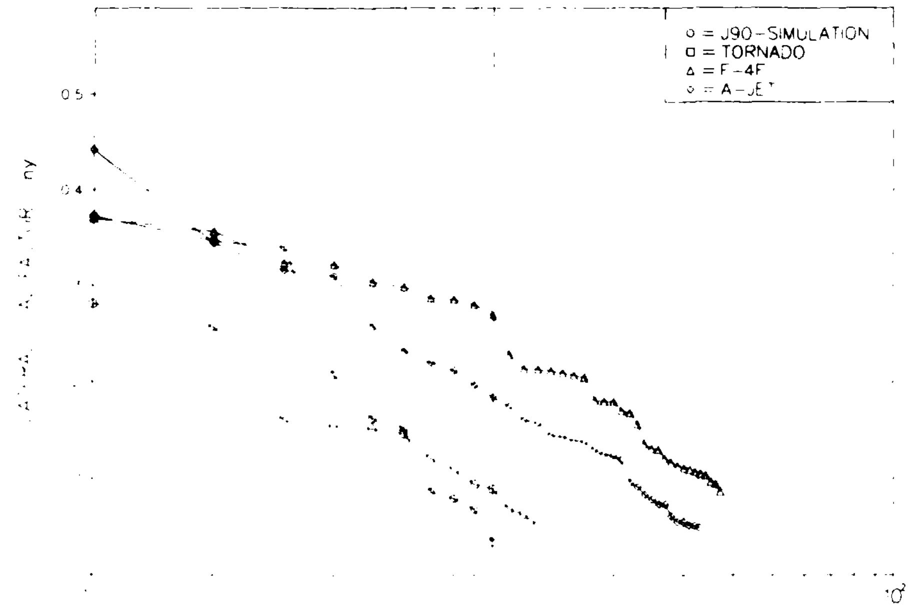

Fig. 8 FREQUENCY OF EXTREME VALUES

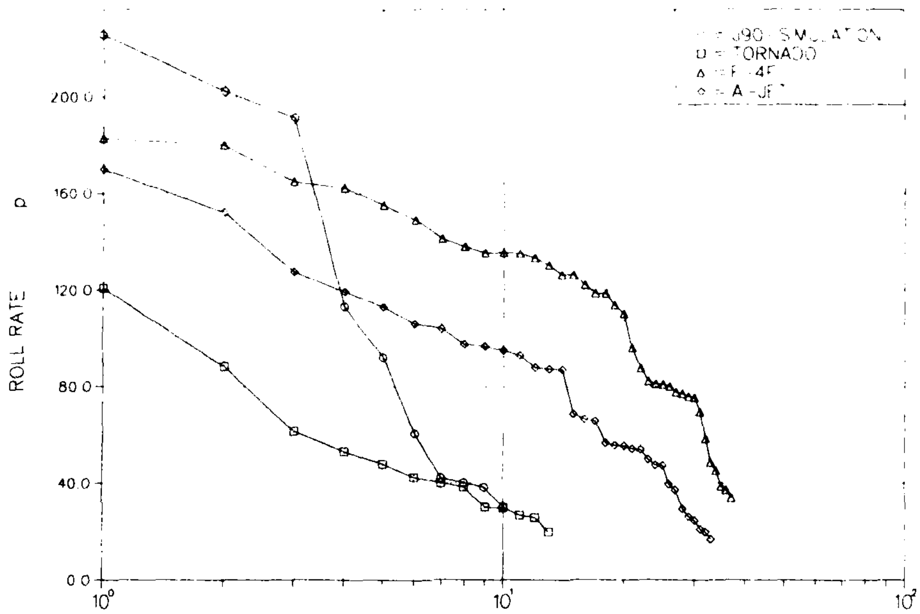

Fig. 9 FREQUENCY OF EXTREME VALUES

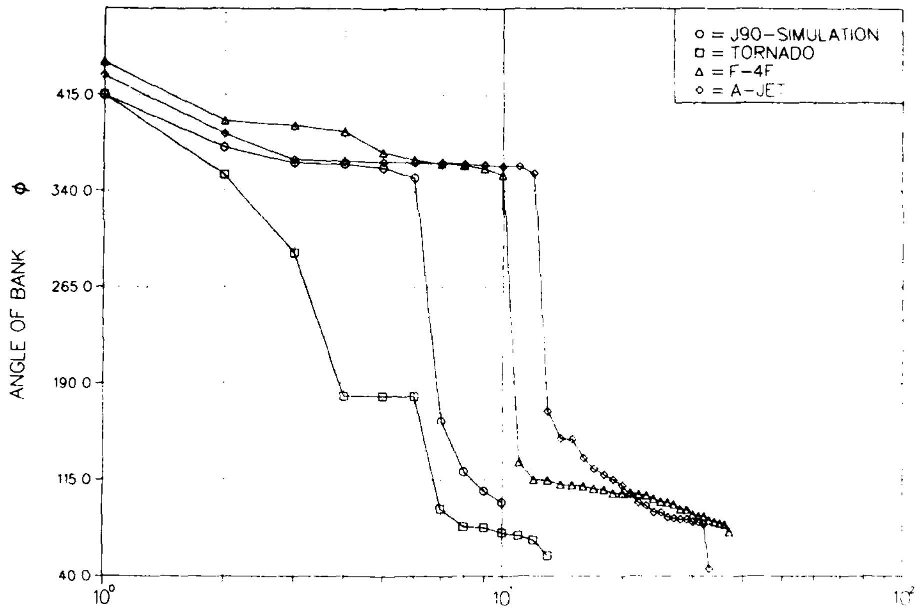

Fig. 10 FREQUENCY OF EXTREME VALUES

The several manoeuvre types are indicated in the plot of the maximum bank angles (Fig. 11). It is evident that the barrel rolls and the high-g-roll manoeuvres are performed as a full roll of about 360° and all others are about 90° rolls.

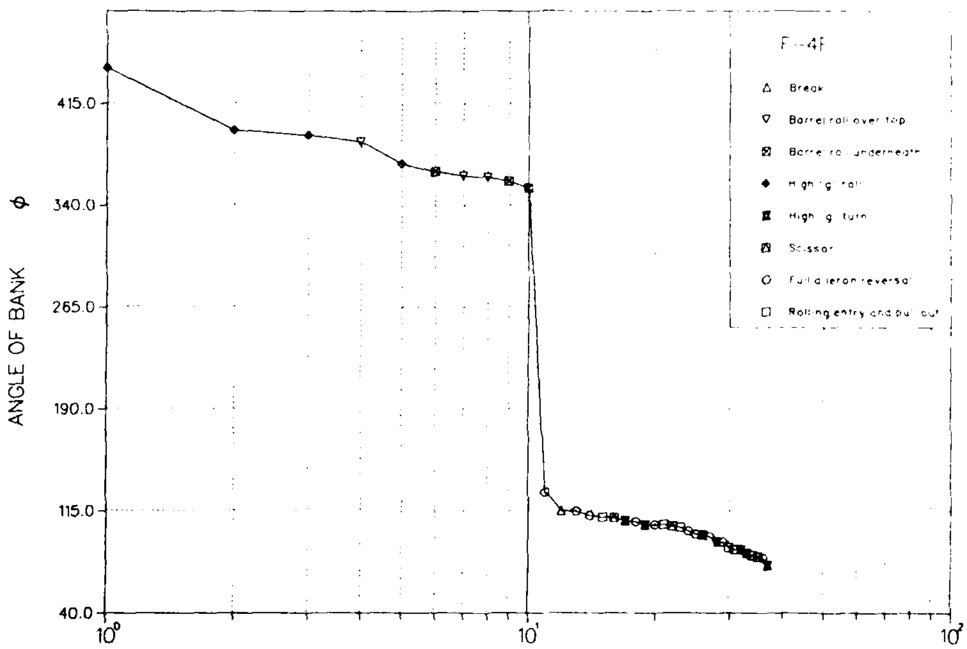

Fig. 11 FREQUENCY OF EXTREME VALUES

Taking into account the maximum values measured in operational manoeuvres a procedure based on extreme value distribution is presented that allows to derive design values. The procedure requires that the sample used be representative. This is not the case for the example given, because adequate measurement results were not available. For this reason the results can only be evaluated as a tendency rather than absolutely.

For the F-4F aircraft the extreme value distrubutions of the main load parameters have been plottet. In Fig. 12 the example is shown for the normal load factor (nz).

The following assumptions are made

1. - design aim 4000 flight hours
   - 4 manoeuvres per flight hour, that means 16.000 manoeuvres in one aircraft life

2. - the extreme values could be approximated by a log normal distribution

The probability that the maximum value of the vertical load factor (once per 16.000 manoeuvres) occur can be calculated for a probability of 50% (occurance at every second aircraft) from the return period [11] as follows:

$$W_{\ddot{u}} = \frac{50\%}{16.000} = 3.13 \times 10^{-3}\ \%$$

This probability leads to a design normal load factor of nz = 6.9.

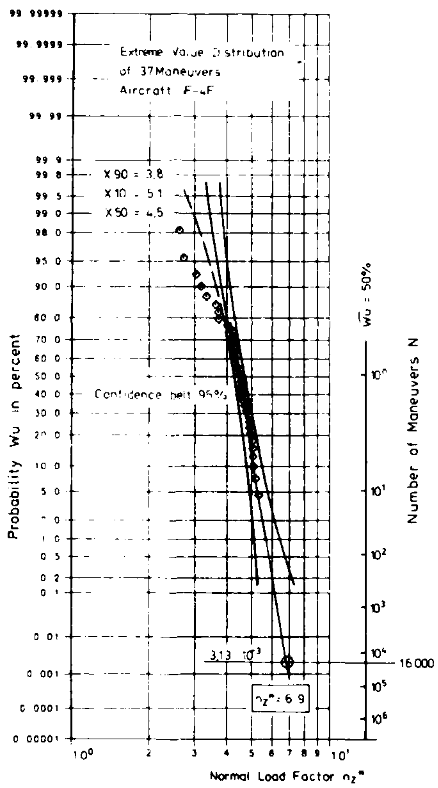

Fig. 12 EXTREME VALUE DISTRIBUTION FOR THE DERIVATION OF F-4F NORMAL DESIGN LOAD FACTOR

Following the assumptions for the derivation of the design normal load factor (nz) of Fig. 12 the same procedure for the other main load parameters is applied. For the lateral load factor (ny) the derived design value is ny = 0.5 as shown in Fig. 13. In Fig. 14 the design roll rate derivation leads to a value of p = 270°/s. The plot of the bank angles (Fig. 15) confirms the two types of rolling manoeuvres, 80 to 110 degree rolls and 350 to 400 degree rolls.

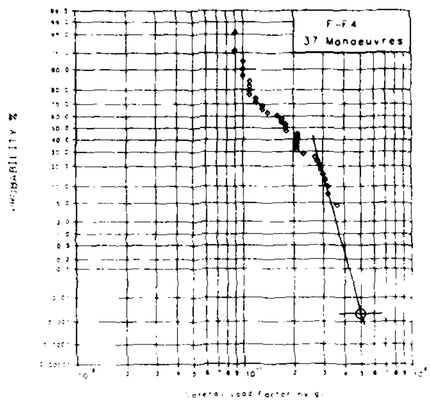

Fig. 13 EXTREME VALUE DISTRIBUTION

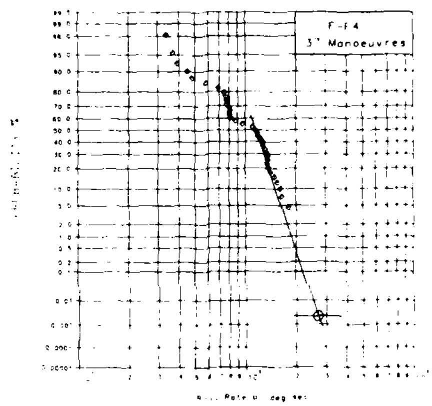

Fig. 14 EXTREME VALUE DISTRIBUTION

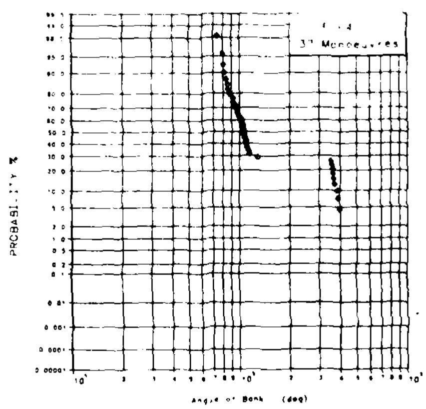

Fig. 15 EXTREME VALUE DISTRIBUTION

4. EVALUATION OF EXTREME OPERATIONAL LOADS AND COMPARISON WITH THE DESIGN LOADS

Bearing in mind the verification of the manoeuvre model for operational manoeuvres, the extreme operational load parameters and thus the extreme operational loads are determinable. [12] The procedure of the manoeuvre model is shown in Fig. 16.

The normalized and verified parameters of the manoeuvre model are to be considered as mean parameters. For deriving the extreme manoeu-res the main load parameters are scaled up to the extreme values to be obtained. The extreme load parameters can be determined with reference to the design parameters required in the regulations or by extrem value distributions e.g.

- the load factors vertical (nz) and lateral (ny)
- the roll angles (Φ)
- and the maximum control surface deflection attainable at the manoeuvre speed to be considered.

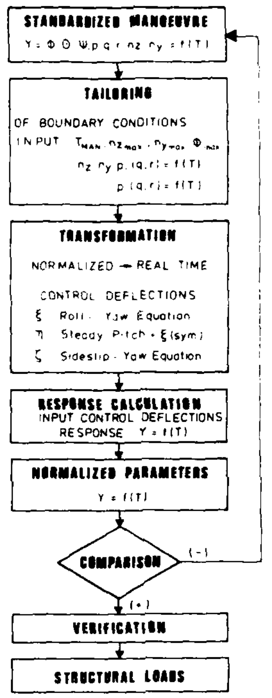

Fig. 16 MANOEUVRE MODEL

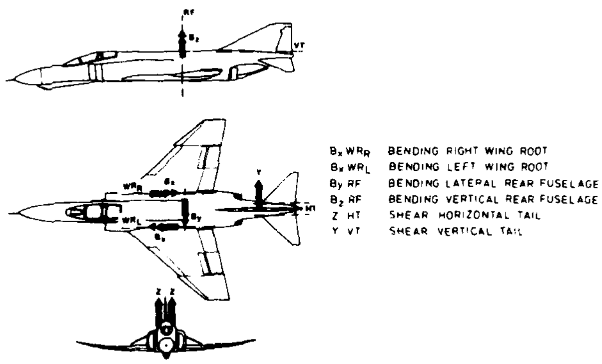

Fig. 17 STATIONS FOR LOAD ANALYSIS

Table 4 shows the mean values and the assumed extreme values for the manoeuvre time (Tman), the load factors (nz, ny) and the roll angles (Φ). Taking into account these extreme manoeuvre load parameters as boundary conditions in the manoeuvre model the extreme operational response parameters and the control surface deflections belonging to the manoeuvre considered are determined. The time history of control surface deflections is plotted for

- elevator in Fig. 18
- aileron in Fig. 19
- rudder in Fig. 20

TYPE OF MANOEUVRE	T_{MAN} (s)		n_z		n_y		Φ (°)	
	mean	extr.	mean	extr.	mean	extr.	mean	extr.
FULL AILERON REVERSAL	11	10.0	5.0	8.0	0.40	0.5	100	100
HIGH-G-BARREL ROLL O. T.	20	5.6	4.0	8.0	0.12	0.5	360	360
HIGH-G-BARREL ROLL UN.	20	6.8	3.5	7.8	0.12	0.5	360	360
HIGH-G-TURN	8	5.3	5.0	8.0	0.25	0.5	90	90
ROLLING ENTRIES + PULL OUT	17	7.5	5.0	7.9	0.15	0.5	100	100

Table 4 MODEL PARAMETERS FOR LOAD ANALYSIS

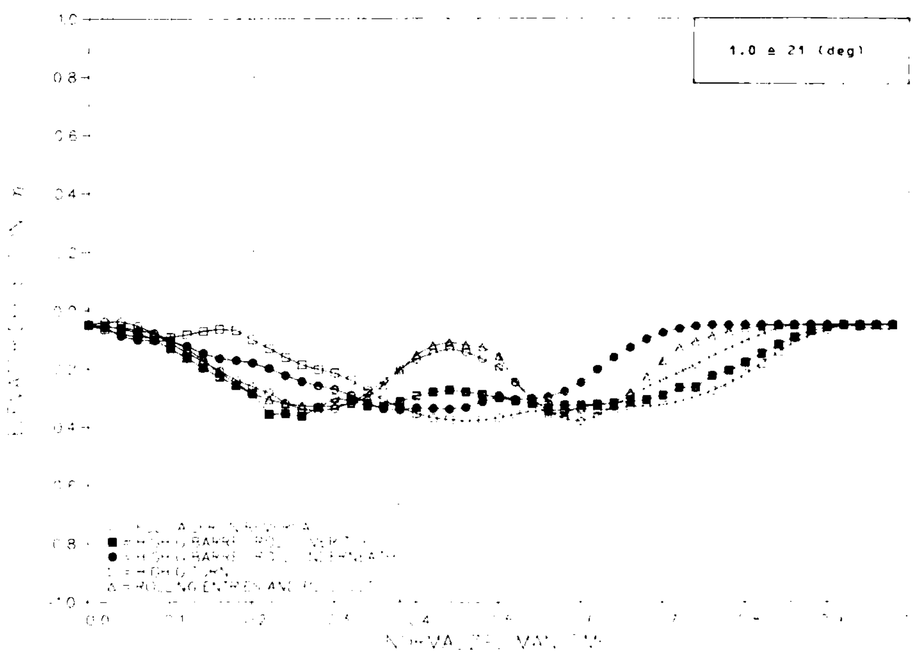

Fig. 18 EXTREME OPERATIONAL MANOEUVRES

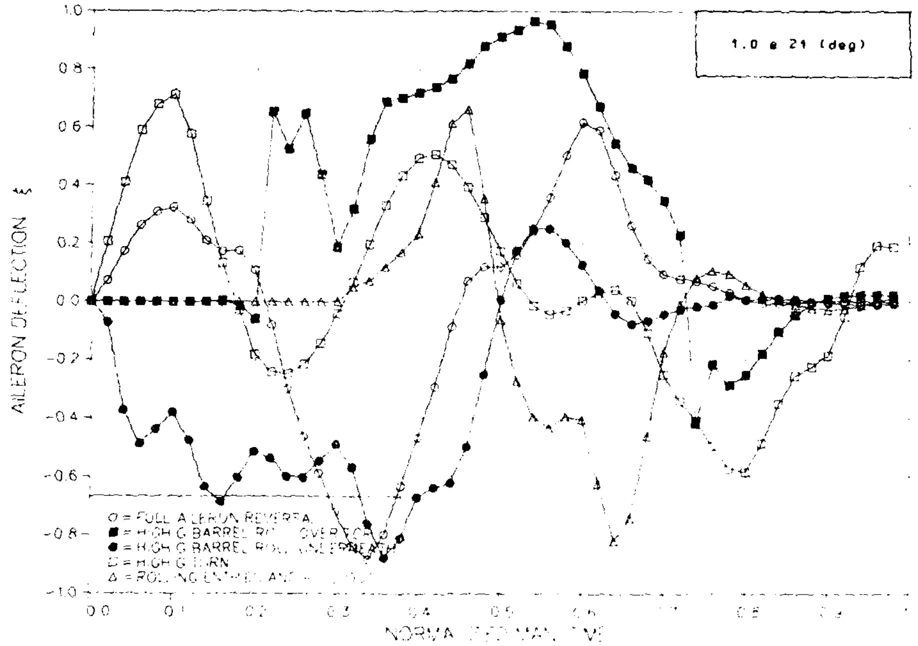

Fig. 19 EXTREME OPERATIONAL MANOEUVRES

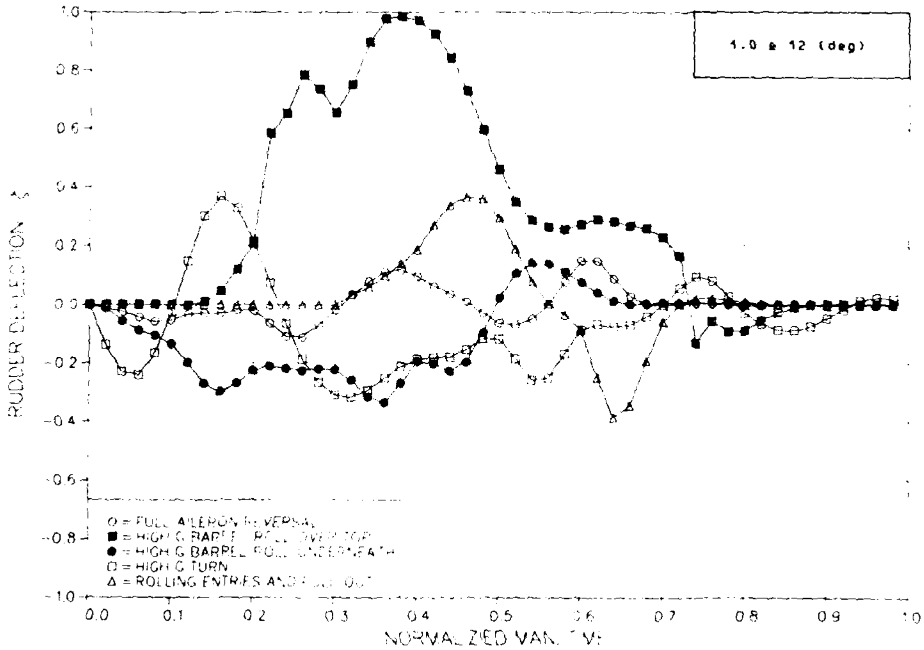

Fig. 20 EXTREME OPERATIONAL MANOEUVRES

The main load parameters are shown for

- normal load factor in Fig. 21
- lateral load factor in Fig. 22
- roll rate in Fig. 23
- angle of bank in Fig. 24

Using these data the loads on the structural components have been calculated. (Fig. 17) For the horizontal tail and the vertical tail the time history of the shear forces are presented in Fig. 25 and 26. The control surface deflections of Fig. 18 to 20 show an interesting course for the five operational manoeuvres. In three manoeuvres alternating control surface deflections have been found, especially for roll- and yaw control. In detail the numbers of alternating deflections are as follows:

	aileron	rudder
- high-g-turn	4	3
- full aileron reversal	3	4
- rolling entries	2	2

Concerning the vertical load factor (Fig.21), the course alternating the most is caused by the rolling entries and the full aileron reversals. The same was found for the structural loads on the horizontal tail. The vertical tail loads alternating the most are obtained at full aileron reversal and high-g-turn manoeuvres. For each of these manoeuvres at least three load peaks can be counted.

In table 5 the maximum values of the main parameters, the structural loads for MIL-Manoeuvres, and the extreme operational manoeuvres are presented. The main load parameters are absolute values but the loads have been normalized using the design loads, resulting from the MIL-Specification. This summary shows that the extreme operational loads for the aircraft considered are lower than the design loads specified in MIL-A-8861. The load level is about 80% of the symmetrical and 90% of the unsymmetrical loads.

This should not lead to the assumption that operational manoeuvres will result in a lower design load level because the combination of symmetrical and unsymmetrical loads is more severe.

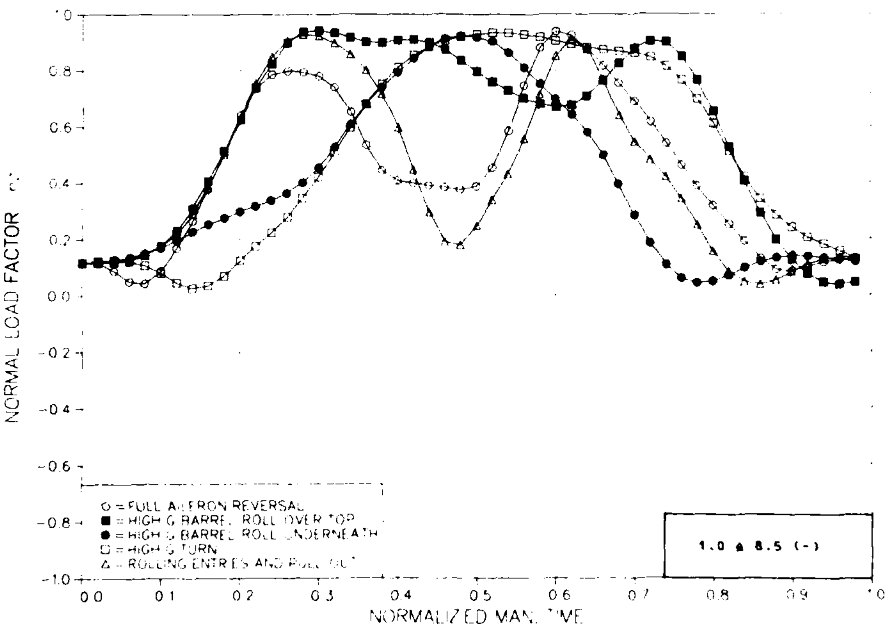

Fig. 21 EXTREME OPERATIONAL MANOEUVRES

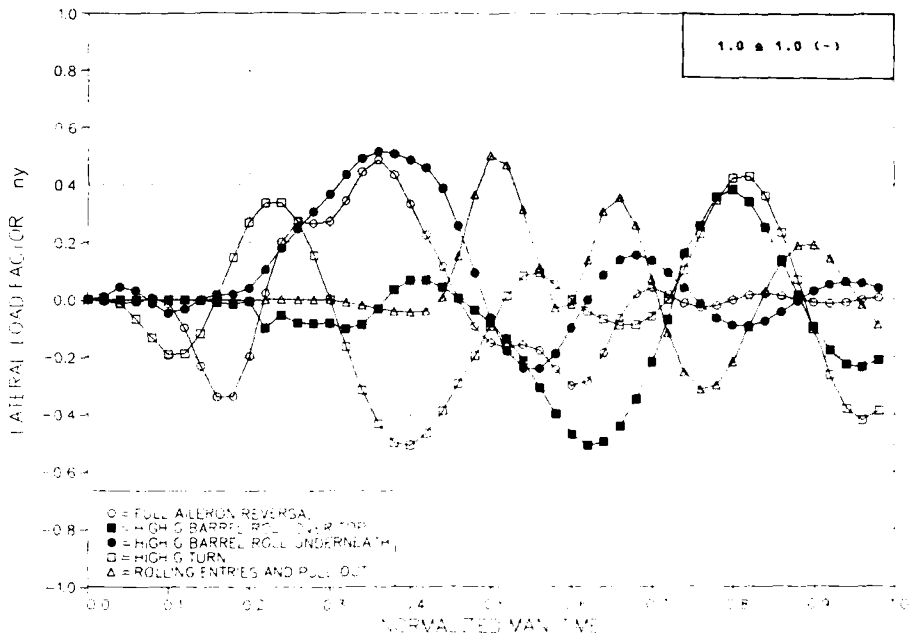

Fig. 22 EXTREME OPERATIONAL MANOEUVRES

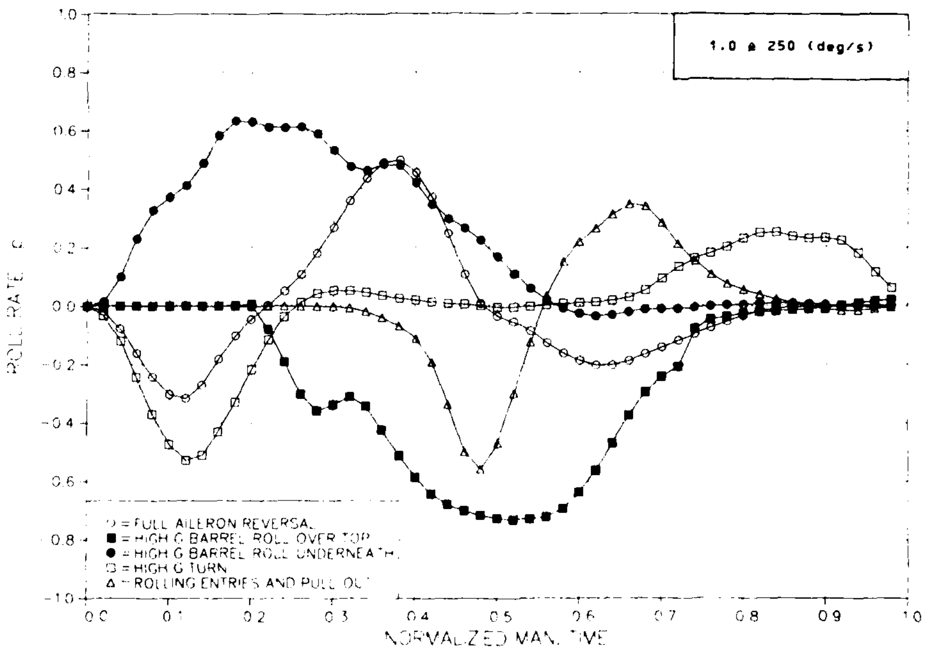

Fig. 23 EXTREME OPERATIONAL MANOEUVRES

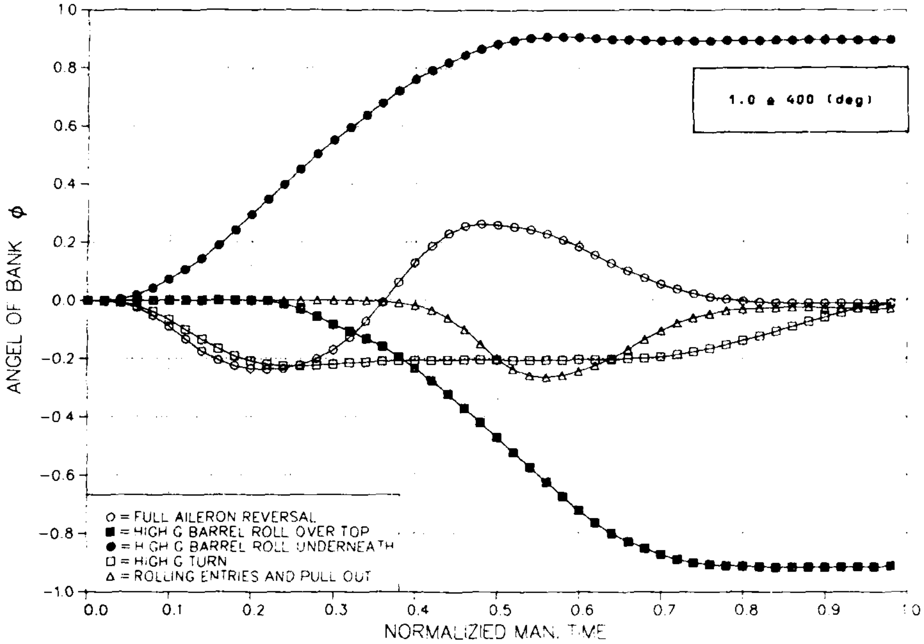

Fig. 24 EXTREME OPERATIONAL MANOEUVRES

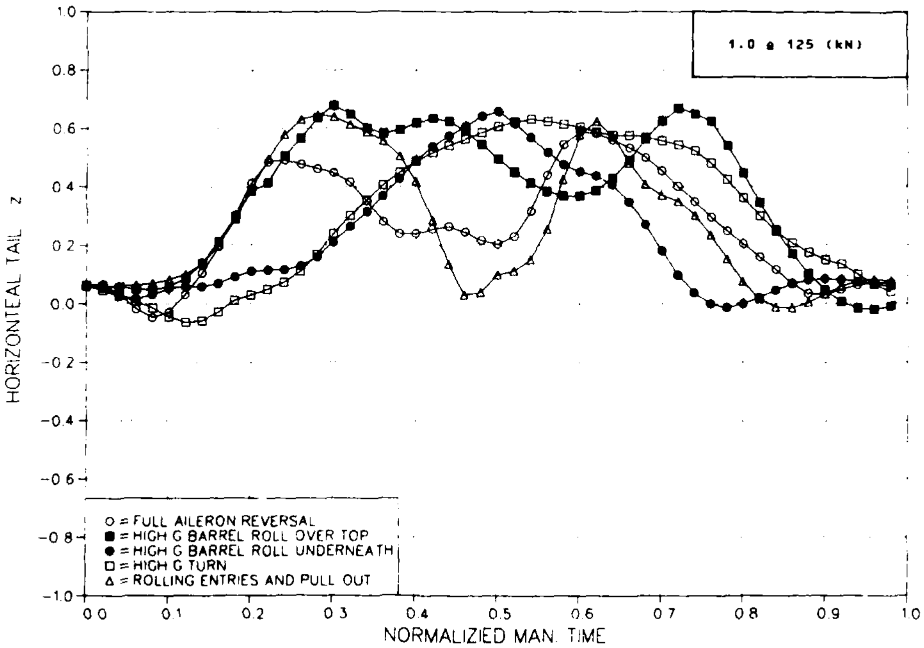

Fig. 25 EXTREME OPERATIONAL MANOEUVRES

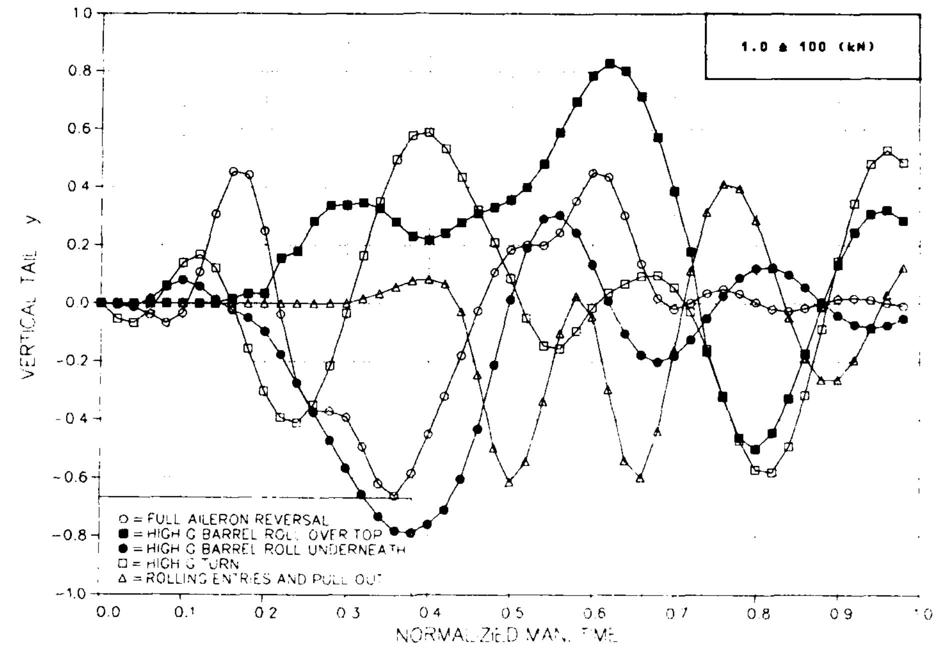

Fig. 26 EXTREME OPERATIONAL MANOEUVRES

	MANOEUVRE	nz max.	nz min.	ny	p [°/s]	β [°]	BENDING Wing-root B_xWR	BENDING Rear Fuselage B_yRF	BENDING Rear Fuselage B_zRF	SHEAR Tailplane ZHT	SHEAR Tailplane YUT
MIL-A-8861	ROLL 180°	0.80	-3.2	0.53	203	3.6	0.22	0.37	0.62	-0.38	0.59
	ROLLING PULL OUT	6.50	+3.9	0.55	124	4.7	0.97	0.31	0.88	0.54	0.77
	ROLL 360°	1.30	-1.1	0.28	210	1.8	0.34	0.39	0.35	-0.18	0.27
	RUDDER KICK	1.10	+0.5	0.83	20	7.5	0.18	0.09	1.00	0.08	1.00
	ABRUPT PITCHING /\	8.0	+0.8	0	0	0	1.00	1.00	-	1.00	-
	ABRUPT PITCHING /‾\	8.0	+0.9	0	0	0	1.00	0.57	-	1.00	-
OPERATIONAL	FULL AILERON REVERSAL	8.0	+0.3	0.50	125	4.1	0.80	0.24	0.70	0.64	0.65
	HIGH-G-BARREL ROLL OT	8.0	+0.3	0.50	183	4.0	0.83	0.25	0.87	0.78	0.72
	HIGH-G-BARREL ROLL UN	7.8	+0.4	0.50	159	3.9	0.80	0.30	0.89	0.72	0.75
	HIGH-G-TURN	8.0	+0.2	0.50	132	4.1	0.80	0.30	0.58	0.70	0.56
	ROLLING ENTRIES + PULL OUT	7.9	+0.3	0.50	140	4.5	0.79	0.32	0.66	0.70	0.58

Table 5 MAXIMUM VALUES OF MAIN PARAMETERS AND STRUCTURAL LOADS
EXTREME OPERATIONAL MANOEUVRES / MIL-MANOEUVRES

5. CONCLUSION

For fighter aircraft that have been in operation up to the present time the structural design level is defined as follows

- the symmetrical load level by the normal load factor (nz)
- the unsymmetrical load level for rolling conditions by roll rate limits and for for yawing conditions by steady sideslip
- the response calculations for all manoeuvre conditions are specified by a few hypothetical control surface deflection time histories.

These design conditions contain distinct load criteria for the loads on the main structural components. This design procedure, when applied to aircraft equipped with an electrical flight control system, does not cover all extreme load conditions that are possible. [4]

Numerous operational parameters usually are recorded and compiled. The vertical load factor is the only main load parameter available as cumulative frequency distribution. By forming the envelope of the spectra available for several fighters in the U.S. and in Germany, a large scatter depending on aircraft and usage is shown.

For this reason, the operational load parameters have been evaluated with regard to extreme values and time histories containing the correlation of the several parameters. The evaluation is focused on combat missions, which are a sequence of several individual manoeuvres. The frequency distribution of the extreme main load parameters has been determined from the manoeuvres evaluated. It is proposed to establish the extreme value distribution for each of the main load parameters in particular for the normal load factor (nz), the lateral load factor (ny), the roll rate (p), and the bank angle (Φ) in order to derive the design values.

In this paper only data for some manoeuvres were available, however, the approach of deriving design parameters from operational measurements could be demonstrated. By using these operational design parameters in a manoeuvre model verified by flight tests and/or simulations, the extreme operational parameters, the control surface deflections and thus the extreme operational loads can be determined.

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Sonderdruck aus "Konstruktion" 20. Jahrg. (1968)
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Operational Loads Data, Page 13

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NLR, Niederlande; IABG, Deutschland
Description of a Fighter Aircraft Loading Evaluation
FALSTAFF, 1976

AD-P005 767

MANOEUVRES BY DEFAULT, BY DEMAND AND BY DESIGN

by

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Summary

The use of strain gauge bridges for the derivation of aircraft manoeuvre loads is reviewed in the context of a recent load measuring flight trial on a British Aerospace TMk4a Harrier.

Some of the pitfalls encountered in the method used for calibration of the gauges and their location are discussed.

A comparison is made between the aircraft behaviour/load patterns expected at the design stage and the flight results obtained when these manoeuvres are flown on the aircraft.

The applicability of these statutory aircraft design requirement type manoeuvres is explored by comparison with manoeuvres flown during Harrier development/operational flying where Flap, Thrust Vectoring and Reaction Control Power have been used to enhance the manoeuvre envelope. Here emphasis shifts from determining or confirming design load levels to ensuring that the known structure strength boundaries are observed.

Conclusions are drawn as to the adequacy of present statutory design requirements. The need for accurate reliable calibrated load measurement in both the aircraft's development and operational stages is demonstrated.

Introduction

The advent of the more agile modern military flying machine has given rise to the use of in-flight strain gauging in order to deduce manoeuvre loads and so hopefully confirm the adequacy of the design loads used in the initial stages of the aircraft's design.

The flight trials data contained in this paper arose from the requirement to demonstrate that the two seat variant of the basic Harrier with its extended rear fuselage, retained sufficient strength in this area and good aircraft handling characteristics. The manoeuvres presented from this flight trial were performed on an instrumented Harrier TMk4a, as depicted in Fig.1. This particular variant of the VSTOL Harrier breed is a two seat trainer and as such perhaps gives rise to an increased likelihood of the aircraft being used/abused for developing new and novel manoeuvres as pilots in training develop their skills. The design requirement type manoeuvres presented were generally flown by a highly experienced company test pilot whilst the operational manoeuvres were flown by a senior Royal Air Force flying instructor who was one of the most experienced Harrier pilots available within the Royal Air Force.

Instrumentation

Given that the requirement of this particular trial was to demonstrate that the revised rear fuselage structure had strength in hand, the main area of interest is shown in Fig.2. Load inputs in this area arise predominantly from air loads on fin and tailplane and inertia loads from the rear fuselage as a whole.

Inertia loads were recovered via accelerometers and rate gyros forming part of the overall aircraft instrumentation. The fin and tailplane were separately strain gauged in order to recover the loads acting upon these components.

The outputs from groups of strain gauges were used to recover loads using equations defined by calibration in a rig. Fig.2b shows the pad positions for the matrix of applied loads employed in the rig. Outputs from the strain gauges were recorded for various combinations of applied loads and a least squares multiple regression analysis, in the spirit of the Skopinski method (Ref.1), was applied to those outputs to recover the loads. From that analysis it was possible both to determine the best gauge pattern for accurate recovery of loads and also best alternate patterns in the event of a gauge failure. Lest one offends , "gauge failure" should be taken to mean a fault, however occasioned, in the load measuring system. Normally such faults occur where the data loss is least tolerable and contrary to popular belief are never as rare as one would like.

It will be left to another forum to consider the applicability of a static calibration to the recovery of dynamic loads.

Whilst not wishing to go into too much detail on the instrumentation/data reduction techniques used,one particular aspect of the system is perhaps worthy of note.Digital record rates of 42 samples/sec were used for flight parameters and 680 samples/sec for the strain gauge outputs.Whilst use of such high strain gauge sampling rates might in this case be considered as overkill it is certainly the authors opinions that record rates of less than 40/50 samples/sec should not be used if accurate recovery of dynamic manoeuvre load levels is required and the higher rates are in fact highly desirable.

Two particular problems encountered on fin load measurement are worth recording since they caused much head scratching at the time.The first arose on a previous flight trial,involving a different aircraft type,when it was discovered that the spanwise load centre was much further outboard than expected.This was caused by the omission of a fairing similar to that shown shaded in Fig.2a during rig calibration.It transpired that the problem arose because the fairing carried load directly into the fuselage,flanking the spar root gauges.Around 20% of the fin shear went missing in that case.The bending error was, however,relatively small; hence the outboard location of the load centre.Having learnt that lesson care was taken to avoid a repeat. Imagine our surprise when a datum shift,having some of the characteristics reported earlier, appeared in mid trial on the TMk4a. It transpired that the fairing had been removed and replaced during a period of extensive aircraft servicing. The fixings which were attached to a rib carrying one of the strain gauge bridges were making a direct input to that bridge causing unreliable load recovery.As luck would have it this bridge had only a small contribution to the overall fin loads and the problem could be overcome by taking care when re-fastening the panel to avoid pre-stressing the area where the bridge was situated.

The Manoeuvres

And so to the main purpose of this paper.The pertinent flight cases are described and discussed here on a case-by-case basis and then the conclusions to be drawn are discussed in the final paragraph.

In all the manoeuvres shown here the loads generated were within the known strustural strength of the aircraft.

Figure 3

The manoeuvre presented here is the stalwart of many a design requirement -The Symmetric Pull-Up- only this one isn't quite symmetric. This case at high transonic Mach number shows a pull up to high 'g' which produces a large downward load on the tailplane and rear fuselage for which it could possibly be the design case.Unfortunately this manoeuvre suffered a wing drop,the recovery from which produced a large sideslip and associated fin load.The resulting fin load is a close match to that produced by the design case Rolling Pull Out.

The design requirement for this "Stall Point" includes an allowance for buffet on the horizontal tailplane symmetric load but does not consider the possibility of it being a design case for the fin. The phasing of the pilot control application to recover the situation aids the generation of the asymmetric tailplane loads.In other cases of this sort the adequacy of the values of the tailplane loads considered in the design case is not a forgone conclusion.The reader may also like to consider the tailplane/fin loads which might result from a wing drop occurring during a push to negative 'g'.

In view of the lack of buffet warning of this shock induced separation/wing drop it is not surprising that this phenomenon can occur quite regularly in service,unless legislated against by additional flight limitations,as new pilots get to know the capabilities of their aircraft.

Figure 4

This figure is an example of the operational pilot maximising the performance of his aircraft by flying by "the seat of his pants". Here the pilot is executing a high rate turn.The required bank angle is achieved by rapid aileron input and the 'g' maximised by flying in moderate buffet.Basically as the speed bleeds off the pilot flies down the v-n diagram stall/buffet line,using his aileron to contain the roll and yaw perturbations.Excursions in both fin and anti-symmetric tailplane loading over a period of about 10 seconds result.

The combination of symmetric/asymmetric loads produced are in this case similar to those considered in the design Rolling Pull Out manoeuvre,with the addition of buffet loads due to flow separations. Larger sideslip/fin loads than this have been recovered from this type of manoeuvre.

Figure 5

Continuing the theme of flying in buffet,this figure compares a design case type Rolling Pull Out at 3'g' and clear of buffet with one at the same speed but 1/2 'g' higher with the aircraft in moderate buffet.The results show that the fin load and sideslip produced are more than doubled by rolling in buffet.

Current design requirements for buffet only consider the effect on tailplane asymmetric loads and rolling in buffet is given only perfunctory consideration but,as seen in the previous manoeuvre and as will be further demonstrated,the operational pilot often flies in buffet as this is his "seat of the pants" indication that he is getting the maximum performance from his aircraft.This phenomenon can have a major effect on the level of the loads generated.

Figure 6

In the first column is a "by the book" Rolling Pull Out (No rudder or longitudinal stick input during the roll) flown by the company test pilot.Compare that with a manoeuvre flown by the operational pilot under similar conditions in column 2.

The design requirements state that rudder should only be used to reduce sideslip and forward stick to prevent the design 'g' being exceeded.But it is common practice for the operational pilot to push forward in order to reduce incidence and so increase roll rate and to use rudder to augment the roll.The input of forward stick during the roll can usually be expected to reduce sideslip/fin loads.In this case the effect of the input of stick and rudder can readily be seen in the fin load trace where an increase in the number of fin load cycles occurs which may have fatigue implications.

Figure 7

In the first column is an example of aileron reversal.This phenomenon can occur at low speed high incidence.Sideslip build-up counteracts the rolling moment from the applied aileron causing the roll to go against the applied aileron at time 4/5 seconds.In the second column is an example of how the pilot overcomes this problem,by using rudder to generate sideslip,so producing a slow roll in the required direction.This use of rudder to roll the aircraft is not addressed by the design requirement and as the next case demonstrates it is not just a low speed phenomenon.

Figure 8

This manoeuvre is one that turned up during a demonstration sortie.The usefulness of this manoeuvre is not entirely clear.The flight condition is such that the aileron control is well behaved but the pilot appears to be using the rudder to reduce the rate of roll demanded by his aileron input.Perhaps it is a case of "because it's there".

By way of illustration,certain bomber pilots on long boring missions found that a swift aileron input caused the wings to flap without rolling the aircraft.This phenomenon was apparently pursued in much the same manner that small boys poke snails to ensure that they really do live in shells.Another example of the pilots inventive abilities occurred on an in-service aircraft type.During an operational load measurement programme apparently random rudder kicks causing large fin loads were often seen to occur at high speed.Investigation revealed that the pilots had discovered that the spread of wind screen washer fluid was improved by causing the aircraft to weave.The words "if it's there someone will find it" certainly seem appropriate in aircraft design.

Figure 9

This manoeuvre demonstrates what can happen when the aircraft is flown outside the cleared flight envelope.Here an attempt is made to roll the aircraft at high transonic Mach number at the stall boundary. The application of aileron caused shock induced separations.This coupled with the pilots attempts to complete the roll produced large uncontrolled sideslip excursions and consequent severe loads.

Figure 10

As the TMk4a is a training aircraft several flights were flown to investigate the loads generated during an aircraft departure,which had been known to occur when pilots manoeuvring with nozzles down at extreme incidence "muffed it".At high incidence the fin loses effectivness,being buried in the wing wake,and the aircraft departs/yaws off into a spiral dive giving high rates of roll and yaw. Recovery is easily effected by judicious centralisation of controls and reduction in nozzle angle.However as demonstrated in the figure rapid recovery to low incidence without a corresponding reduction of sideslip produces a sharp rise in fin load and a vicious recovery as the fin suddenly finds itself in clear air.Rather like a large wave hitting the harbour wall.

The final two traces demonstrate phenomena which, whilst we know they occur are probably beyond legislation.

Figure 11

During the trial the Harrier was flown in 1 v 1 air combat against various aircraft types in order to assess the effect on loads of the operational use of Vectored Thrust.During one of these flights the aircraft flew through the wake of a Hunter,producing the quite significant fin load spike shown and an associated roll pertubation.

Figure 12

During trials flying on a Hawk aircraft stick and tailplane rates achievable by the pilot were quantified in order to determine appropriate load dependencies.Following completion of that trial and with the aircraft otherwise employed,the trace as seen here was recovered.It transpired that a glider had crossed the flight path at close range,just above cloud.The stick rate achieved was treble that seen previously and very close to the aircraft system limit.

Conclusions

Current statutory design requirements should be reviewed to ensure that they encompass manoeuvres of the type shown here.

The results show that the pilot,by flying the aircraft close to the handling boundary in order to maximise its performance,produces manoeuvres/loads not considered at the design stage.The current trend in aircraft design of using leading edge devices and A.C.T. systems suppresses buffet warning and actively encourages flight in the pre/post stall regime,where current methods for load/manoeuvre evaluation at the design stage are least reliable.

With the increasing use of active control systems which modify the aircraft control system independent of the pilot there is a clear need for the control and loading engineers to get together at the design concept stage to ensure design loads are soundly based.

A definite need has been demonstrated for in flight load measurement both at the pre-production and post development stage if safe aircraft flight limits/structural integrity are to be defined/ demonstrated.Also the case for providing such a calibrated load measuring aircraft for use by service pilots,in order to cope with both th totally unforeseen and the inventiveness of the pilot has been proven.This most definitely means fully calibrated load measuring with simultaneous recording of a comprehensive set of flight parameters.

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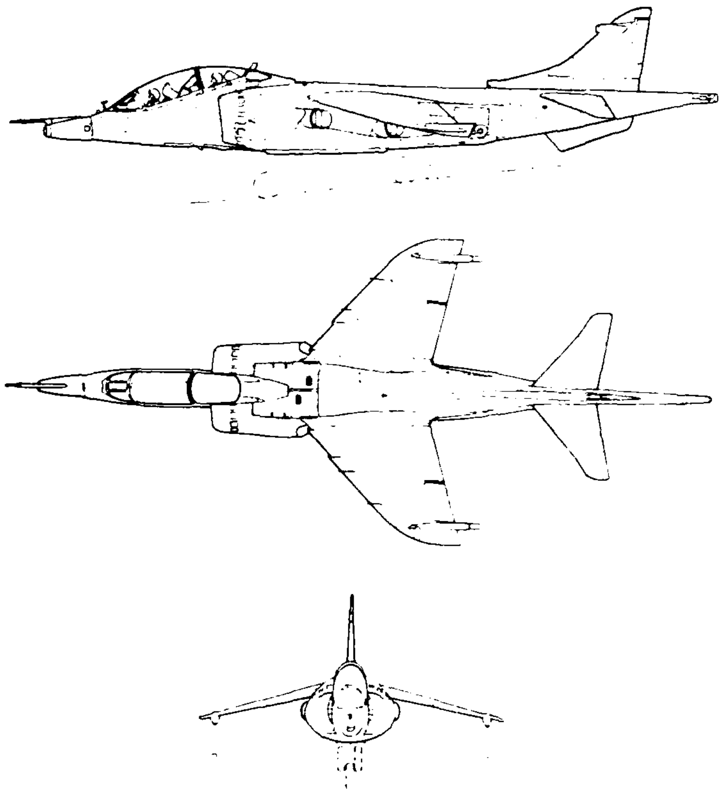
YAD 5117 (B.Ae. Brough) September 1985

Item 2 contains reference to all the reports on the flight trial,covering both handling and loading,which may be of interest to the reader(They carry a RESTRICTED classification).

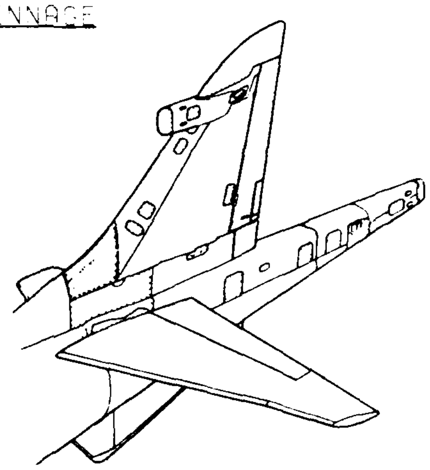
FIGURE 1



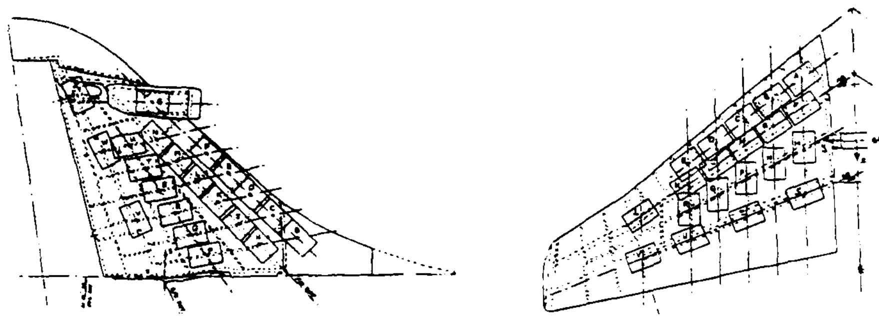
HARRIER TMK.4A - GENERAL ARRANGEMENT

FIGURE 2

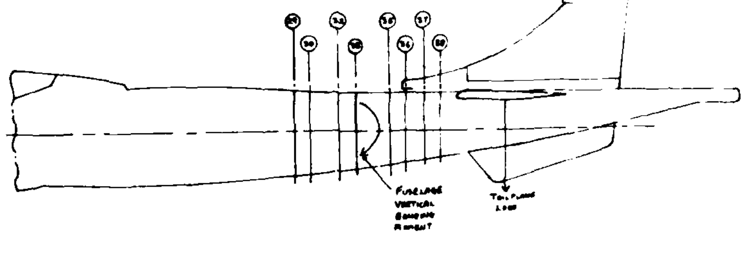
(A) REAR FUSELAGE EMPENNAGE



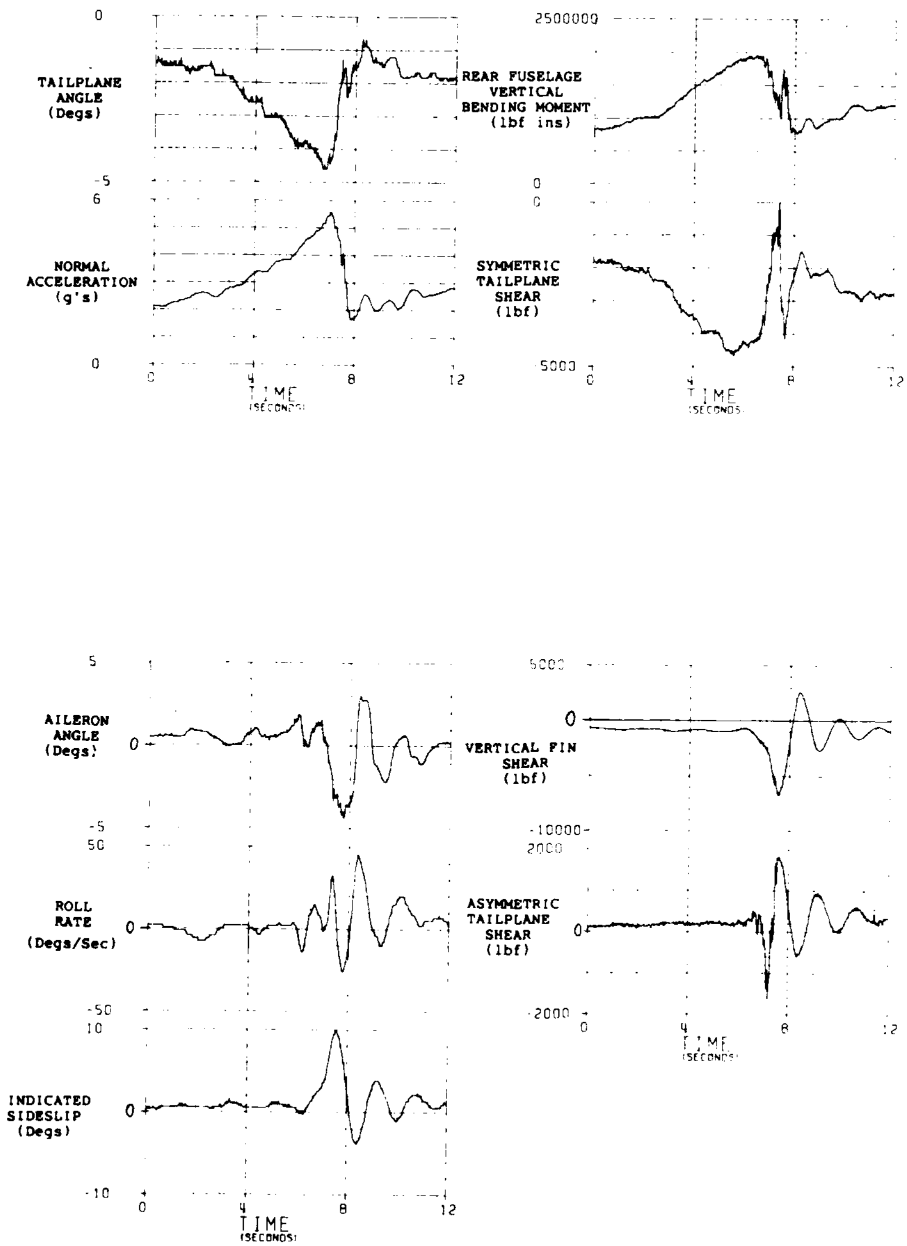
(B) FIN AND TAILPLANE LOAD PAD POSITIONS



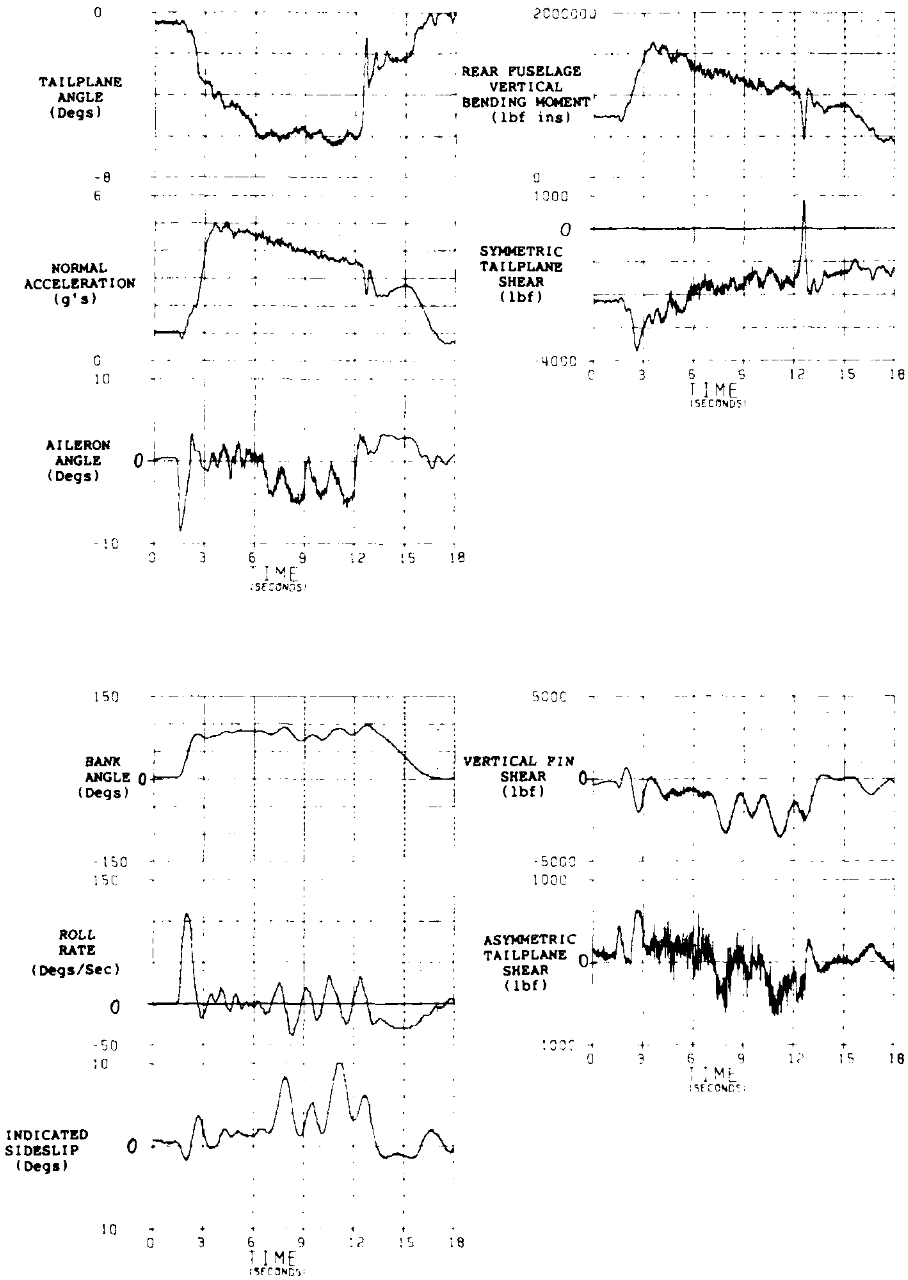
(C) REAR FUSELAGE FRAMES



STEADY SYMMETRIC PULL UP FIGURE 3



OPERATIONAL TYPE BANKED TURN FIGURE 4



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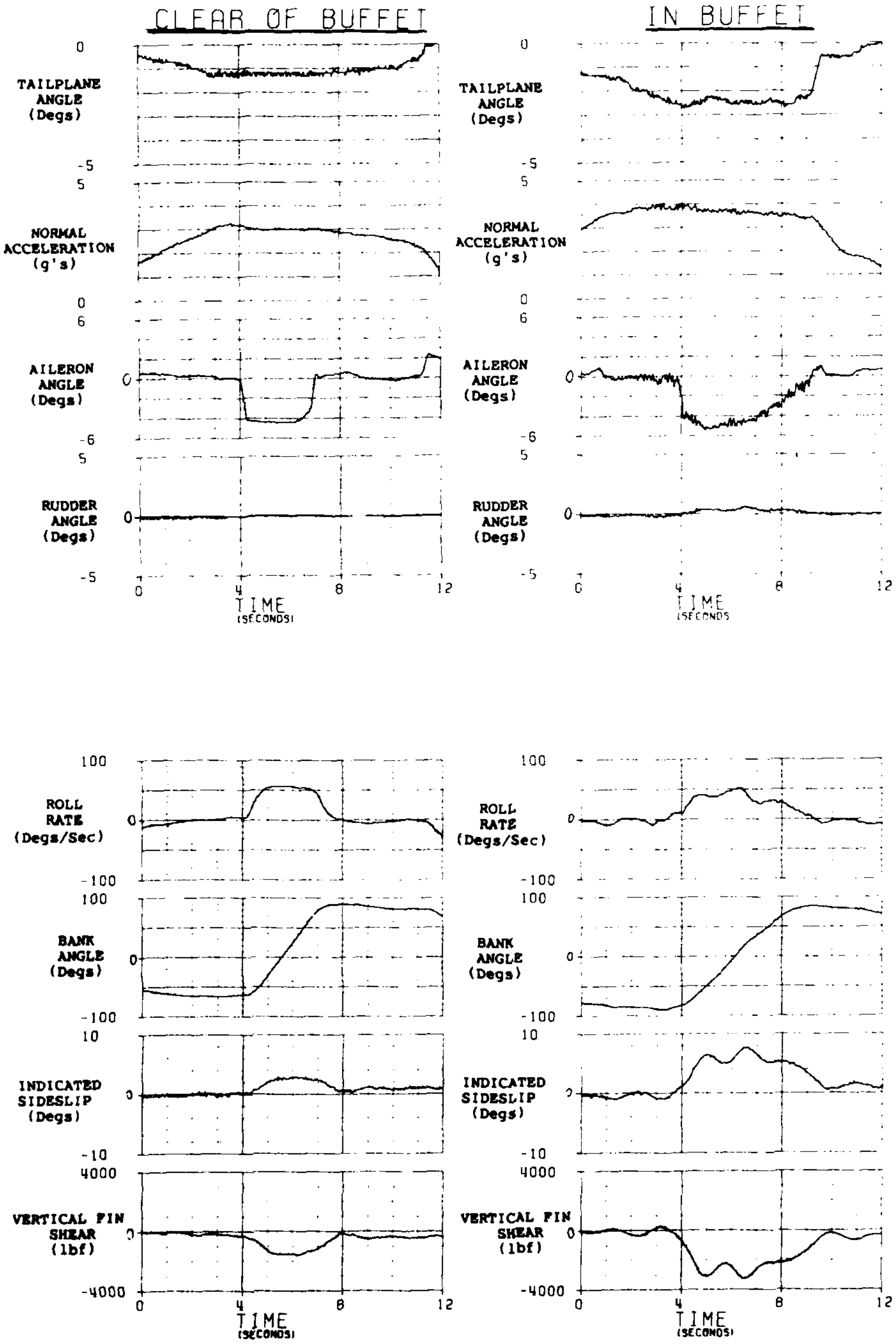
MIL-SPEC TYPE ROLLING PULL OUTS FIGURE 5



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COMPARISON OF ROLLING PULL OUTS FIGURE 6

MIL-SPEC TYPE OPERATIONAL EQUIVALENT

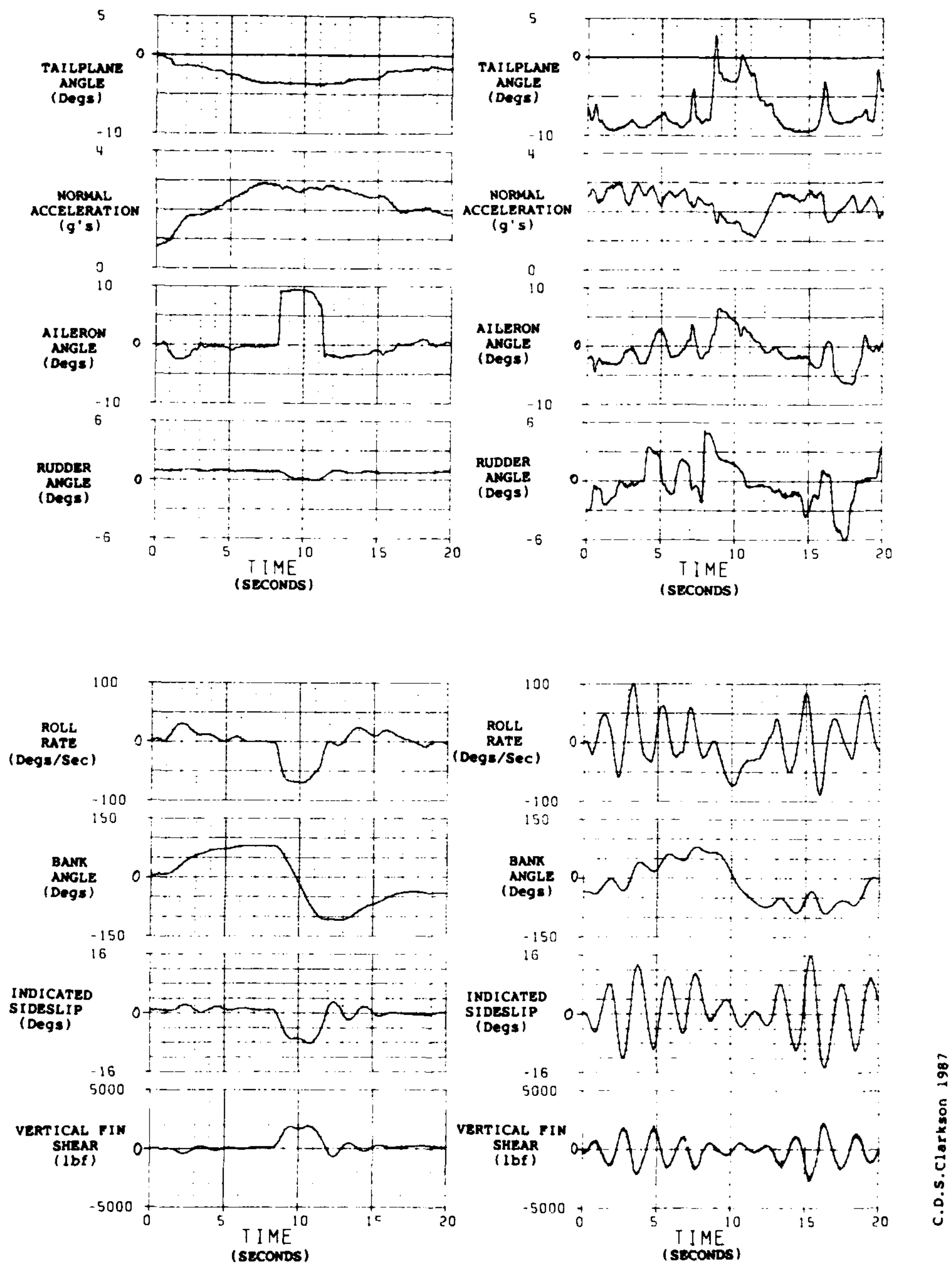


FIGURE 7

LOW SPEED HIGH INCIDENCE ROLLING

ATTEMPT USING AILERON — USING RUDDER

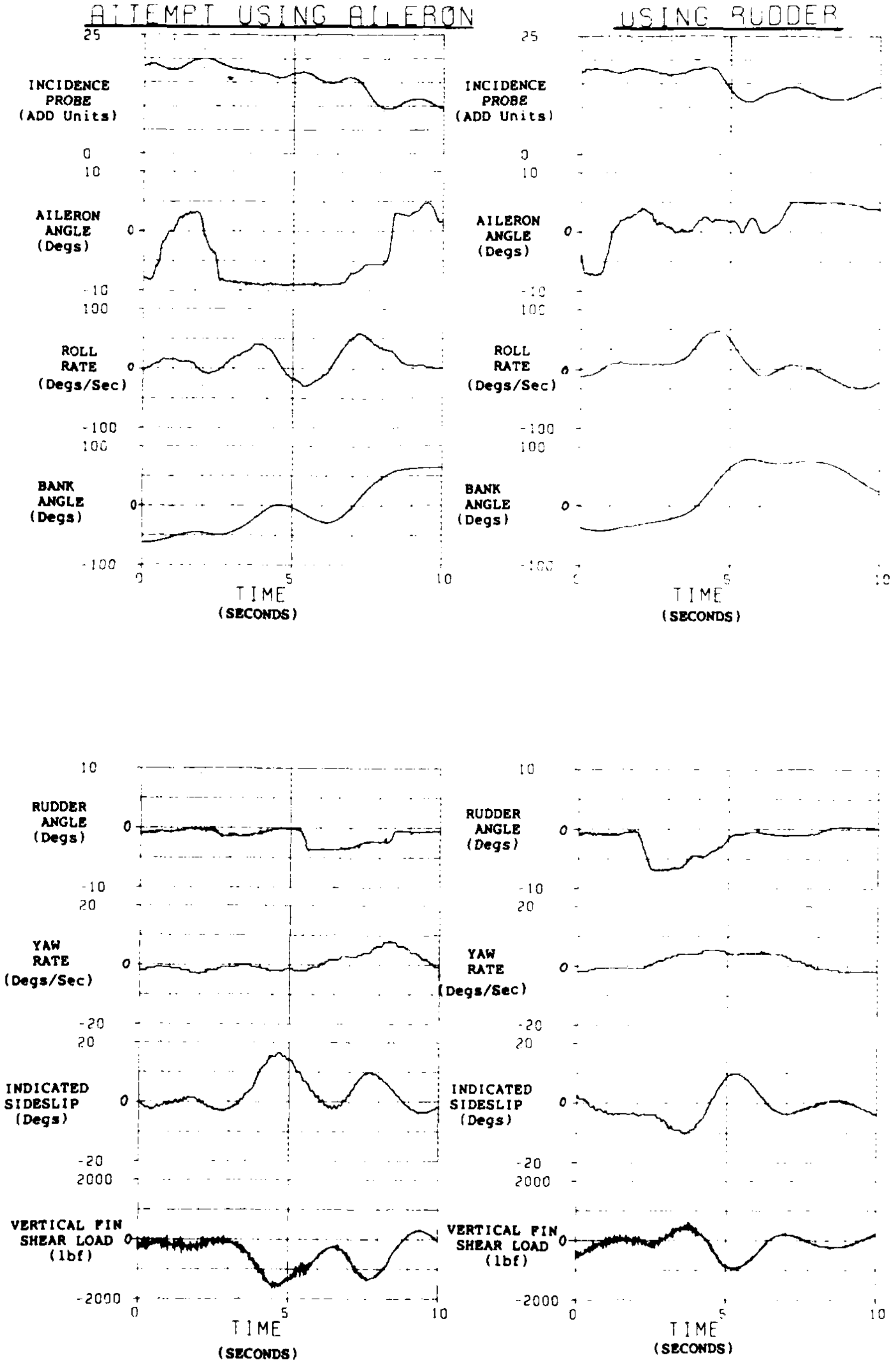


FIGURE 8

AEROBATIC SLOW ROLL USING AILERON AND RUDDER

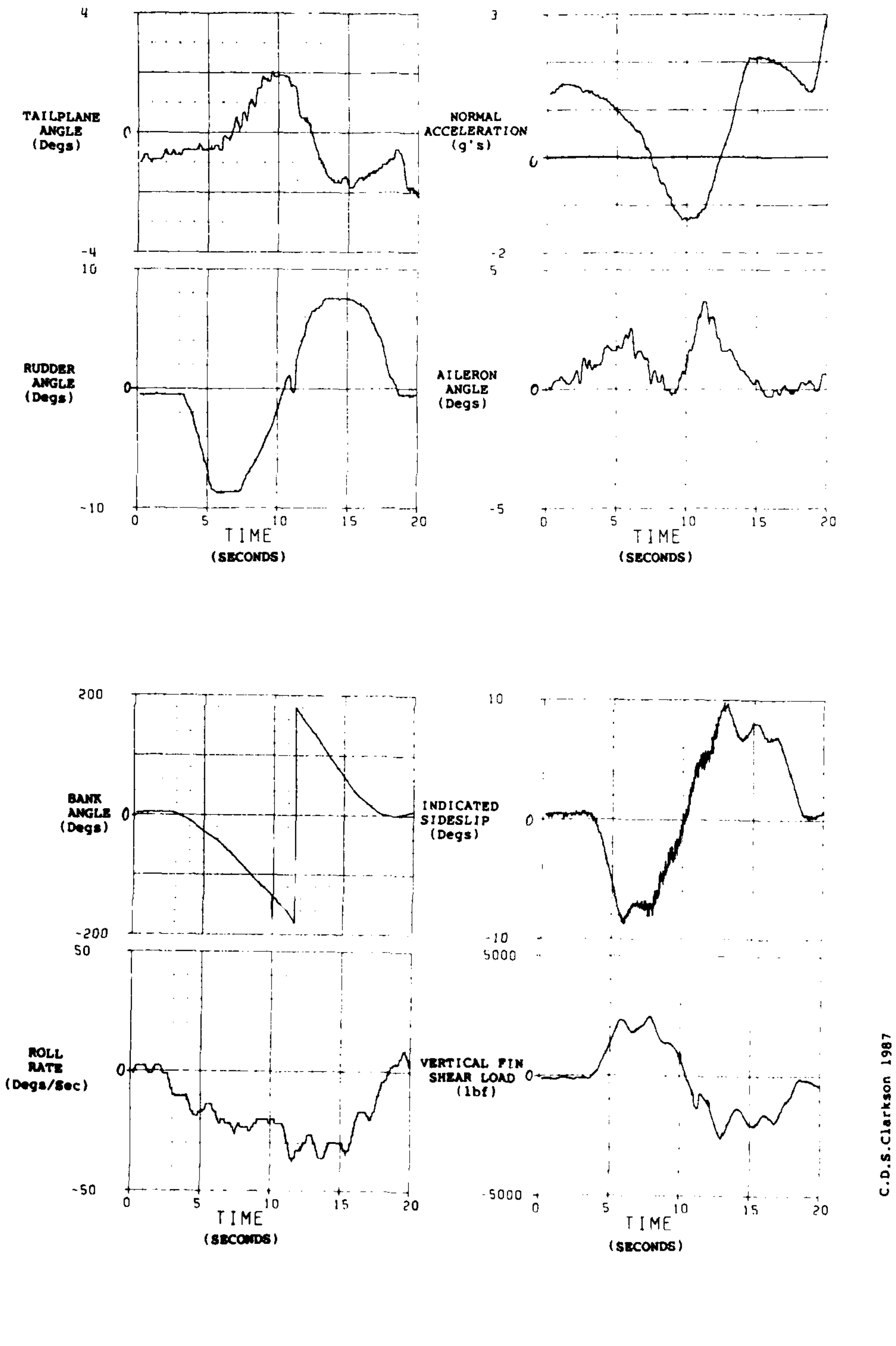
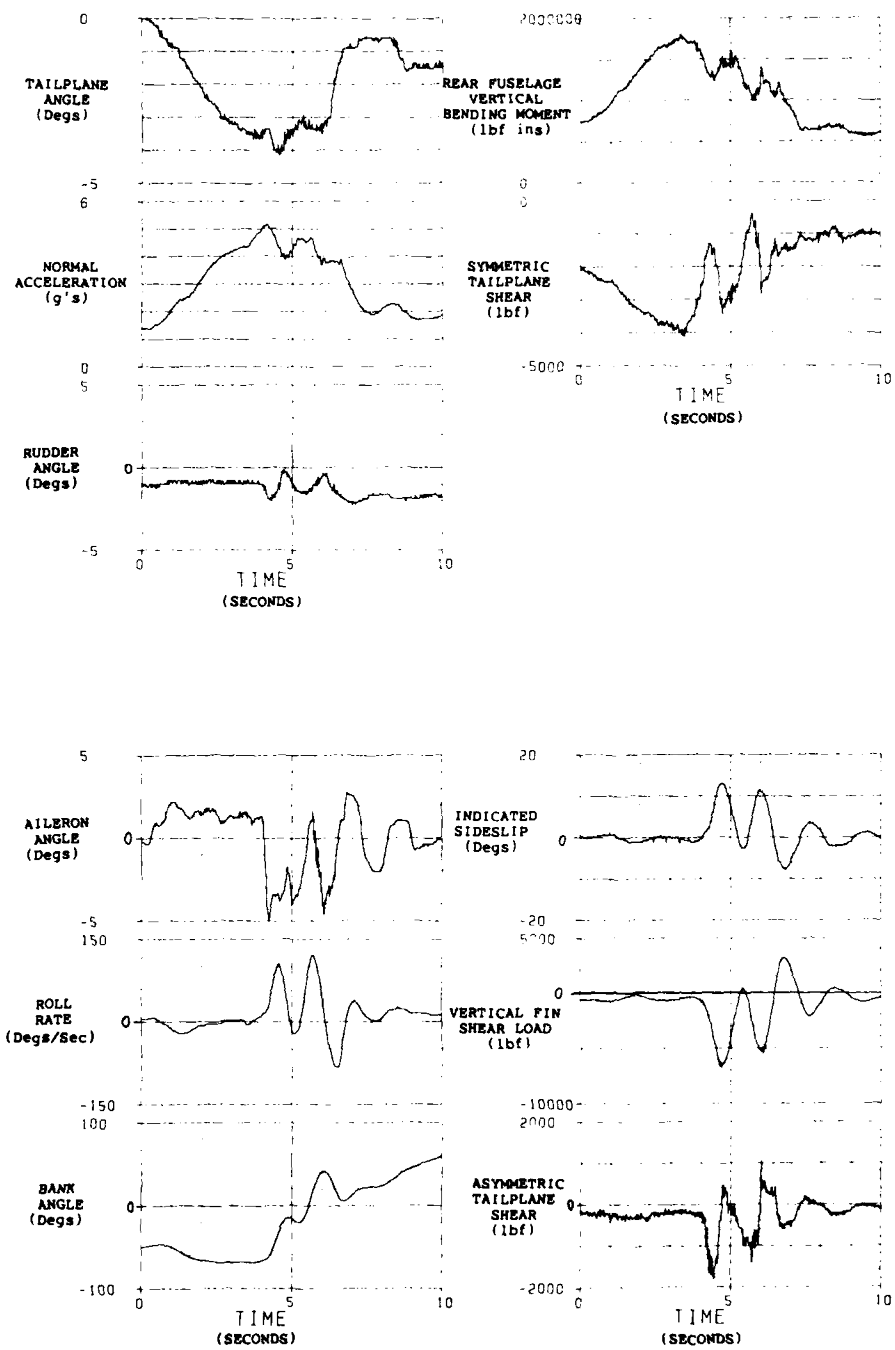


FIGURE 9

ROLLING PULL OUT



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NOZZLE DOWN DEPARTURE — FIGURE 10

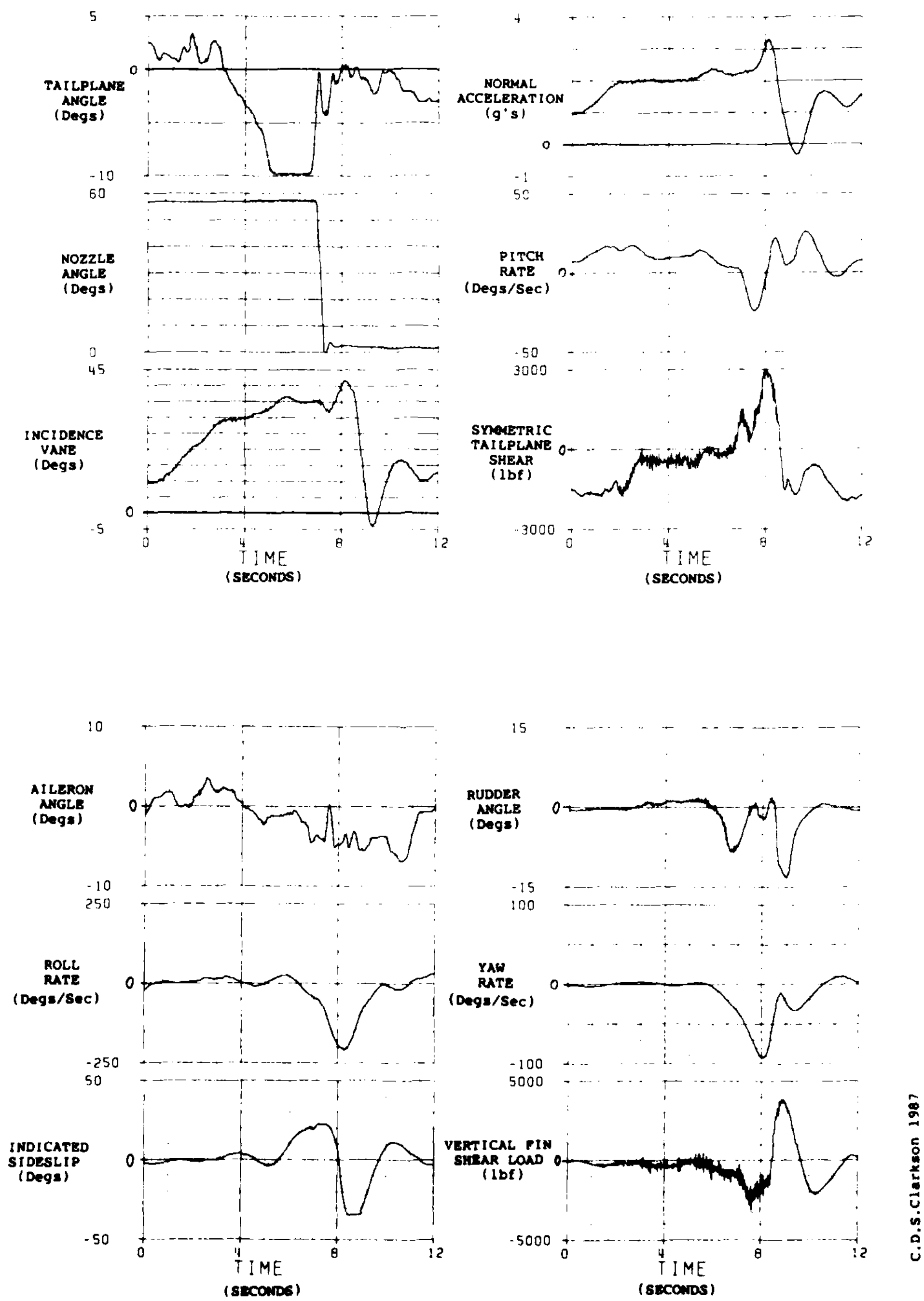


FIGURE 11

FLIGHT THROUGH LEAD AIRCRAFT'S SLIPSTREAM DURING 1 V 1 AIR COMBAT

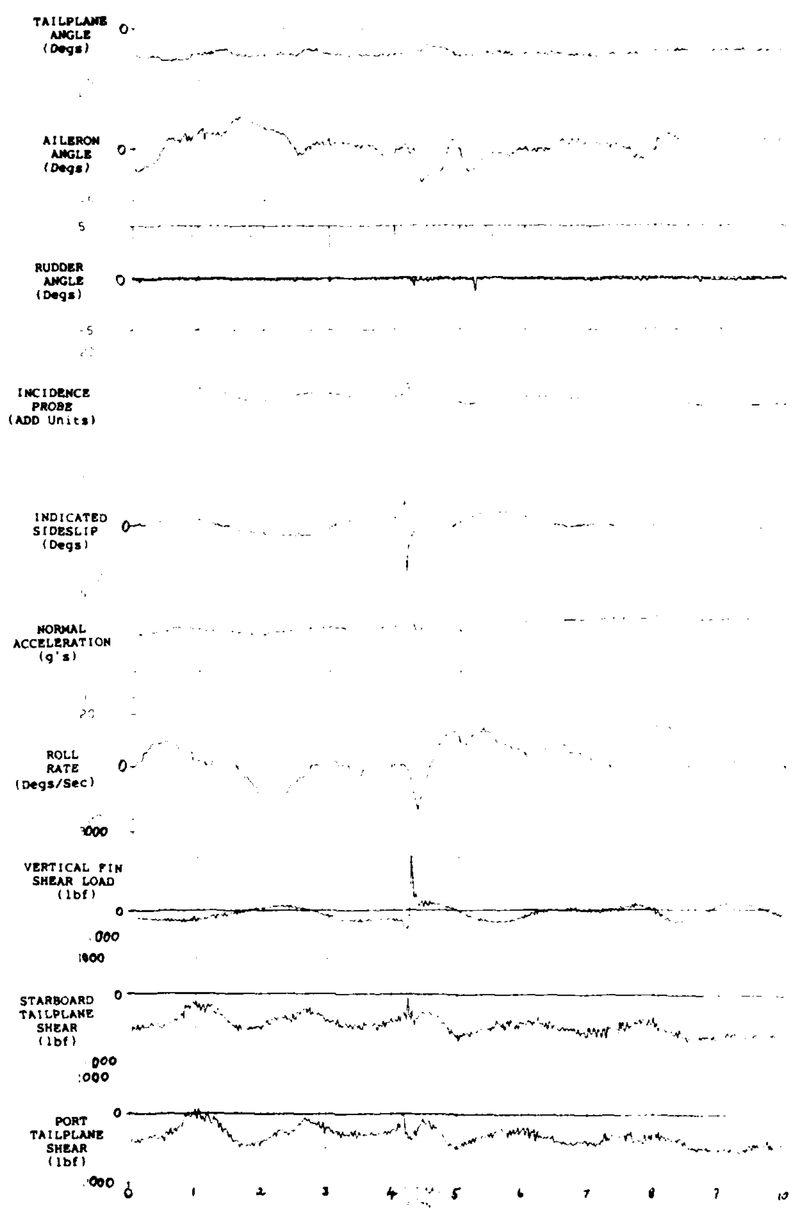
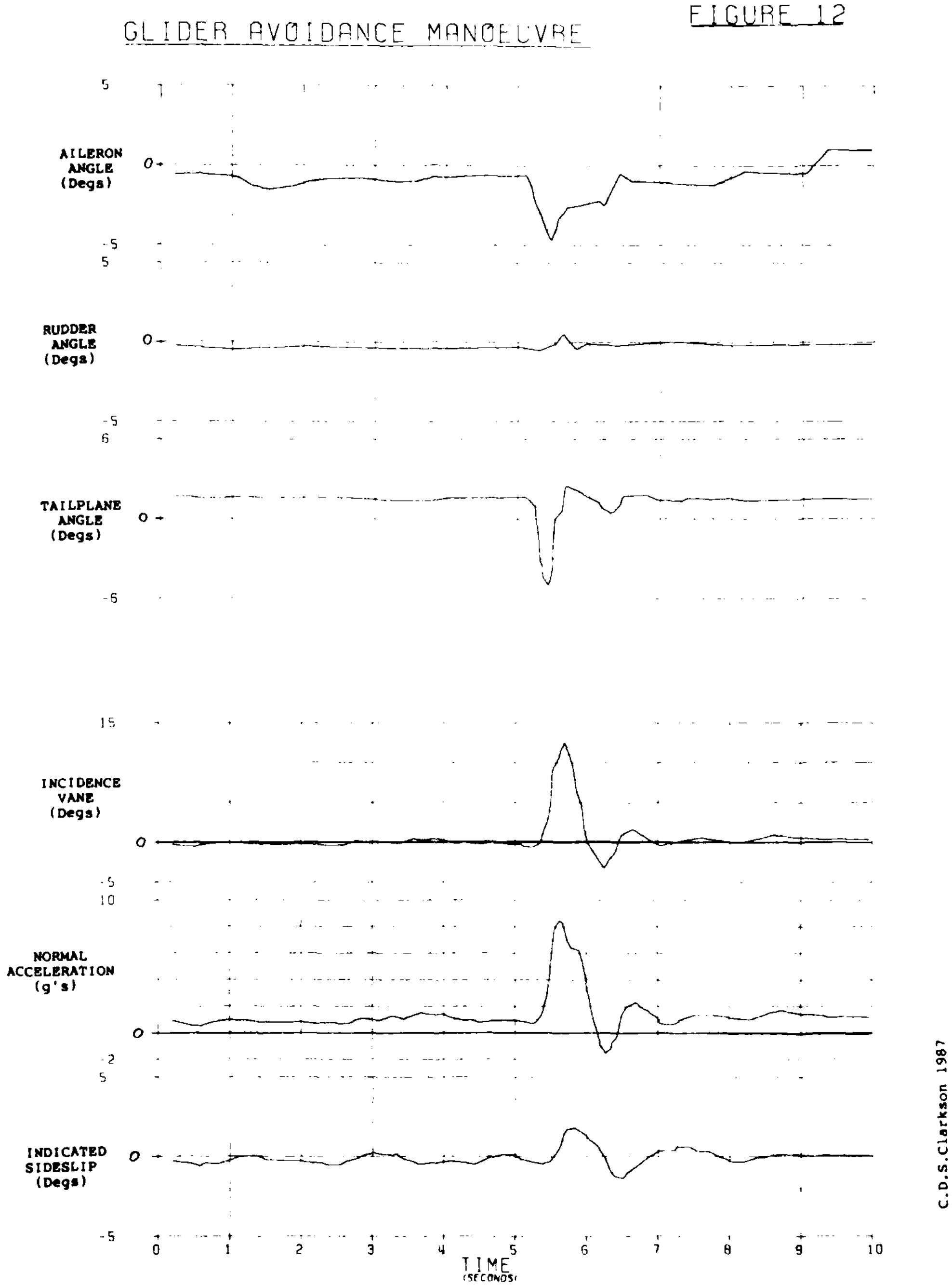


FIGURE 12


GLIDER AVOIDANCE MANOEUVRE
AILERON ANGLE (Degs)
RUDDER ANGLE (Degs)
TAILPLANE ANGLE (Degs)
INCIDENCE VANE (Degs)
NORMAL ACCELERATION (g's)
INDICATED SIDESLIP (Degs)
TIME (SECONDS)
C.D.S.Clarkson 1987

DESIGN LOADS FOR SWEDISH MILITARY AIRCRAFT IN A TWENTY YEARS' PERSPECTIVE

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SUMMARY

The Swedish Viggen aircraft was designed according to Swedish regulations which had matured during a long time. The design phase is discussed as well as the need for usage data when the aircraft was in service. When the latest Swedish advanced military aircraft, the JAS39, was planned, it was the intention to use the US Military Specifications with minor changes. The experience during the design phase is discussed.

LOADS ON THE SAAB 37 VIGGEN

The Saab 37 Viggen aircraft which made its maiden flight in 1967 was designed according to specifications founded on experience of earlier aircraft especially the Saab 35 Draken. There were also several incentives from contemporary US and British military specifications on load cases. These latter specifications were primarily written for wing-and-tail aircraft whereas Draken and Viggen have slender delta wings and elevons. The symmetric maneuvers specified in e.g. [1] are not so essential for delta wings as for aircraft with tails. It was sufficient to determine a coarse value of extreme pitch acceleration in addition to limit load factors. The determination of symmetric flight loads could then be limited to the variables in table 1 with the appropriate flight envelope.

Max and min	Normal load factor
Max and min	Pitch acceleration
Max and min	Longitudinal load fac'or
Store loads	

Table 1. Symmetric flight loads

Max roll rate
Max roll acceleration
High and low normal load factor
High speed rudder kick
Reversed rudder
Store loads

Table 2. Unsymmetric flight loads

On slender delta wing configurations appreciable angles of side slip occur during fast rolling maneuvers due to inertia and aerodynamic coupling. An important cause of aerodynamic coupling on these aircraft is the side load on the fin caused by different elevon angles on port and starbc rd elevon during a rolling maneuver. During the development of Draken fin loads were measured on a windtunnel model and later in flight. This was reported in [2]. These studies were successful after quite a lot of work and provided the starting point for the development on the Viggen aircraft.

Load cases for unsymmetric conditions were determinded for the variables in table 2 throughout the flight envelope. Rolling maneuvers combined with low normal load factors give large side slip and consequently large loads on the fin and on stores. Combinations with high normal load factors give high loads on the wing.

Limit loads, as discussed above, must be accompanied by load spectra. Aircraft specifications in those days gave only a few basic numbers such as number of flying hours and number of flights. Measured load spectra on similar aircraft are undoubtedly the most valuable source of information when compiling design load spectra, especially when the way in which the aircraft was used when the spectrum was measured is known in detail. Load factor spectra for different versions of Draken, measured by the Swedish Air Force, and data on the use of the aircraft e.g. navigation training, normal flights, dogfights were the starting point together with analysis of the intended use of Viggen. In the compilation of a load spectrum for the latter aircraft other aircraft state variables then normal load factor where taken from [3]. An example of the importance of coupled motion for a part of the main wing is the shear load spectrum for the main wing rear attachment see fig. 1, taken from [4]. It was obviously also necessary to take care of all sorts of loads during the design phase. Table 3 gives as an example of the different loads that were relevant for the spectra of the fuselage joint between canard and main wing.

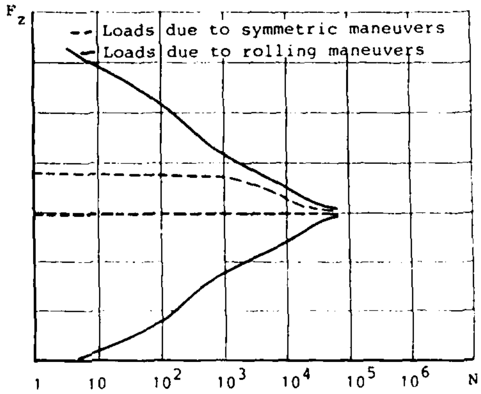

Figure 1. Shear load spectrum main wing rear joint

Loads due to maneuvers and gusts
Loads due to landing impact on main gear
Loads due to landing impact on nose gear
Ground-air-ground cycles
Loads due to taxying and turns

Table 3. Contributions to spectra of the fuselage joint between canard and main wing.

The loads and spectra discussed so far were pure calculations and were the bases for the design of the aircraft. During preparations for large fatigue tests it was realized that loads for symmetric cases were of sufficient quality whereas it was necessary to improve data on unsymmetric cases. A set of flight tests was performed with typical rolling maneuvers occurring during the service of the aircraft. The types of maneuvers are shown in table 4. All of these maneuvers have coupled motion including normal load factor, rolling motion and side slip and the main motivation for the tests was the determination of the load combinations in actual usage. Three pilots performed the 13 types of maneuvers and they showed quite large variations of action in some cases. Generally it can be stated that the tests gave a wealth of data which were not easy to analyse and the analysis performed would not totally satisfy a statistician. Nevertheless the data were analysed and used in the fatigue test of the aircraft.

The analysis was not performed with sofisticated pattern recognition or parameter estimation techniques but by hand i.e. visual studies of curves, hypotheses and tests. As was expected the analysis gave no simple answers but resulted in quite a lot of work before the loads for the fatigue tests were determined. Only condensed results will be discussed here. Figure 2 shows the relation between normal load factor at the time of extreme roll rate and the extreme normal load factor during the maneuvers. All types of combinations occur but combinations of max load factor and max roll rate are rare. The same can be said about figure 3 which shows simultaneous values of extreme roll rate and normal load factor and the same type of envelope as [3]. The aircraft has full powered hydraulic servos both for elevons and rudder and is assisted by a control system in pitch, roll and yaw. Figure 4 shows simultaneous values of side slip and rudder angle. There obviously is no linear dependence between them. The examples are a little exaggerated as there is no division into the 13 types of maneuvers but it fair to say that flight tests do not give simple answers even for the actual aircraft. The use of data from one aircraft to another is still much more complicated.

The data from the flight tests were also set in relation to the design load cases. The most interesting cases are those for the fin as the calculated loads were determined with more assumptions than those of other parts. There were no loads measured during the tests. The loads must thus be determined from state variables. Fin loads were in the calculations, mainly functions of dynamic pressure, side slip, rudder angle and elasticity of the fin. The effect of elevon angle was much smaller. Figures 5 and 6 show limits for the combinations of side slip and rudder angle multiplied by dynamic pressure and lines for constant bending moment for the design load cases. The limits for the tests data have not been drawn with corrections for the effect of elasticity, an effect that would further tighten the area of measured data. The extreme loads during the maneuvers were well within the limits of de design loads as they should be for such a limited number of flights.

o	Normal turn
o	IMC turn
o	Quick turn
o	Avoidance maneuvers
o	Scissoring turn
o	Jinking maneuvers
o	Turn/altitude change
o	Top roll
o	Barrel roll
o	Exercise half roll
o	Combat half roll
o	Air-to-ground attack
o	Air-to-air combat

Table 4. Types of rolling maneuvers

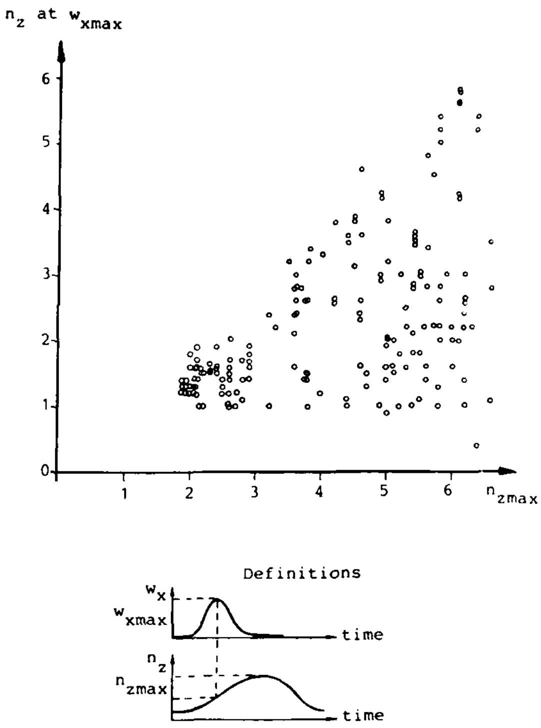

Figure 2. Load factor at max roll rate

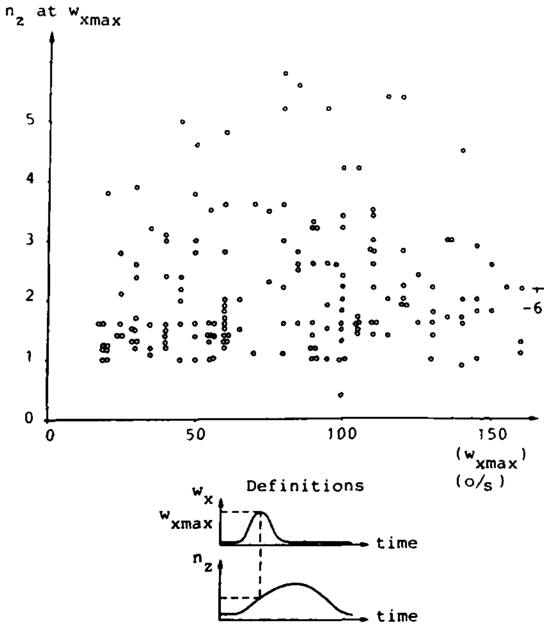

Figure 3. Load factor at max roll rate

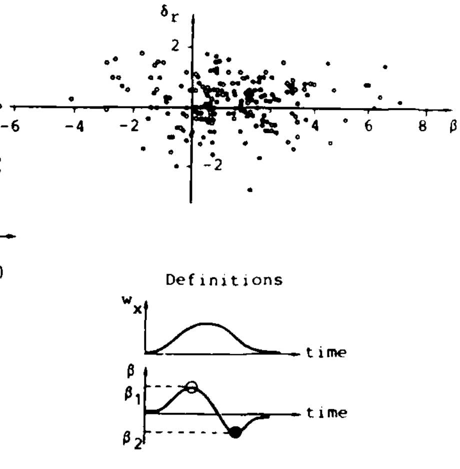

Figure 4. Rudder rotation simultaneous with extreme side slip

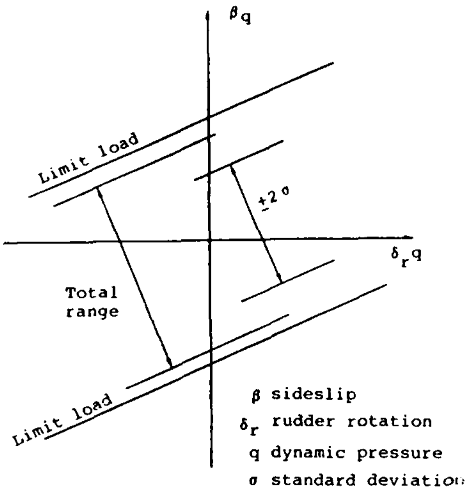

Figure 5. Verification of fin main joint bending moment

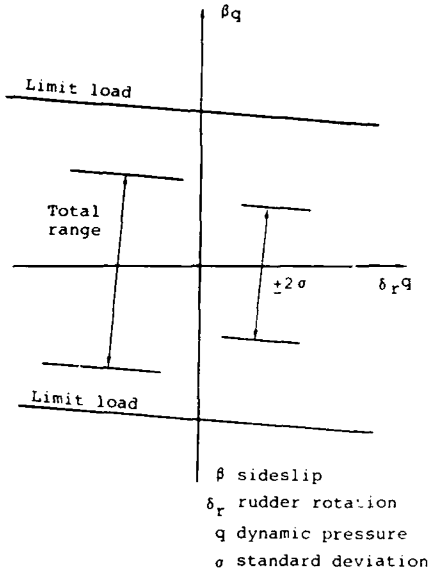

Figure 6. Verification of fin forward joint bending moment

DESIGN CRITERIA FOR THE JAS 39 AIRCRAFT

The experience from the Viggen aircraft was the foundation when a new aircraft was specified, a new aircraft for air-to-air, air-to-ground and reconnaissance missions. The initial letters in Swedish are J, A and S. The aircraft was given the name JAS39. The contract between the Swedish Defence Material Administration and the manufacturer, a group of Swedish companies, contains a specification which shows how loads shall be handled. The priorities of documents are shown in table 5. The project specification contains only a few data which are important for loads e.g. limit load factors, weights and normal load factor spectrum. In the specification of service usage there is a detailed description of types and numbers of missions and maneuvers during each mission. The normal load spectrum derivable from this document is compatible with the spectrum in the project specification. The general specifications are some of the US military specifications. These specifications are completed with project specific data and in certain cases changed as specified in a separate document "Application of load specifications".

<u>Highest priority</u>

Project specification

Application of load specifications

Specification of service usage

<u>Lowest priority</u>

General specifications

Table 5. Priorities between specifications

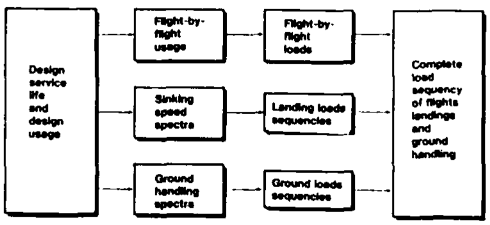

Figure 7. From usage to load sequences

It is of special interest to discuss the specification of flight loads. The paragraphs on maneuvers in [5] i.e. paragraph 3.19-3.20, have been replaced by wordings like "The specified cockpit lateral control forces are not applicable. Suitable maneuvers shall be agreed upon". It is thus the responsibility of the manufacturer to design the aircraft to fulfil requirements on performance and flight characteristics but when doing so he has the freedom to minimize loads using control system techniques. On the other hand the manufacturer cannot rely on one certain maneuver but must cover maneuvers compatible with the service usage of the aircraft. In the determination of loads it is necessary to have a six-degree-of-freedom model of the aircraft with proper representation of nonlinear aerodynamics especially the coupling between pitch and yaw forces. The simulation model must also include the control system as no simulation of unstable systems is possible otherwise.

Even for stable aircraft, simulation without control system, e.g. without yaw damper, is of no value. Besides stability augmentation the simulation model must also contain the maneuver limitations of the control system. The simulation of the function of these facilities is one of the main tasks in the determination of limit loads. The simulation model is built up during a long time as the aerodynamics is modified by more accurate calculations, windtunnel tests and corrections for the effect of the elasticity of the aircraft, which in their turn effect the control system. It goes without saying that good judgement is invaluable at an early stage.

As the use of the aircraft is in the form of sequences of states it has been possible to build up a sequence of balanced load cases for the total use of the aircraft, including flight, landing and ground handling which is shown in figure 7.

The computer programs which we have developed for sequences are very versatile and it is very easy to study the effect of changes of the use of the aircraft and of the way maneuvers are performed i.e. it is easy to generate new sequences of stresses and strains. The main work load lies in the following calculations of fatique life or damage tolerance.

CONCLUSIONS

The design process of the JAS 39 is going on. The first flight is scheduled to late this year so it is not possible to assess the value of our work yet. During preparation of this paper we read [6]. It contains two review papers which it has been difficult not to duplicate. Their conclusions are very much in line with our own modest results.

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DETERMINATION DES CHARGES DE DIMENSIONNEMENT DES AVIONS DE COMBAT ACTUELS

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RESUME

La présence simultanée sur les avions de combat modernes, de servo-commandes puissantes et de systèmes de commandes de vol électriques conduit à des aménagements dans le choix des cas de charge dimensionnant la structure, tels qu'ils sont donnés dans les normes US MIL ou françaises 2004 E.

L'expérience des avions mis en vol depuis le MIRAGE 2000 jusqu'au RAFALE a conduit vers un processus itératif de détermination des charges limites qui doivent couvrir l'ensemble du domaine des manoeuvres accessibles au pilote à travers les CDVE (Pilotage "care free") ; ce processus est intégré dans l'optimisation de l'ensemble du projet (forme aérodynamique, surface des gouvernes, puissance des servo-commandes, dimensionnement de la structure, architecture CDVE), l'objectif principal étant d'assurer les qualités de vol requises.

On part avec une première sélection de cas de charges statiques forfaitaires dont le choix résulte de l'expérience et des qualités de vol requises.

Ces charges conduisent à un premier dimensionnement de la structure effectué par les techniques d'optimisation structurale ; on satisfait simultanément à des critères de résistance des matériaux et d'aéroélasticité.

Pour ce dessin optimisé, on élabore des opérateurs permettant la reconstitution aisée, pour toutes manoeuvres, des efforts internes ou des contraintes aux points sensibles de la structure.

Ces points sensibles sont surveillés systématiquement dans les simulations de manoeuvres complexes servant à la mise au point des commandes de vol électriques.

Le dépassement des contraintes admissibles peut se traduire, soit par une adaptation du système de commandes de vol, soit par une révision des cas de charge dimensionnants.

L'utilisation de la procédure d'optimisation facilite les choix, car on dispose directement sous forme de "multiplicateurs de Lagrange", des taux d'échange entre la masse de structure et l'ensemble des exigences, dont les charges et les performances de manoeuvrabilité.

1 - CONTEXTE

Les charges limites en manoeuvre sont définies par les règlements classiques (Normes US MIL, AIR 2004 D), à partir de manoeuvres type (facteur de charge, manoeuvre contrée).

Ces manoeuvres type sont définies par des arguments simples (Accélération, Braquage maximum des gouvernes, Effort maximum des servo-commandes), ce système étant censé présenter certains avantages :

- Définition claire et explicite des cas de charge dimensionnants pour le concepteur

- Relation simple avec les performances de mécanique du vol

- Expression simple des consignes de pilotage.

En pratique un pilote peut réaliser assez facilement des manoeuvres plus ou moins complexes où les facteurs de charge et les efforts servo des manoeuvres limites normalisées ne sont pas dépassés, mais où les contraintes engendrées sur la structure le sont (Exemple : double manoeuvre contrée de lacet). Les constructeurs se sont couverts contre ces situations, tant par des consignes de pilotage que par des renforcements structuraux fondés sur des règles issues de l'expérience, plus sévères que les règlements officiels.

L'arrivée vers 1975 du MIRAGE 2000 et des avions qui l'ont suivi (MIRAGE 4000, MIR.III NG et RAFALE) avec leur système de commande de vol électrique et leur stabilité artificielle, a achevé la mise en évidence de l'obsolescence des méthodes classiques de définition des charges.

Les situations de charges réelles dimensionnantes correspondent pratiquement toujours à des manoeuvres plus complexes que celles prévues dans les règlements :

- Les manoeuvres stabilisées sont précédées et suivies de transitoires rajoutant des efforts (voir Planches 1.1 à 1.3).

- Les manoeuvres contrées des règlements ne sont pas réalisables, les braquages des gouvernes étant sujets au contrôle des CDVE qui interdisent certaines situations.

- De façon générale les systèmes de CDVE sont conçus pour dégager le pilote du souci de la surveillance des limites structurales, tout en tirant le meilleur parti opérationnel des qualités de vol de l'avion ; il en résulte que les limites structurales peuvent être atteintes quotidiennement sur des manoeuvres dynamiques complexes (Voir Planche 2).

2 - LES NOUVELLES REGLES

Pour la définition des charges de manoeuvres des avions de combat à commandes de vol électriques on tend vers l'adoption de la règle suivante :

Les charges limites résultent de l'enveloppe des manoeuvres autorisées par le système de commandes de vol, quoi que fasse le pilote.

La deuxième proposition peut être tempérée en ajoutant :

... qui ne soit pas formellement interdit par le manuel de pilotage, et dont on se soit assuré de la possibilité pratique de respect de l'interdiction.

A partir de cette définition des charges limites la discussion sur les coefficients de sécurité des charges extrêmes est ouverte ; en effet, en théorie, on devrait pouvoir diminuer le coefficient de sécurité classique (1,5) du fait que les commandes de vol électriques garantissent mieux qu'auparavant contre les excursions au-delà des charges limites ; pratiquement nous considérons qu'il n'y a pas d'urgence vers cette démarche, en particulier pour deux raisons :

- Les parties métalliques des avions munis de CDVE sont souvent dimensionnées par la fatigue (Spectres de fatigue nettement plus sévères que ceux des avions classiques).

- Pour les parties en matériaux composites, peu sensibles à la fatigue, on peut échanger la meilleure connaissance des charges contre la moins bonne connaissance de la dispersion de la résistance du matériau.

3 - MISE EN PRATIQUE DES NOUVELLES REGLES

3.1 - Organisation

L'intéraction complète entre le dimensionnement de la structure et la conception des CDVE, nous oblige à repenser l'organisation des projets ; on arrive actuellement à la procédure itérative suivante :

- Opérations relevant du calcul des structures :

  . Sélection de cas de charges forfaitaires pour le dimensionnement

  . Dimensionnement de l'avion par la technique d'optimisation structurale

  . Elaboration d'opérateurs permettant le "suivi" des contraintes structurales aux points sensibles pendant les manoeuvres, et des valeurs limites correspondantes.

- Opérations relevant de la mécanique du vol :

  . Calcul systématique des contraintes "suivies" dans toutes les simulations de mécanique du vol.

  En cas de dépassement des valeurs limites.

  . Modification du réglage des CDVE

  ou

  . Rediscussion du dimensionnement en définissant de nouvelles manoeuvres pour les charges forfaitaires.

3.2 - Sélection des cas de charges forfaitaires pour le dimensionnement

C'est à ce niveau qu'apparaît l'expérience du constructeur, car ce choix détermine directement les qualités de vol de l'avion ; de façon générale on est amené à se contenter de manoeuvres "statiques" définies par des niveaux d'accélération, ou d'effort de servo-commande maximum ; la non définition au départ des CDVE ne permet pas d'effectuer des calculs de réponse dynamique.

A ce niveau seul les "arguments" (Accélérations, Efforts servo) des manoeuvres sont choisis ; la sélection des cas enveloppes dans le domaine Mach, altitude, configuration massique est intégrée au calcul d'aéroélasticité de la phase de dimensionnement.

3.3 - Dimensionnement de l'avion par optimisation

Il est maintenant effectué complètement par les techniques d'optimisation structurale que nous avons détaillées dans les références 1 à 4.

L'ensemble des opérations est effectué en manipulant un maillage Eléments Finis de l'avion complet, avec l'enchaînement suivant :

- 1ère Analyse Eléments Finis

  . Maillage de l'avion complet avec un échantillonnage simplifié.

  . Résolution avec les cas de charge simplifiés (pour la vérification du modèle).

- Aéroélasticité statique - Calcul des charges (Voir référence 5)

  . Coefficient Aérodynamique avion "souple".

  . Calcul des charges pour les manoeuvres forfaitaires.

  . Enveloppe des cas de charge, charges dimensionnantes.

- Calculs dynamiques

  . Modes propres
  . Flutter

- Optimisation structurale (minimisation de la masse)

  Contraintes :

  . Résistance des matériaux sous tous les cas de charge dimensionnants
  . Coefficients aéroélastiques, divergence statique, performances de mécanique du vol
  . Flutter
  . Technologiques

- Dessins dimensionnés de la structure

En pratique ils demandent de nombreuses itérations d'optimisation.

L'ensemble du processus, qui fait intervenir dessinateurs et calculateurs de structure, aboutit à un dessin échantillonné en principe optimal de l'avion, pour supporter les charges forfaitaires qu'on s'est donné, et satisfaisant à l'ensemble des autres contraintes (Aéroélasticité statique, Flutter, Technologie).

Ces travaux sont effectués à prix raisonnable par notre logiciel général de calcul de structure ELFINI.

3.4 - Opérateurs de structure pour la mécanique du vol

A partir de la structure optimisée on élabore 3 familles d'opérateurs permettant les calculs de mécanique du vol avec CDVE ainsi que la surveillance de la structure pendant toutes les évolutions.

Nous avons détaillé dans la référence 5 la technique d'élaboration de ces opérateurs par la branche CHARGE de notre logiciel ELFINI ; ce sont :

- Les coefficients aérodynamiques "avion souple".
- Les fonctions de transfert entre les paramètres aérodynamiques (Incidences, Braquage de gouvernes) et les capteurs de mouvements, entrées des CDVE.
- Les opérateurs de réponses des efforts et contraintes aux points sensibles de l'avion en fonction des paramètres aérodynamiques (Incidences, Braquages de gouvernes).

Ces réponses de points sensibles sélectionnés, que nous appelons "suivis", sont en nombre de l'ordre de la centaine, leur fonction est de couvrir au mieux l'ensemble des charges générales de l'avion.

Les "suivis" sont composés :

- d'efforts généraux classiques
- de réactions et d'efforts internes (Attaches voilure, efforts servo, etc...)
- de contraintes en des points critiques.

On fournit pour chaque "suivi" les valeurs limites, qui ne devront pas être dépassées pendant le vol normal de l'avion, ce qui aboutit à ne plus définir le domaine de vol par des charges mais plutôt par des contraintes limites sur la structure.

L'ensemble de ces opérateurs est élaboré dans le domaine Mach, altitude, répartition massique ; les non-linéarités aérodynamiques doivent être prises en compte, et les 3 familles d'opérateurs doivent dériver rigoureusement des mêmes hypothèses aérodynamiques. (Dans le cas contraire on ne satisferait pas aux équations d'équilibres).

3.5 - Intéraction structure mécanique du vol

Nous n'entrons pas ici dans le détail du principe de conception des commandes de vol électriques, nous rappelons simplement qu'il vise deux objectifs :

- optimisation des qualités manoeuvrières de l'avion
- garantie de la sécurité, tant du point de vue du contrôle de la mécanique du vol que de la résistance de la structure.

C'est sur ce dernier point qu'apparaît l'intérêt de la fourniture des "suivis" de structures ; ils sont utilisés systématiquement :

- dans les calculs de mise au point des CDVE
- dans les simulateurs de vol en temps réel, ce qui permet de vérifier le non dépassement des contraintes limites dans un nombre maximum de circonstance avec un pilote "humain".

S'il s'avère que les limitations structurales handicapent trop les qualités de vol de l'avion, on admet de pouvoir revoir le dimensionnement de l'avion en redéfinissant, de façon circonstanciée, les charges forfaitaires de l'optimisation de l'avion.

De façon générale une itération de revue du dimensionnement doit toujours être faite après identification exacte des charges aérodynamiques de l'avion en vol ; nous avons exposé en détail dans la référence 6 la procédure d'étalonnages au sol et des mesures de jauges de contrainte en vol, qui permet de vérifier et d'ajuster les modèles de calcul par Eléments Finis et d'aéroélasticité qui fournissent les coefficients aérodynamiques "avions souples" et les "suivis structuraux".

4 - CONCLUSIONS

On arrive à un système où on ne définit plus les états limites de la structure par les charges mais par les contraintes engendrées.

Le processus global de dimensionnement de la structure et des CDVE est empirique, au sens qu'il est basé sur l'expérience de l'avionneur, cela bien que chaque discipline isolément s'appuie sur des techniques d'optimisation très poussées.

Si on n'avait à tenir compte que de manoeuvres déterminées on pourrait aisément concevoir un processus d'optimisation globale ; la difficulté vient de ce qu'on veut donner toute liberté au pilote dans ses manoeuvres.

A court terme les meilleurs progrès pour l'optimisation de la conception générale sont attendus d'une exploitation rationnelle des informations sortant des optimisations de chaques disciplines sous la forme des multiplicateurs de Lagrange des contraintes actives ; ainsi l'optimisation structurale peut fournir directement les taux d'échange entre les diverses qualités de vol de l'avion et la masse de la structure.

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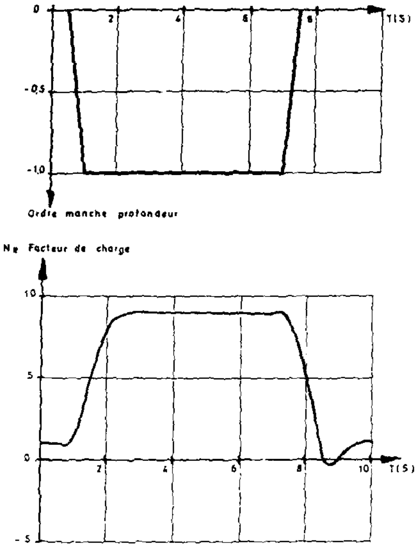
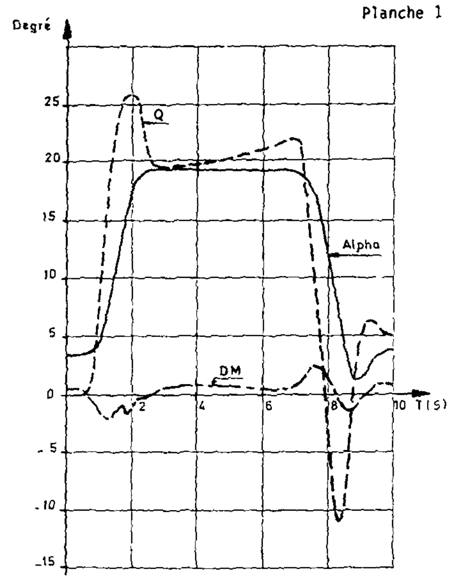
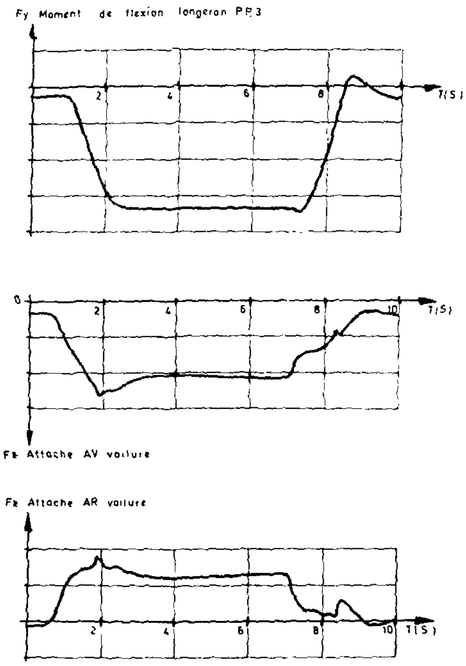
Planche 1



Manœuvre de profondeur

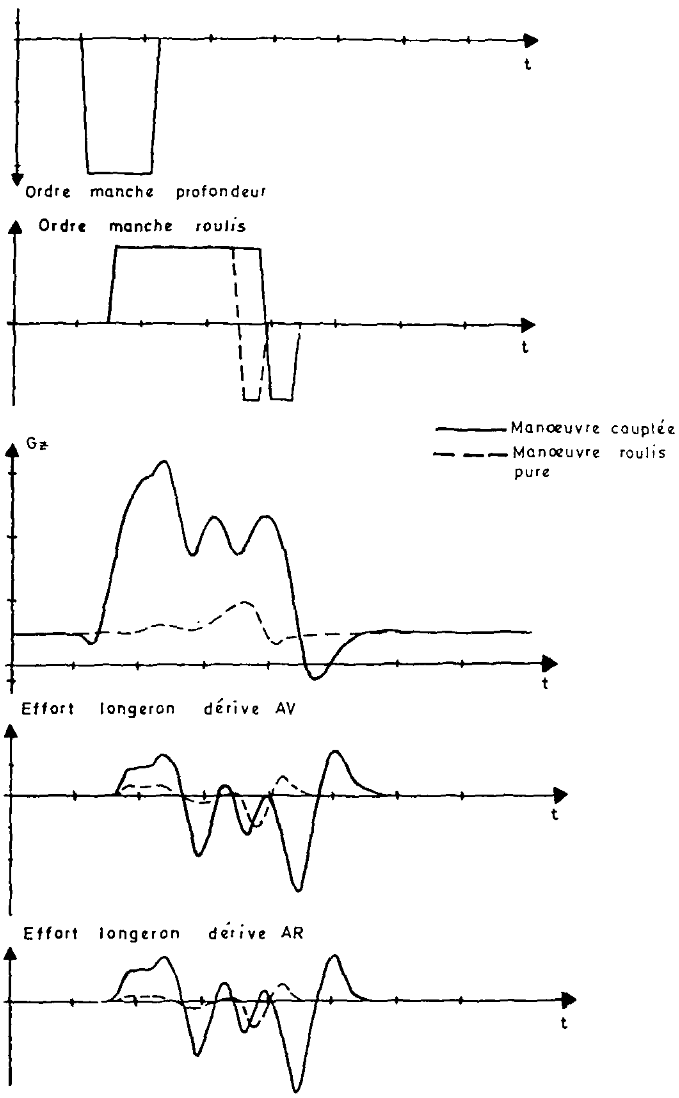


Manœuvre de profondeur
Réponse Alpha, DM, Q



Manœuvre de profondeur
Réponse des efforts aux attaches voilure

Planche 2



Manœuvre complexe

INTERACTION BETWEEN STRUCTURAL CONSIDERATIONS AND SYSTEM DESIGN IN ADVANCED FLIGHT CONTROLS

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SUMMARY

The performance requirement of modern combat aircraft can only be met with airframes which are naturally unstable, relying on the Flight Control System to provide the required stability.

This is the main reason for the choice of Fly by Wire systems, with full authority and digital computing to allow the implementation of the complex control laws required to fulfil this FCS basic requirement.

The achievement of sufficient stability margins is the primary task in the design of the FCS, followed by the need to provide good Handling Qualities.

Handling criteria developed in the past have shown not to be adequate to describe correctly the behaviour of current high order systems, requiring dedicated research work to define new design criteria.

Digital FBW system give the possibility of implementing new features, such as automatic protection against exceedance of given manoeuvre limits (carefree handling).

These features are implemented as part of the basic flight control laws.

The design loads for the structure can then be defined in terms of combination of response parameters in order to cover all the operational manoeuvres with limited margins to allow significant mass savings.

LIST OF ABBREVIATIONS

α	-	angle of attack
β	-	angle of sideslip
p	-	roll rate
q	-	pitch rate
r	-	yaw rate
i/b	-	inboard
o/b	-	outboard
g, n_z	-	normal acceleration
n_y	-	lateral acceleration
ATR	-	Attained Turn Rate
CSAS	-	Control and Stability Augmentation System
FCS	-	Flight Control System
FBW	-	Fly by Wire
H.Q.	-	Handling Qualities
STR	-	Sustained Turn Rate

1 INTRODUCTION

Design of advanced combat aircraft can be optimized onl: by integration of the different aspects of the design.

Taking into consideration the interaction between the different areas from the preliminary design stage is the only possible way to fully exploit the possibilities offered by the currently available technology and drive the design in such a way that the various disciplines take full advantage by the others.

This paper deals with some of the specific aspects of the interactions between the Flight Control System design and the structural design.

Next generation of advanced combat aircraft will make use of Active Control Technology to an even greater extent than the current in-service aircraft. The need to control airframes which present high levels of aerodynamic instability, and the request of extreme manoeuvre capabilities has dictated the need for Flight Control Systems based on Fly by wire technology, with full authority and digital computation.

Such systems can implement the complex laws and functions which allow the FCS to fulfil its main requirement: provide adequate stability and handling qualities under all circumstances.

Integrity requirements are satisfied by a multi-redundant system architecture, incorporating multi-lane and self monitoring features.

The powerful capabilities offered by modern systems provide the possibility of realizing, by the FCS, functions which have a major impact on the structural design criteria: particularly the capability of automatically limiting the aircraft's response to the pilot's input within predefined envelopes (Carefree Manoeuvring).
This specific aspect of the FCS design is treated in some detail in this paper in consideration of the impact it has in the definition of the design loads.

This is but one of the aspects of the interaction between the FCS and the Structure design, there being others of great interest (Structural Coupling just to name one) that are not treated here as they do not fall directly under the theme of this workshop.

Since any integrated approach to the design is feasible only when all the parties involved know each other's point of view and the technical challenges they have to face, the first part of the paper is dedicated to a brief description of the "classical" stability and control requirements for next generation of fighter aeroplanes. This section is intended to give non FCS specialists a brief overview of the FCS design task.

The specific requirement for "Carefree Manoeuvring" is then considered and an indication of the possible realisation of such a feature in a digital FCS is given.

The third part of the paper gives an indication of how the automatic control and limitation of the aircraft response parameters, provided by the carefree manoeuvring features, can be used to define design loads for the structure which allows structural mass savings while not compromising manoeuvrability.

2 THE FCS DESIGN TASK

One of the purposes of this workshop, sponsored by the Structures and Materials Panel, is to assess the influence of advanced flight control systems technology on the structural design criteria for advanced fighters.

As the audience of this workshop is likely to include mostly structural designers, this section is intended to give non-FCS specialists some information about the Flight Control System design task.

2.1 FCS Evolution

Flight Control Systems have gone a long way from the first applications of powered controls in the 1950's. This step was imposed by the need to allow full use of the envelope capability provided by the relatively high performance jet aircraft of the time.

A very limited authority allowed the use of these systems to slightly modify the natural dynamic behaviour of the aircraft, increasing the damping with very simple rate feedback circuits.

Increased confidence in the hardware reliability allowed a progressive expansion of the authority of the controllers, progressing from simple dampers to "Control and Stability Augmentation Systems" (CSAS) in the early 1970's.

Relatively low authority and low computing capacity (analogue computing) prevented the development of complex integrated systems, limiting the functions of the FCS to the traditional Flight Mechanics aspects.

The real breakthrough in FCS has occurred with the introduction of digital computing, associated with full authority, fail operational Fly by Wire systems.

The driving factor for achieving such a breakthrough has been the capability to fly with reduced natural stability for improved performances combined with enhanced handling.

Stability and handling are then the basic FCS functions and some more detail about these aspects is given in next sections.

2.2 The Stability Problem

Ever increasing requirements for high manoeuvrability, low drag and small size are such that can only be achieved with airframes which are aerodynamically unstable.

2.2.1 Rationale For Aerodynamic Instability

The advantages of an inherently unstable configuration are clear, from an aerodynamic point of view: tail loads to trim for a naturally stable aircraft are detrimental to performances, as they increase trimmed drag and reduce the maximum trimmed lift. This effect is reversed for an unstable - or better, artificially stable - aircraft (fig 1 - ref. 1).

Additional advantages in terms of induced drag are obtainable by automatic scheduling of wing camber by use of leading and trailing edge surfaces: full advantage of this effect can only be exploited by an artificially stable configuration (fig 2).

2.2.2 Maximum Allowable Instability

From the aerodynamic point of view, there is a clear case for high levels of basic instability.

However, there are limitations which define a maximum level of instability that can be allowed by the FCS.

The maximum allowable level of instability is strongly dependent on the vehicle's basic aerodynamic pitching moment characteristics, the available control power in all axes, and the dynamic characteristics of the FCS.

Two are the most critical flight conditions for FCS design:

- the low speed/high incidence region, where the low control effectiveness requires large and rapid control surfaces deflections.
- the high subsonic region, where the maximum dynamic instability (expressed in terms of time to double amplitude) is normally located.

2.2.3 Minimum Stability Margins

The maximum dynamic instability point is the most severe from the relative stability point of view.

Principal Requirement in the design of an inner loop for the stability augmentation system is the achievement of adequate stability margins.

Stability margins are the measure of the variation of the characteristics of the open loop system with respect to the nominal which are allowed before the closed loop system becomes unstable (fig 3). A Flight Control System is normally conditionally stable, showing low and high frequency gain margins and a phase margin.

Uncertainties in the aerodynamic model used for the control law design and in the performance characteristics of the FCS, require adequate margins to be maintained in all flight conditions, typically 45° phase margin and ± 6 dB gain margin.

In order to accommodate all the high order effects which are present in the system, all the hardware lags, software delays, anti-aliasing, notch and control filters must be included in the design for a correct evaluation of the stability margins (fig 4). Neglecting these effects may lead to overgeared, high bandwidth systems, and a gross overestimation of the real stability margins (fig 5 - ref. 2).

Minimum stability margins set the limit for the basic aerodynamic instability, affecting the performance of the aircraft. The need to minimize the effects which erode the stability margins results in severe requirements on the FCS hardware, particularly on the computer which must have a very high update to minimize delays.

2.2.4 Structural Coupling

One of the areas which require a strong integration between FCS and structural design is that of Structural coupling, only briefly considered here.

Control systems for highly unstable aircrafts require extensive lead and a wide bandwidth.

The increased sensitivity of such systems to high frequency effects, requires a very effective cancelling of the structural modes interaction with the FCS.

The traditional solution of notch filters in the feedback paths to attenuate the signal at the structural frequencies has a major drawback because of the increase in phase lag, with negative consequences on the system's stability margins.

As the stability margins are rapidly eroded with increasing levels of basic instability, additional lags are to be minimized as they could result in a limitation in maximum allowable instability with penalties on the overall aircraft performance.

This matter has just been touched here as an example of the level of integration of the various aspects of the design and the implications on the overall vehicle's performances.

2.3 Handling Qualities

The other key aspect of an FCS design is that of Handling Qualities.

"Good" Handling Qualities normally imply that the response of the aircraft to a pilot's input is immediate, fast and well damped so that he can control the aircraft easily and precisely.

2.3.1 Handling Qualities Levels

Current military specifications define three "Levels" of Handling Qualities.

Level 1 requirements are the desired goal for normal operations throughout all mission phases.

Level 2 requirements are typically intended for failure situations resulting in degraded system's performance and Level 3 requirements to allow safe flight in emergency situations.

Today's fail operational fly-by-wire control systems are designed to provide Level 1 handling qualities even when a failure is present in the primary system.

Level 2 requirements are normally used for back up systems, operating after multiple failures of the primary system.

Recently, and additional level of H.Q. has been defined as "Level 1*".

This level is associated with handling qualities optimum for the task, requiring minimum pilot's workload.

2.3.2 Current Trends

Active Control Technology has influenced the Handling Qualities aspect of the design in several ways: new, unprecedented possibilities of shaping the aircraft response, new modes of operation of the aircraft, and also unexpected problems have highlightes in these recent years the need for a significant research effort in this field.

It is well outside the scope of this paper to approach the overall problem, but it is worthwhile to give an indication of the current areas which have been identified for future work (ref. 3). There are:

- Handling Qualities criteria for unstable aircraft
- Task Tailored Handling Qualities
- Combined manoeuvres Handling Qualities.

2.3.2.1 H.Q. For Highly Unstable Aircraft

Application of Active Control Technology offers a significant potential to provide handling qualities superior to conventional aircraft.

However, early applications have been some times disappointing as a large proportion of Fly by wire aircraft has shown poor handling characteristics, with sluggish responses and pilot-induced oscillations (PIO) in both pitch and roll axis (ref. 4).

Response of the aircraft to pilot's inputs is now dominated by the FCS with additional response modes: both long and short term response characteristics differ from traditional aircraft, essentially dictated by aerodynamics.

These problems have shown the inadequacy of traditional "low order" requirements when applied to highly augmented system of much higher order.

An example of the problems occurred on early generation FBW aircraft is the PIO case (ref. 5). PIO characteristics are determined largely by the frequency response around 180 degrees phase lag.

The essential difference between low and high order systems is shown in fig. 6, showing the attitude to stick force frequency response.

Three factors contribute to increase the probability of occurrence of PIO's:

- Low crossover frequency
- High aircraft gain
- Rapid increase of lag vs. frequency.

Traditional criteria, as those offered by ref. 6 fail to identify potential areas of problems; new criteria have been developed using experience gained in early FBW design and have been used with success to design out PIO tendencies also in highly unstable aircraft.

2.3.2.2 Task Tailored H.Q.

Flight Control Systems design for the generation of aircraft currently in service have been developed to give Level 1 Handling Qualities for all the range of flight tasks.

The need to cover with a single set of control laws different tasks results in a compromise of dynamics characteristics, with some tasks not being covered optimally.

The ideal level 1* of H.Q. is then reached only for determined tasks and not throughout the mission.

By "Task Tailoring" the dynamic behaviour of the aircraft can be adjusted to the extend that the minimum amount of pilot's compensation is needed for each major mission phase/task.

Such a feature is reasonably feasible within the current Hardware/Software Technology and the FCS designers have the means to provide for almost any set of task-tailored H.Q. characteristics of the aerodynamic and system constrains of the aircraft configuration.

Significant results have already been obtained by specialised research programs in the USA and in Europe.

Much more research work is still needed to built up the required data base for comprehensive criteria, as up to now "task tailored Handling Quality Criteria" have not yet even developed to the extent to be usable as guidelines for the design of a production aircraft.

2.3.2.3 Combined Manoeuvres

One additional point of concern is that of Handling Qualities for combined (multi axis) manoeuvres.

Current Handling Qualities criteria are valid for single axis manoeuvres only, with the assumptions that Level 1 is provided for the other axis.

As modern FCS allow full up of the control in all axis at the same time, inter-axis coupling effects cannot be any more neglected.

So far, no specific criteria exists to help the designer in the assessment of the system, other than the fulfilment of performance and loads requirements.

3 CAREFREE MANOEUVRING

Carefree manoeuvring is one of the main requirements for tomorrow's advanced fighters.

The importance of such a requirements cannot be overestimated: the combat scenario for the 2000 and beyond will be so demanding on the pilot that his full attention will be dedicated to monitor the tactical situation and manage his weapon system.

The task of actually "flying" the aeroplane should involve a minimum of pilot's workload, in order not to affect negatively the mission effectiveness.

As seen in chapter 2.3, handling qualities play a major role in defining the pilot's workload in the various mission's tasks, but they do not give a full picture.

Additional workload is put on the pilot when he has to observe limitations in the control's inputs to respect the handling and loading boundaries appropriate to the current aircraft configuration and flight condition.

The capabilities of a modern FCS can provide an automatic limitation of aircraft response in order to allow the pilot free use of the stick and the pedals, with no danger of departures or overstressing of the airframe. In this chapter some indications of the specific features of the FCS control law are given as an example of a possible implementation. Carefree manoeuvring is a very broad requirement, involving several areas of a design (FCS, engine, cockpit etc.), here mainly the FCS functions related to the structural aspects are considered.

3.1 FCS Design Features

Main features of a Flight Control System to provide a carefree manoeuvring capability can be briefly specified as follows:

- Automatic protection of stall departure and spin, including incidence control/limiting for both positive and negative incidences
- g onset limitation to improve the protection of the pilot against sudden loss of consciousness
- Automatic protection against exceedance of handling/loading boundaries for all combinations of pilot's inputs, including crossed controls
- Normal g control/limiting for both positive and negative g, to allow full use of the manoeuvre capability without overstressing.

The first two points listed here are mainly related to the handling aspects. The other two points are instead directly related to the structural design of the aircraft (see chapter 3).

3.2 Control Laws for Carefree Manoeuvring

The constituent functions of a typical flight control system that provide carefree pitch and lateral manoeuvre capability are described as an example of a possible implementation.

3.2.1 Longitudinal Axis

The pitch control system can be divided into two main parts: low speed and high speed. In the high speed region, normal load factor limiting is achieved with a g-demand system. The functional component of such a system are shown in fig. 7.

An error signal, given by the difference between the demanded g and the measured g, is fed to an integrator, the output of which is used as a position demand signal for the pitch control surfaces, thus driving the error to zero. Normal load factor limiting is achieved by assigning values of the positive and negative incidence limits to the g-demand signal associated with full aft and full forward stick travel.

3.2.1.1 Pitch Stick

The pitch stick together with manoeuvre limiting functions relating stick displacement to the g-demand signals are shown in fig. 8.

A range of stick travel aft of the normal back stop is provided to allow the pilot to override the g-limit in an emergency such as collision avoidance. Stick forces to enter the override, however, are significantly higher than at the normal back stop to avoid inadvertent exceedance of the g-limit.

Since the pilot can not be expected to control g when operating in the override, due to the relatively high break-out forces, max g demand in this region must be limited to values below the ultimate load factor. The value of the new limit is a matter of concern for structural designers, as damage to the structure may be expected.

3.2.1.2 Stick Filter

Filtering of the Stick pitch filter is powerful way to modify the aeroplane's handling qualities without affecting the inner (stability) loop.

Non-linear filtering of the stick signal can be used to provide a fast response for small stick inputs and a shower well damped response for full amplitude inputs to avoid overshoots in the maximum g.

3.2.1.3 Rate Limit

The rate limit is one of the key elements in allowing combined pitch/roll inputs to be performed respecting the handling/loading boundaries.

The pitch stick signal is rate limited in the software to prevent:

- Control surface rate saturation
- excessive pitch acceleration in push (pull manoeuvres)
- excessive g-onset rates

The rate limit in the pitch command path can be scheduled with lateral stick position (fig. 9) to give lower g-onset rates (and lower $\dot{q}$) at high roll rates.

This schedule is intended to prevent:

- Exceedance of the airframe boundary associated with ($\dot{q}$ - pr) due to pitching manoeuvres superimposed with high α roll manoeuvres.
- High energy spin entry caused by comgined roll/pull manoeuvres.
- Autorotation caused by combined roll/push manoeuvres.

Reduced g-onset in pulls and pushes from rolling manoeuvres will allow time for the lateral control laws to reduce roll rate to respect the roll/normal acceleration load boundaries.

3.2.1.4 Demand Gain

The demand gains at high speed are set to a value corresponding to the maximum normal load factor applicable to the specific flight condition (fig. 10).

Max normal load factors limits are normally valid for an aircraft mass at or lower than the design stressing mass. This means that the limits need to be scheduled with the current aircraft mass, to avoid overstressing or loss in performance.

3.2.2 Lateral Axis

Principle of operation of a typical lateral control system is shown in fig. 11.

A roll rate demand type of controller is normally used, with a gain or a function in the lateral stick path relating stick displacement to a p-demand signal.

3.2.2.1 Lateral Stick

A typical roll stick force/displacement characteristics is parabolic, to give sufficient pilot ratings and to prevent lateral PIO tendency in connection with small inputs.

No override capability is provided as an increased roll rate does not have any advantage under emergency conditions.

3.2.2.2 Rate Limit

A Rate limit in the lateral stick path may be included to improve handling qualities and reduce peak accelerations at initiation of the manoeuvre.

3.2.2.3 Demand Gain

As in the pitch axis, the demand gain plays a major role in the implementation of the carefree manoeuvring function (fig. 12).

Scheduling parameters of the maximum demanded roll rate are:

- Dynamic pressure
- Incidence
- Normal load factor.

Scheduling with dynamic pressure must ensure that at low speed the demand does not exceed the available roll rate commensurate with the reduced control power, not to drive the surfaces to their end stop.

Maximum demanded roll rate is also reduced at the upper and lower extremes of the incidence range to avoid autorotation or uncontrollable pitch-ups due to inertial coupling.

Normal load factor scheduling can be specially suited to respect the appropriate load boundaries.

3.2.3 Yaw Axis

The principle function of the yaw axis controller with regards to carefree manoeuvring is to limit the amount of sideslip that can be generated by pedal inputs to the rudder (fig. 13). The primary scheduling parameters on pedal authority are dynamic pressure, incidence and normal acceleration.

Maximum demanded sideslip is scheduled according to an inverse dynamic pressure law to respect the load boundary. Pedal authority is reduced as the incidence limits are approached to prevent loss of control (fig. 14).

3.3 Integrity Aspects

The Carefree Manoeuvring feature of an FCS is intended to provide a relief of pilot's workload, providing an automatic limitation of the aeroplane's response to his inputs.

In conventional aeroplanes, this has to be done by the pilot, who has to adjust his inputs as a function of the flight condition and of the store configuration.

Loss of the carefree manoeuvring function must then be considered only with regard to to pilot's workload, as no performance losses are involved and the operational mission can be fulfilled.

The essential requirement is the identification of any failure leading to the loss of the function, after which the pilot will have to be warned as he has now to respect the limits.

Two main types of failures can be identified:

- failures internal to the FCS, leading to some reversionary mode of control
- failures in the identification of the appropriate limits to apply.

In the first case, the FCS looses the capability to control adequately the aircraft response due, for example to the loss of the incidence signal.

This will normally occur only after multiple failures in the sensors or in the computing system of the aircraft and this type of failure will in any case be detected, and therefore a warning can be given to the pilot.

The FCS can in this case revert to a back-up mode, based on a reduced number of sensors, to allow safe flying, but normally such functions as carefree manoeuvring are lost.

In the second case, the FCS is still fully operational but the identification of the actual limits applicable is lost.

The definition of the applicable limits is a very complex task, involving identification of the aircraft mass and of the store configuration.

These information relay on several sensors, normally external to the FCS, whose requirements are normally not as severe as dictated by this specific application.

An unidentified failure could have safety implications, e.g. if it would result in a false mass indication, allowing the FCS a maximum load factor demand, higher than the maximum allowable for the specific case.

It is essential that all the systems involved in the computation of the applicable manoeuvre limitation have a very low probability of not detecting a failure (indicatively $1 \cdot 10^{-7}$).

4 STRUCTURAL DESIGN CRITERIA

The application of existing military specifications for structural design of modern fighter aircraft no longer is as clear as in the past. E.g. MIL-A-008861A defined a variety of "single axis" pitch, roll, yaw, gust, spin and engine setting manoeuvres which have been proven to be appropriate for covering the operational use of military aircraft. By relying on those "clinical manoeuvres" the designer didn't necessarily need to deal with numerous different operational manoeuvres but could concentrate on the investigation of the well defined flight conditions only.

The Flight Control Systems (FCS) of modern fighters are now aimed for "carefree handling" features allowing superposition of arbitrary combined pilot control inputs in roll, pitch and yaw. Whilst the French AIR-2004 as well as the British DEF-STANs do not contain any advice on the use of combined manoeuvres the latest US-MIL-Specs as MIL-A-87221(USAF) and MIL-A-8861B (AS) at least adopted some new requirements as:

- o Input of all longitudinal, lateral and directional controls
- o Ground Target Tracking
- o Jinking manoeuvres
- o Missile break manoeuvres

It must be emphasized however, that a verbal description of course touches the problem but no advice is given about the procedure how to produce time histories by pilot inputs in a way to cover a wide range of operationally meaningful manoeuvres like the former "clinical manoeuvres".

4.1 Design Features for Major Aircraft Components

Fig. 14 shows typical design envelopes for the attachment of the major aircraft components front/rear fuselage and wing (ref. 7).

Whilst front and rear fuselage are mainly inertia dominated with respect to up/down loads the lateral loading at these components and the wing are dominated by aerodynamics. Which response parameters can now be based for design, possibly in an initial phase without knowledge of FCS and the resulting design manoeuvre time histories:

- o Max/min 'g' for symm. and unsymmetrical manoeuvres at the aircraft c.g. is given as an initial design value.
- o Max. local 'g' result from consideration of the additional increments from the Euler equations, mainly $n_z = (\dot{q} - p \cdot r) \cdot x/g$ and $n_y = (\dot{r} + p \cdot q) \cdot x/g$
- o Aerodynamics are caused mainly by the angle of attack, angle of sideslip and control deflections.
  - Angles of attack can be derived by simple trim calculations (using e.g. for a delta canard configuration different foreplane settings optimized in agreement with handling aspects).
  - Sideslip angles can be taken as a first guess by using the MIL-Spec Gust and possibly Fuselage-Aiming-Modes (FAM) requirements ($\beta \cdot q_{max}$, $n_{y\ max}$)
  - Control deflections may be assessed by a one degree of freedom consideration:
    - a) from the aerolastic max. roll rate requirement in order to achieve diff. flap or tailplane angles or
    - b) from threshold values of pitch and yaw accelerations in order to achieve foreplane, trailing edge flap/tailplane and rudder deflections or combinations thereof.

      Mainly in the early beginning of an aircraft project it is an iterative process between handling system and structural designers to validate the different results without incorporating too much conservatism in the assessments of design loads which could imply unacceptable mass penalties.

4.2 Design Response Parameter Boundaries

As assigned in the foregoing paragraph the response parameter boundaries as shown in Fig. 15 play - along with the aerodynamic features $\alpha \cdot q_{max}$, $\beta \cdot q_{max}$ - the important role for the derivation of the initial design of major components:

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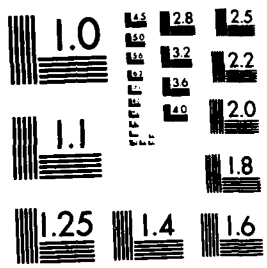
1.0
1.1
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1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0

- n_z vs. q-pr — for vertical bending of front and rear fuselage as well as for derivation of control deflections (mainly pitch)
- n_y vs. r+p·q — for laterals as above
- n_z vs. p... — for combination of pitch and roll cases
- acceleration vs rate — as a measure for combining rates with accelerations (mainly for external stores attachment design).

4.3 Satisfaction of Structural Requirements during FCS Design

The derivation of initial design loads is related, as explained, to a set of simplified assumptions which have to be verified continuously during the definition phase by an interdisciplinary process.

In detail the following points of interest are to be monitored and assured by checking aircraft handling, performance and agility requirements:

- For a possible reduction of pilot related contribution of ultimate safety factors in context with the "carefree handling" features control max./min 'g' limitations by FCS (overshoot and 'g'-recovery).
- Verify the response parameter boundaries of Fig. 15 by proper FCS layout or at least by continuous monitoring during definition work.
- Verify flap/foreplane schedules and manoeuvre load alleviation features (as diff. trailing edge flaps o/b to i/b wing) to be optimal.
- Assess overpull capability for emergency cases from structural fall out investigations.
- Try to find procedures in order to find and demonstrate actually critical pilot inputs at design conditions (Altitude, Mach, Manoeuvre combination) by flight test.

5 CONCLUSIONS

Integration of various disciplines is the key to the optimisation of a design.

In particular, integration of Flight Control System and Structural Design is feasible within the currently available technology to an extent which offers significant gains over traditional approaches to the design.

Realisation of Carefree Handling features by the FCS allows the application of Structural Design Criteria for safe structural design with significant reductions in structural mass.

The impact in the FCS design is an increase in complexity, both software and hardware, and finally an increase in the certification effort.

This is a price to be paid for the benefit of the overall aircraft performance, but is also a factor to be considered when new integrated functions are proposed.

The urgent need for updating of Design and Certification requirements in various areas, including Handling and Structural Design, is one of the major problems as current specifications are not directly applicable to aircraft incorporating advanced control technologies.

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The views contained herein, however, remain our own.

FIG. 1 - **Performance Benefit Due to Instability**

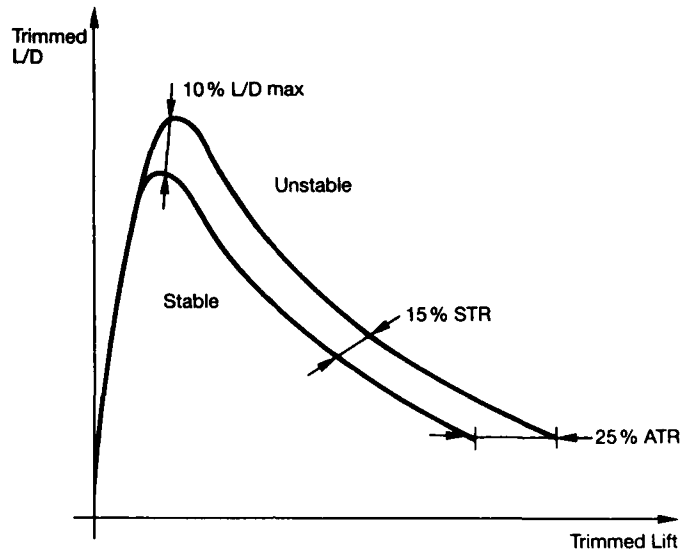


FIG.2 - **Performance Benefit Due to Wing Camber Scheduling**

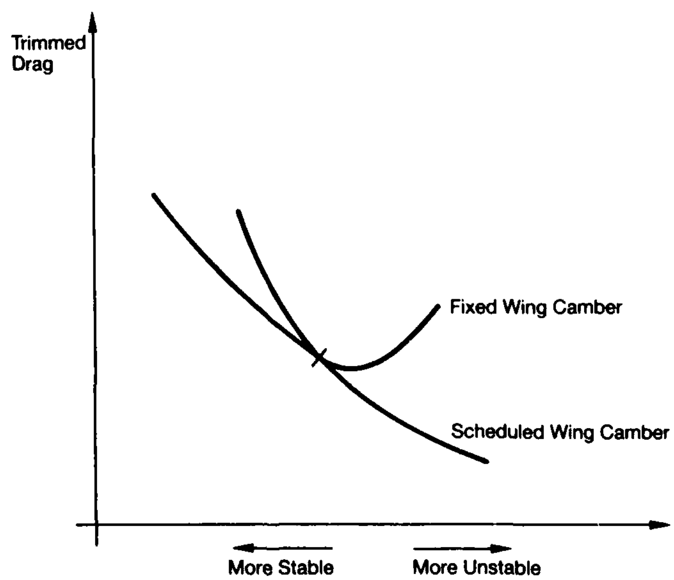


FIG. 3 - **Stability Margins**

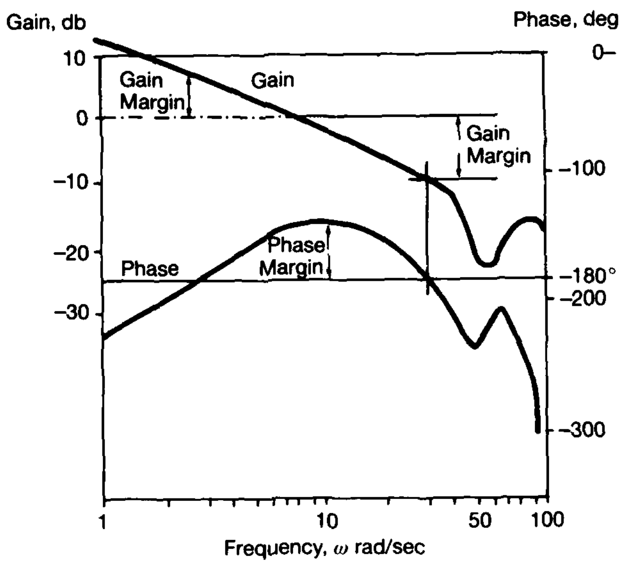


FIG. 4 - **High Order Components of the FCS**

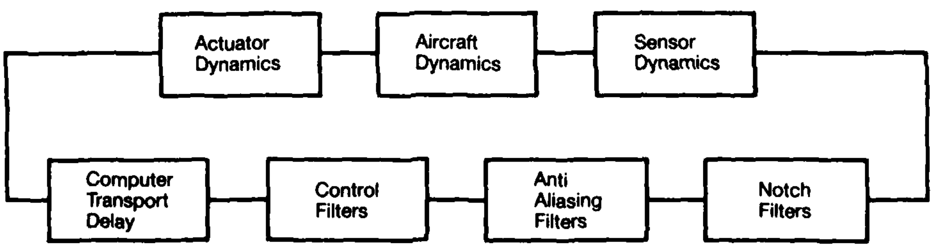


FIG.5 - **Impact of High Order Effects on System's Stability**

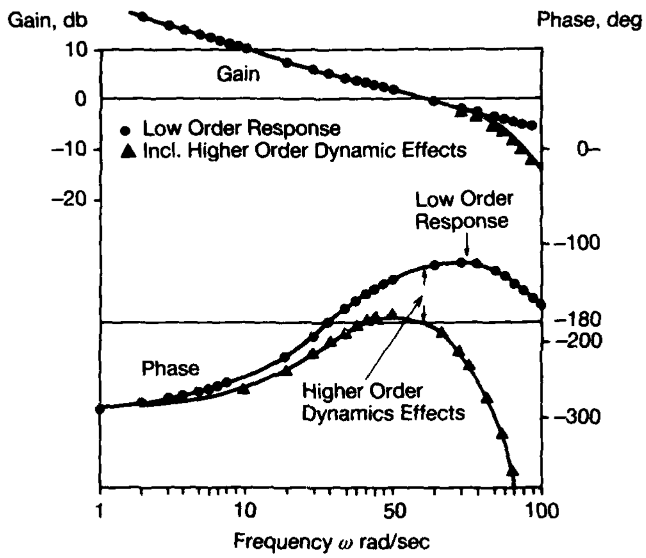


FIG.6 - **Attitude to Stick Force Frequency Response for Low and High Order FCS**

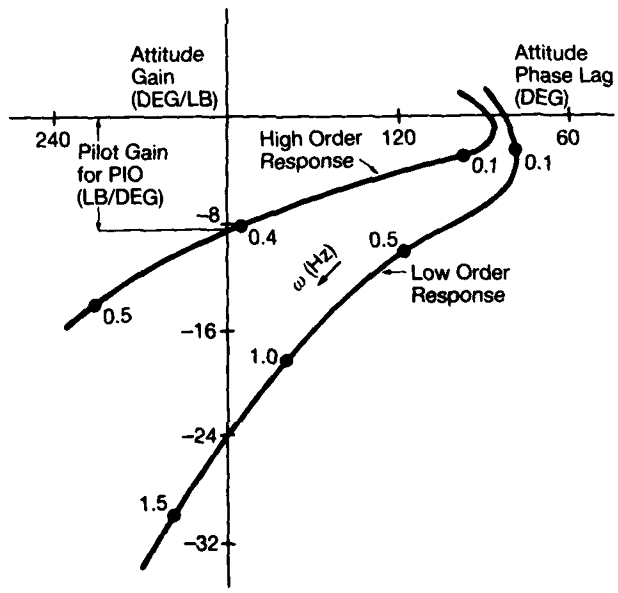


FIG.7 - **Control Laws Functions**

Longitudinal Axis

Manoeuvre limiting is achieved with a manoeuvre demand form of controller

Integral feed back provides precise control of normal load factor

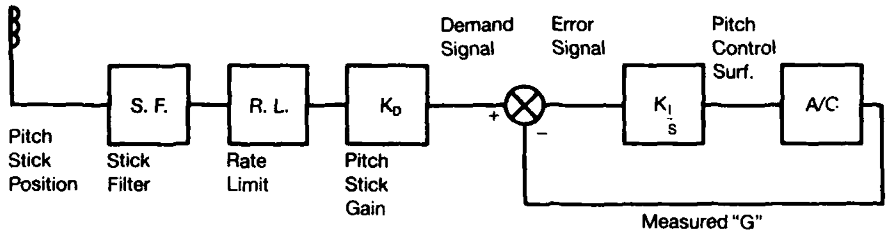


FIG.8 - **Control Laws Functions**

Stick Forces and Normal Load Factor Limit

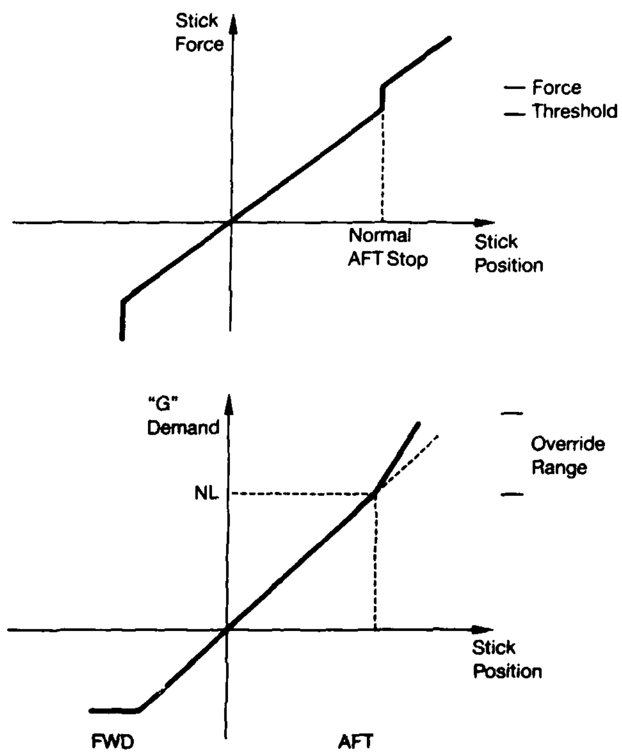


FIG. 9 - **Control Laws Functions**

Pitch FCS Rate Limit

FIG. 10 - **Control Laws Functions**

Normal Load Factor Demand Scheduling

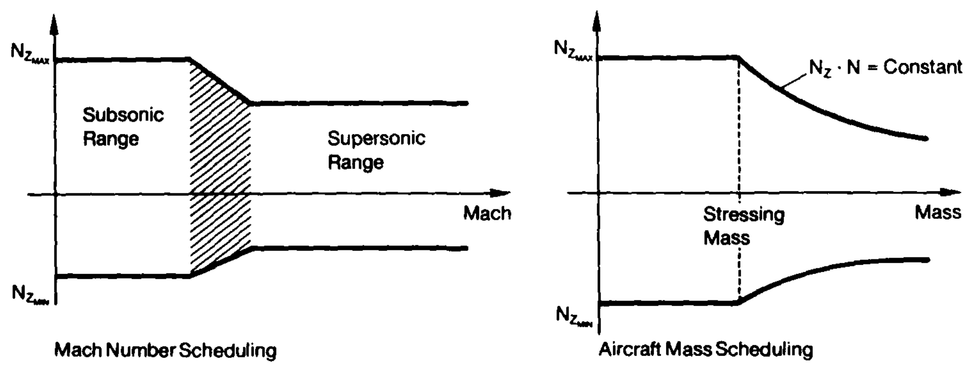


FIG. 11 - **Control Laws Functions**

Roll Axis

Roll rate control and limiting is achieved with a roll rate demand form of controller

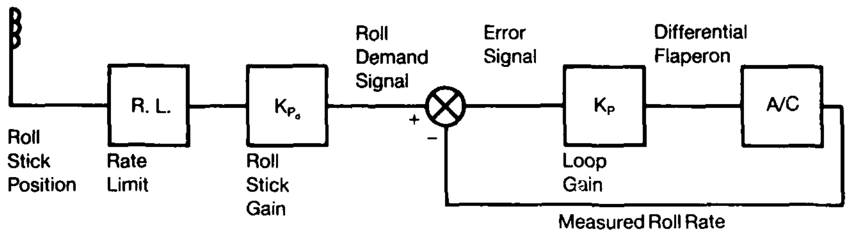
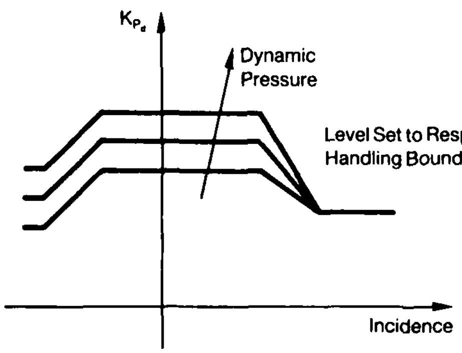


FIG. 12 - **Control Laws Functions**

Roll Axis – Roll Rate Demand Scheduling

Roll Rate vs Incidence



Roll Rate vs "G"

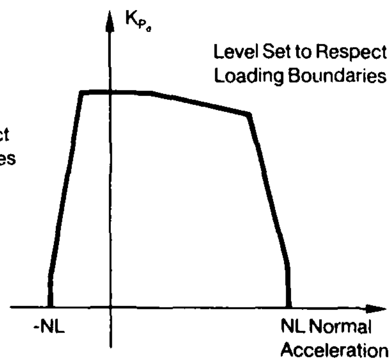


FIG.13 - **Control Laws Functions**

Yaw Axis

Sideslip limiting is achieved with a β-demand form of controller

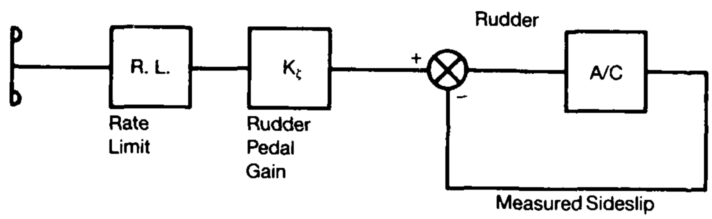
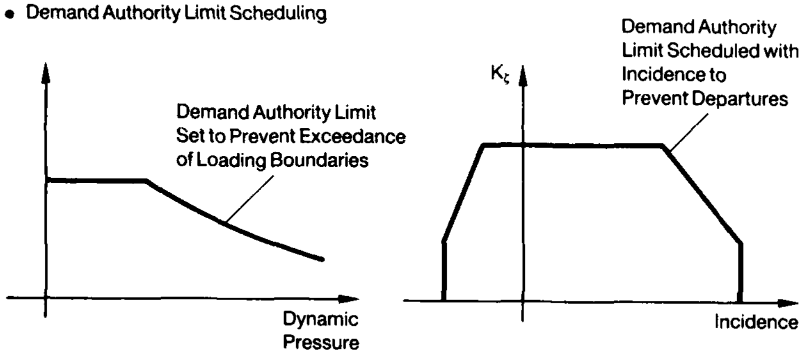


FIG.14 - **Control Laws Functions**

Yaw Axis

- Demand Authority Limit Scheduling

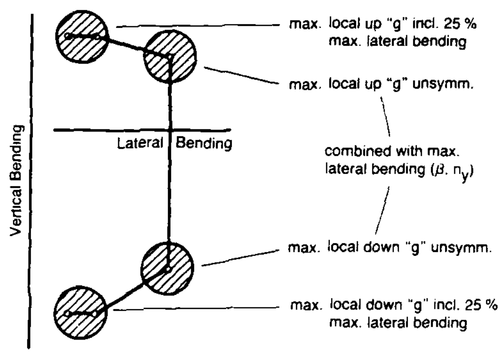


- Rate Limit

Rate Limit Value Set to Prevent Rudder Surface Rate Saturation

FIG.15 - **Major Aircraft Component Loads Envelopes**

Fuselage Loads Envelope at Front/Rear Manufacturing Joint



Wing Load Envelope

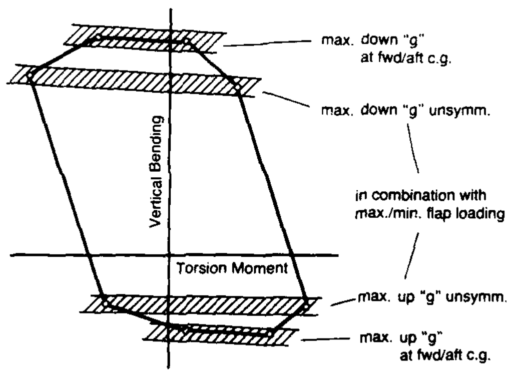
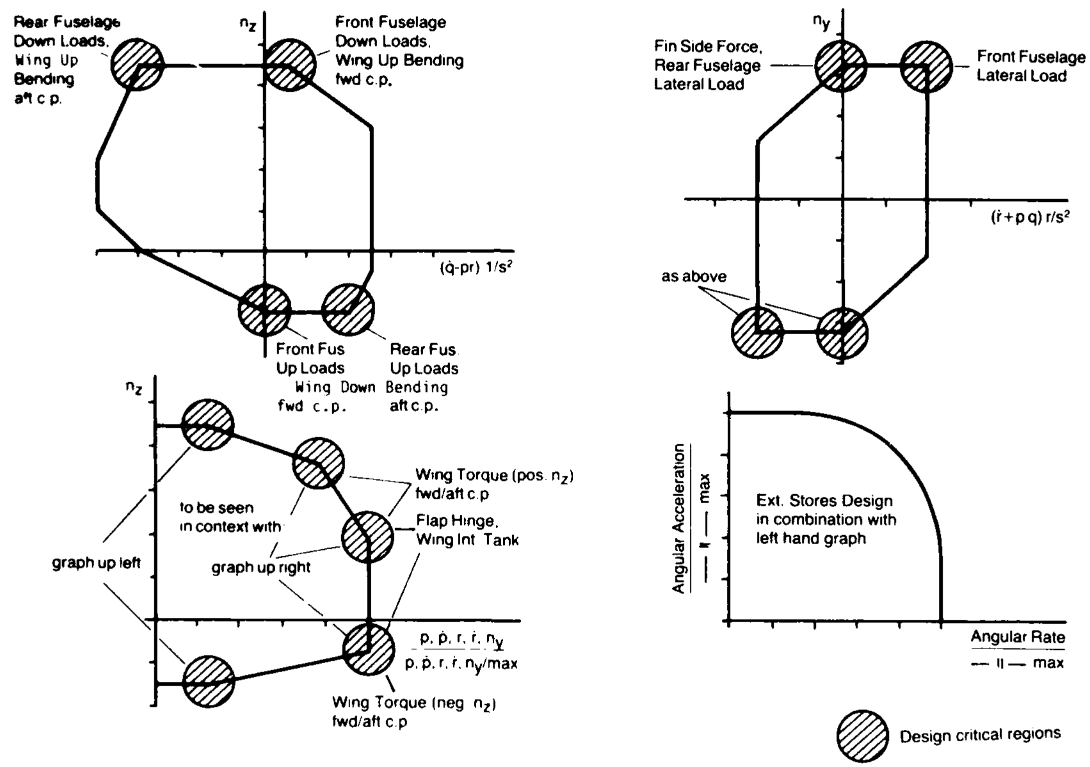


FIG.16 - **Flight Parameter Envelopes for Structural Design**



AD-P005 770

MANNED SIMULATION: HELPFUL MEANS TO DETERMINE AND IMPROVE STRUCTURAL LOAD CRITERIA

by

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SUMMARY

The load requirements in most specifications are based upon experience with previous aircraft and do not reflect the future potential needs arising from technology advances.

Since load assumptions of future aircraft have a great impact on weight, inservice time and flight performance, a manned combat simulation with future type aircraft, in the expected future combat scenario, can fill the gap between the load assumptions based upon the specifications and the actual spectrum of these assumptions in air combat.

In modern unstable aircraft the flight control system has to manage all limitations imposed by load assumptions. In this area a manned simulation can help to optimise the adaptation of the structure envelope to the actual flight and maneuver envelope under the aspect of carefree handling.

Manned simulation is the last step before real flight. Therefore the data obtained by simulation have to be correlated to real flight maneuvers from flight tests to increase the confidence level. With these correlated data the specification of the aircraft can be updated.

1. INTRODUCTION

For the development of future unstable combat aircraft an accurate determination of the structural load is required due to the impact on structural in weight in service time, and flight and mission performance of the aircraft. Under the requirement of minimum mass the structural envelope has to be adapted and optimised to the flight envelope and operational requirements, determined by the flight control system.

Since modern fighter aircraft are optimised in their requirements to certain combat tasks in a future aircombat scenario, the specifications (based upon experience) cannot define the most demanding load requirement in these future aircombat scenarios.

In this area a manned simulation with future aircraft in a future combat scenario can be helpful in finding the mission part with the greatest impact on structural loading and can help optimising the structural envelope to the operational envelope by documenting actual loads occurring in these future airfights.

2. MANNED SIMULATION AT IABG

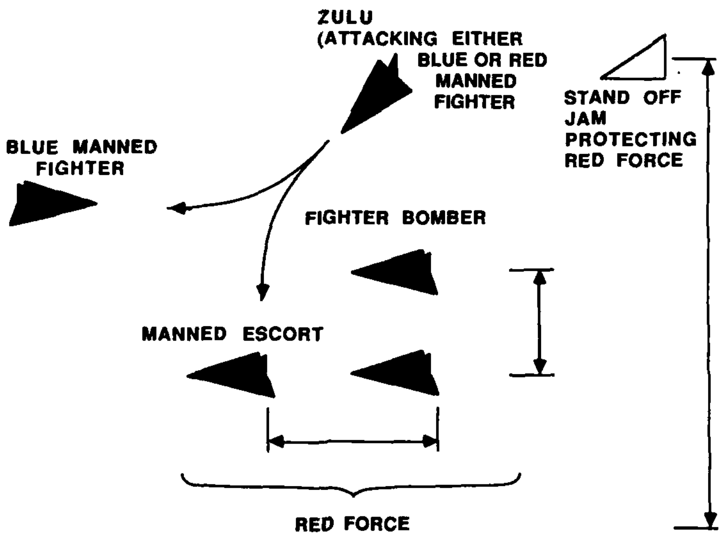
Manned combat simulation in the Dual Flight simulator (DFS) at IABG, Ottobrunn fulfils above mentioned requirements.

The further explanations aim at providing an impression of the evaluation capabilities of manned simulations using the DFS at IABG.

2.1 DFS SCENARIO

The scenario consists of two manned fighter, one computer driven fighter (ZULU) and two fighter bomber aircraft. The scenario represents next generation aircraft, weapons, todays avionics, and assumptions of tomorrows combat based upon an agreed scenario. These simulations can start from various types of starting conditions - short and medium range.

Fig. 1: Scenario



OPPONENTS

- **MANNED FIGHTER (BLUE)**
- **UNMANNED FIGHTER (BLUE OR RED)**
- **UNMANNED FIGHTERBOMBER (RED)**
- **MANNED ESCORT (RED)**

AVIONICS

- **A/A FUNCTIONS OF APG 65**
- **FIRE CONTROL APG 65**
- **RADAR WARNING RECEIVER**
- **IR WARNING RECEIVER**
- **IDENTIFICATION SYSTEM**

WEAPON

- **AMRAAM, AIM 9L+, GUN**

COUNTERMEASURES

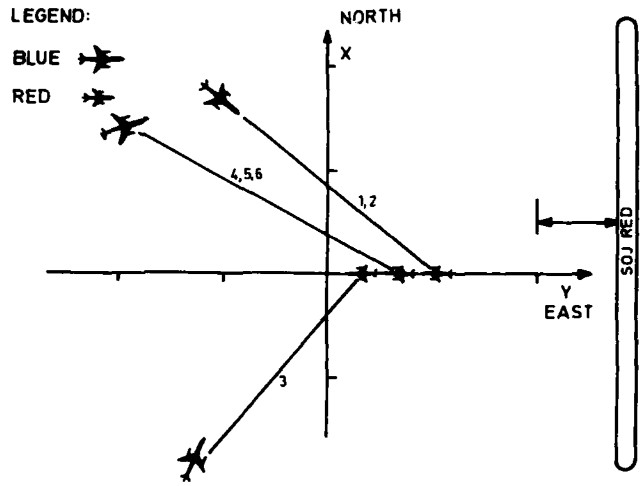
- **STAND OFF JAM**
- **DECEPTION JAMMER**
- **FLARES**

TACTICS

- **PRIMARY TARGETS FOR THE BLUE FIGHTER ARE THE FIGHTER BOMBERS.**
- **THE RED ESCORT HAS THE TASK TO PREVENT THAT HIS FIGHTER BOMBERS ARE BEING KILLED OR FORCED TO FLY HOME.**
- **THE RED ESCORT TACTIC WILL ONLY BE FIGHTER SWEEP.**

MEDIUM RANGE Starting Conditions
(Supersonic Airspeeds for Blue)

Fig. 2:



Short Range Starting Conditions Subsonic Starting Airspeeds

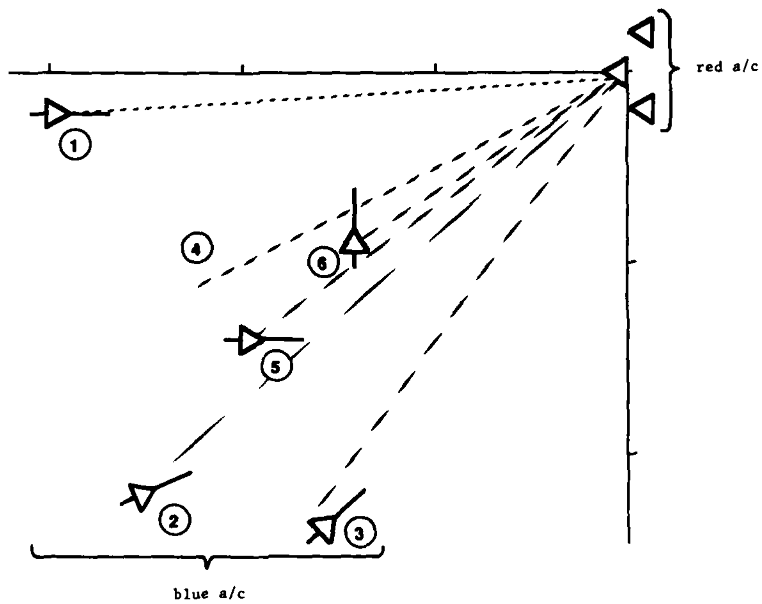


Fig. 3: Short Range Starting Conditions Subsonic Starting Airspeeds

2.2 DATA RECORDING

During the simulation a set of data is recorded every 50 m/sec, reflecting the pilot inputs (stick-, rudder-, and throttle-position), aircraft performance data (speeds, altitude, accelerations, decelerations p, p, q, q, r, r) as well as the movements of the control surfaces.

3. EVALUATION

In the past the DFS combat simulations have been used as a means to define the operational requirements for a future combat aircraft, and is now used for weapon system analysis based upon tomorrows combats. At least 144 air fights for one simulation case are flown by operational airforce pilots to have enough statistical data for the system analysis.

Since the simulation was used in the past to help define the operational requirements based upon future combats, it also can be used to record and analyse the occurrence of load factors in various types of aircombats.

3.1 EXAMPLES

The following examples show a small part of the evaluation which has been done in the past, and shall give an impression of the evaluation capability of manned simulation in the DFS.

3.1.1 G (NZ) LOADS IN DIFFERENT TYPES OF AIR COMBAT

The relative frequency of g (n_z) load was recorded independent of stressing mass considerations and shows only the frequency of load conditions which occured within the total airfight time of 144 airfights (symmetrical and unsymmetrical).

<u>Combat out of short range starting conditions</u>

Lower Performance Aircraft

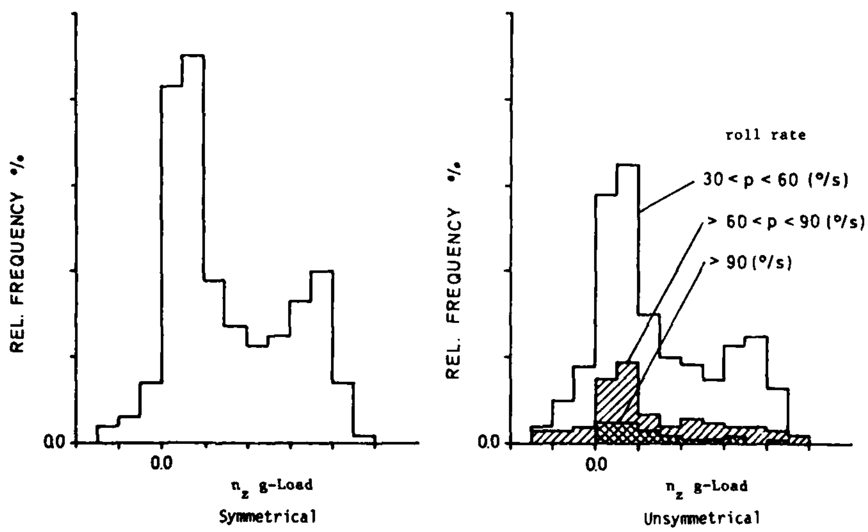


Fig. 4: g-load

High Performance Aircraft

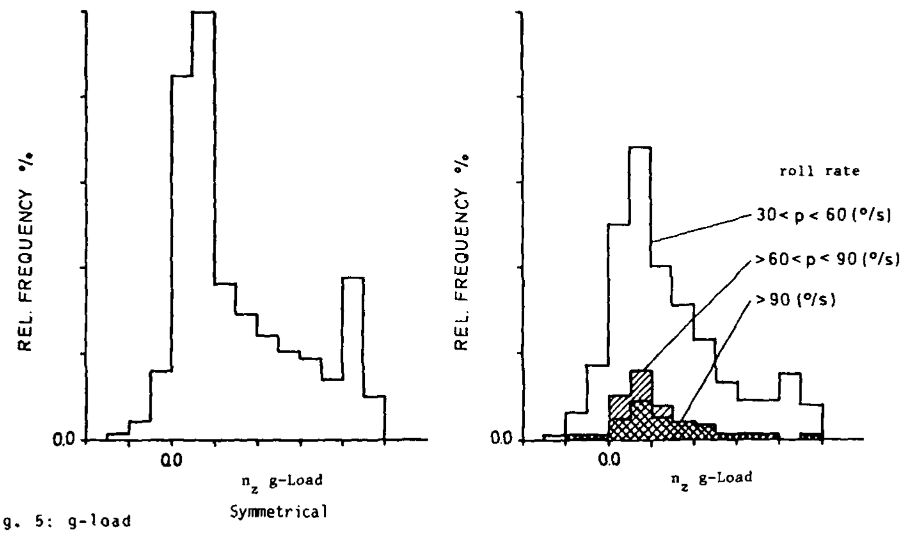


Fig. 5: g-load

The Lower Performance Aircraft shows a higher demand for high g loads (symmetrical and unsymmetrical) in airfights out of the short range combat scenario in the DFS (figure 4, 5).

<u>Combat out of medium range starting conditions</u>

High Performance Aircraft

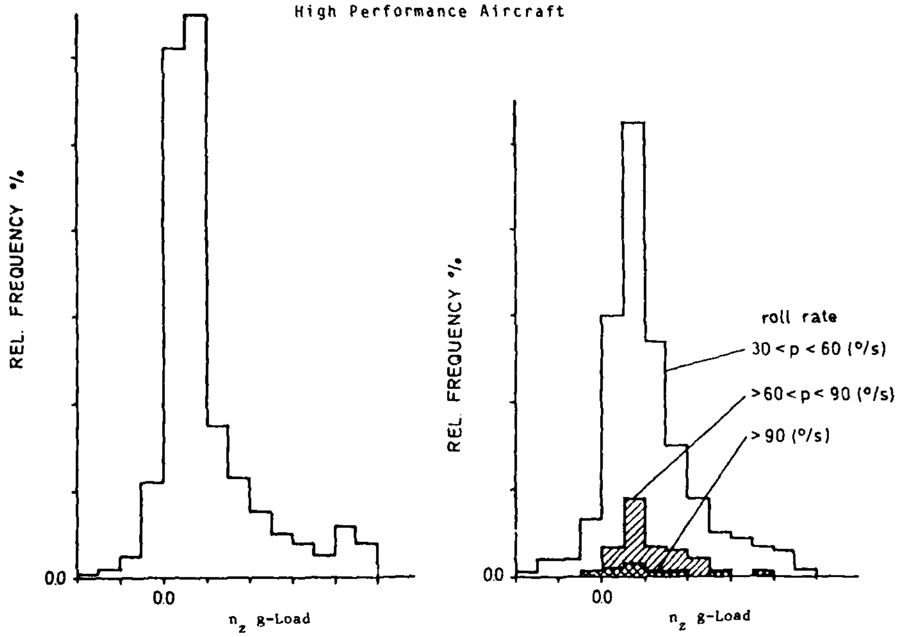


Fig. 6: g-load

The comparison of combats out of the short range starting conditions with the medium range starting conditions shows less demand for high g loads in supersonic medium range air combat (figure 5, 6).

All unsymmetrical load cases show a relatively high demand for rolling g loads, which have to be taken into consideration when designing a new fighter airplane (figures 4 - 6).

An additional evaluation of the following flight parameter envelopes for structural design has been made (figures 7 - 9).

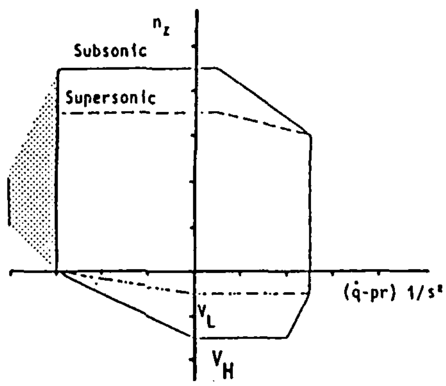


Fig. 7: Load Parameter

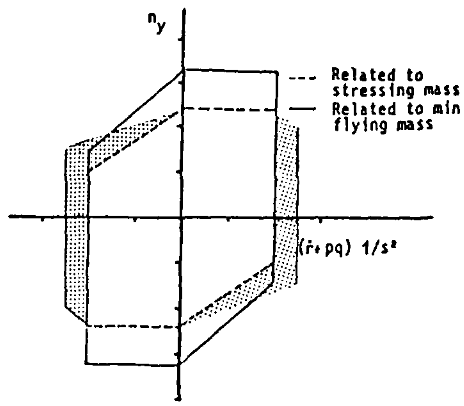


Fig. 8: Load Parameter

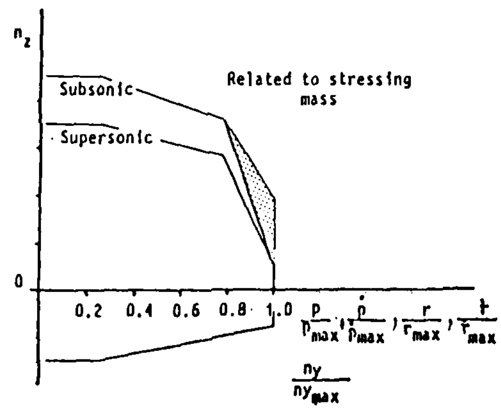


Fig. 9: Load Parameter

These recordings shall only be understood as an example of the evaluation capabilities of a manned simulation with respect to structural design.

The data do not reflect the most demanding mission of the aircraft with respect of structural design load.

Figures 10 - 23 show the occurrence of these parameters in theair fights. The positions inside the envelopes are marked by a dot at a sample rate described in the head line.

Fig. 10: FIGHTER BLUE, STRESSING MASS +/- 10 PERCENT
Sample Rate 2.500 (1/s)

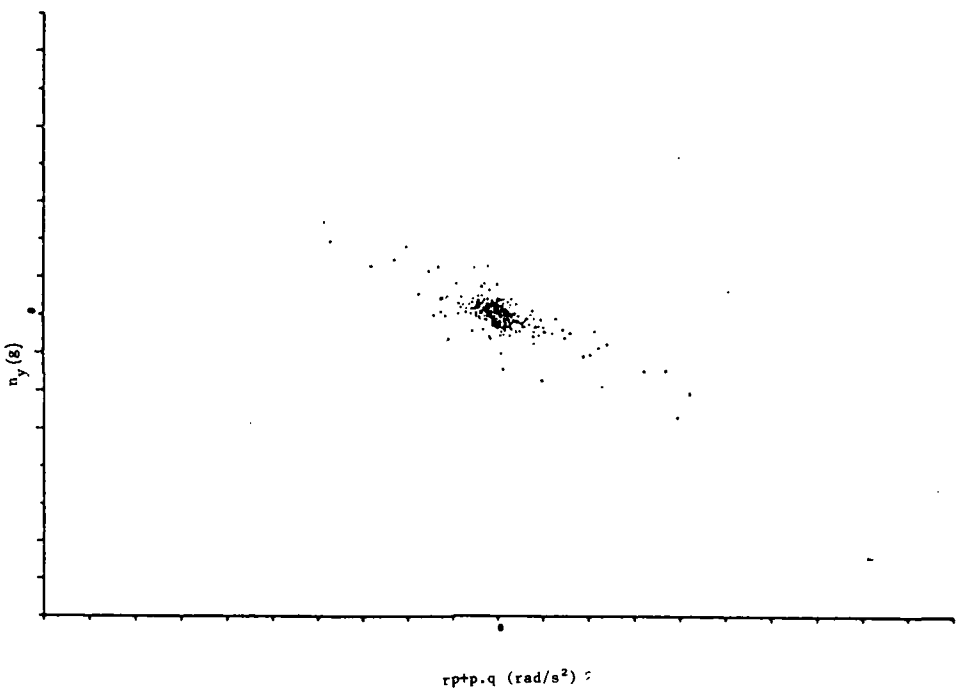


Fig. 11:

FIGHTER BLUE, SUBSONIC
Sample Rate 2.500 (1/s)

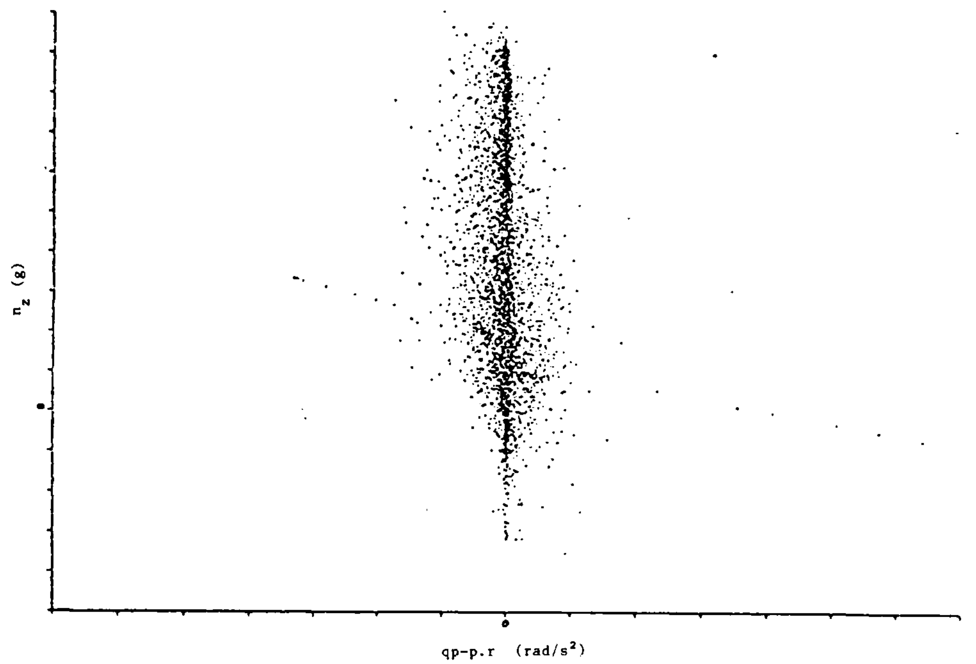


Fig. 12:

FIGHTER BLUE, SUPERSONIC
Sample Rate .125 (1/s)

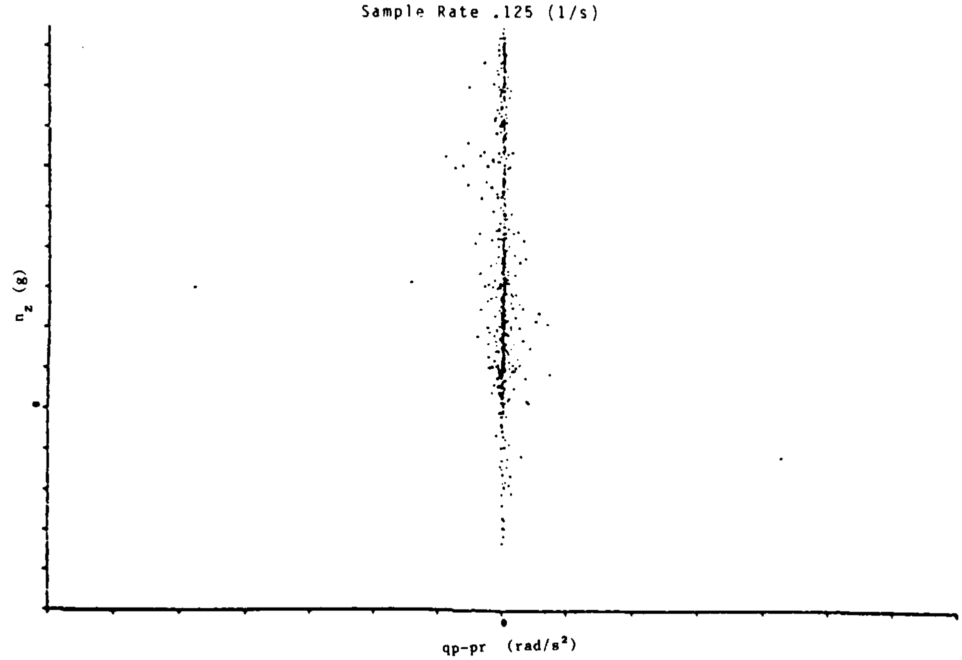


Fig. 13: FIGHTER BLUE, STRESS. MASS +/- 10 %, SUBSONIC
Sample Rate 1.250 /1/s)

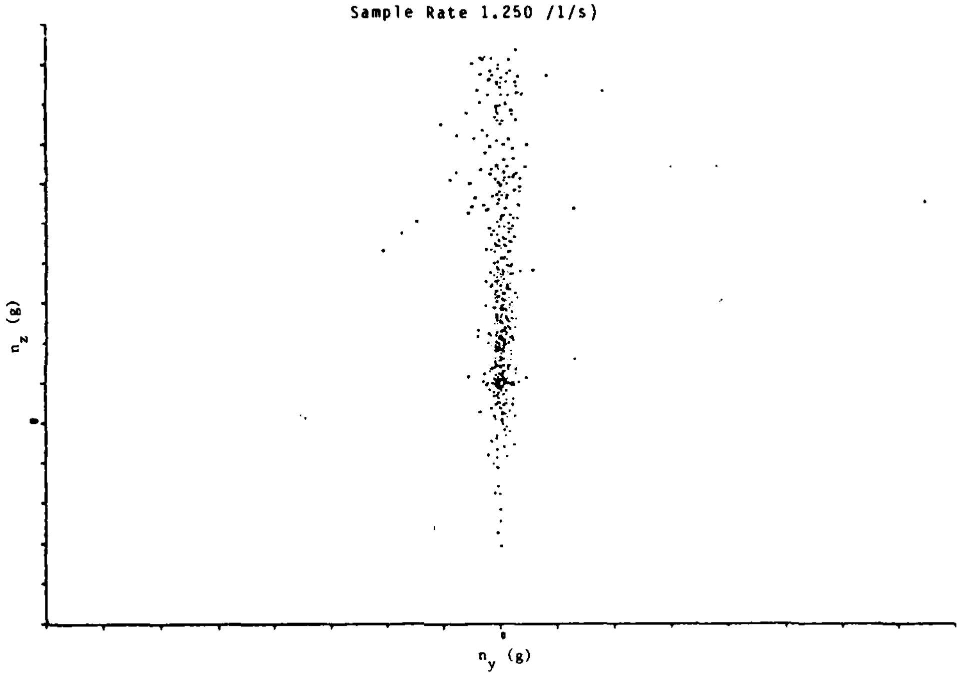


Fig. 14: FIGHTER BLUE, STRESS. MASS +/- 10 %, SUPERSONIC
Sample Rate 1.250 (1/s)

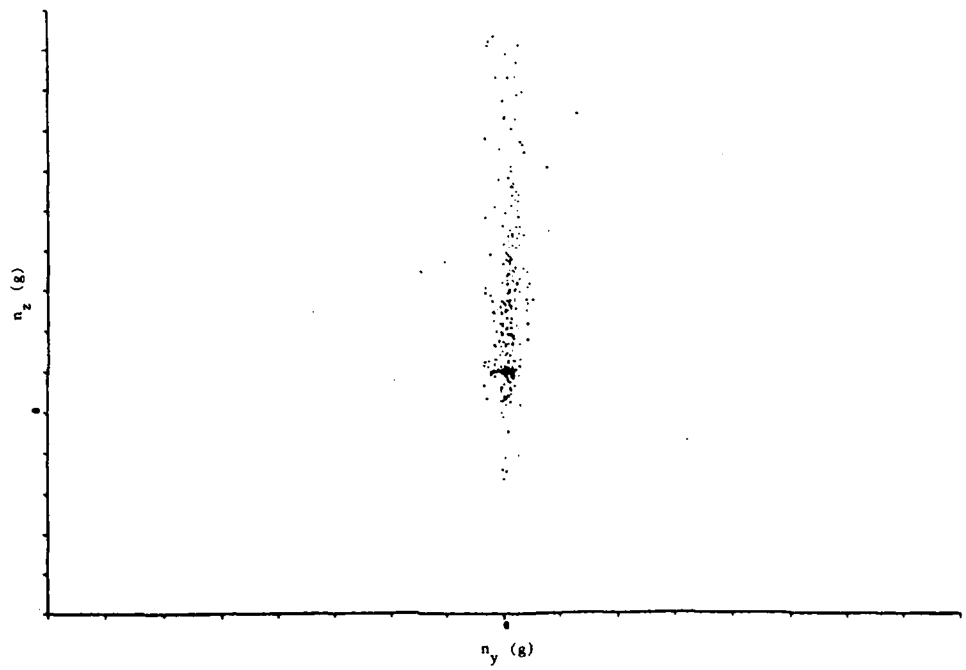


Fig. 15: FIGHTER BLUE, STRESS. MASS +/- 10 %, SUBSONIC
Sample Rate 1.250 (1/s)

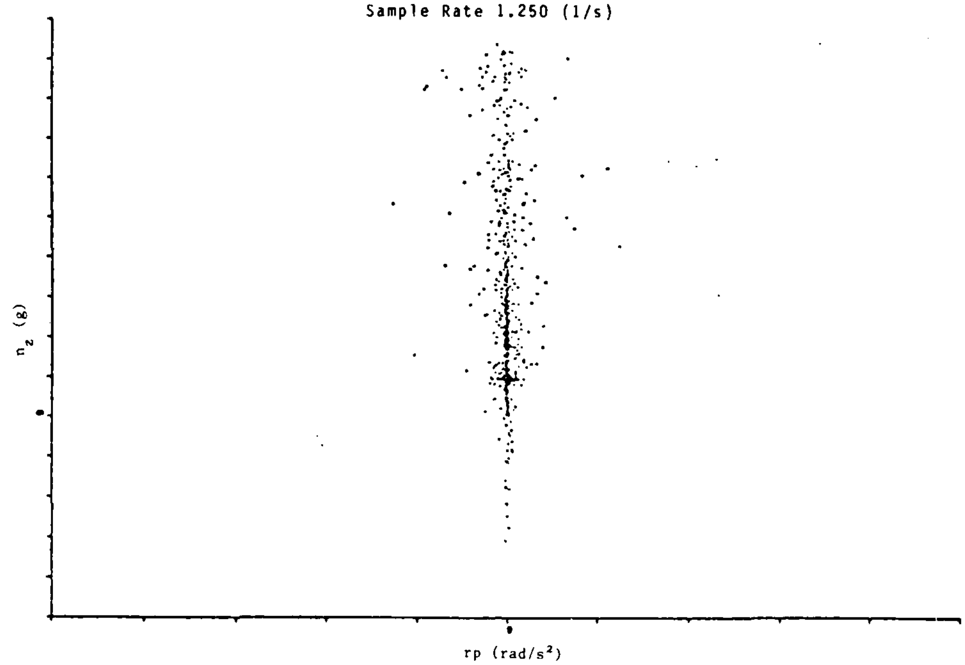


Fig. 16: FIGHTER BLUE, STRESS. MASS +/- 10 %, SUPERSONIC
Sample Rate 1.250 (1/s)

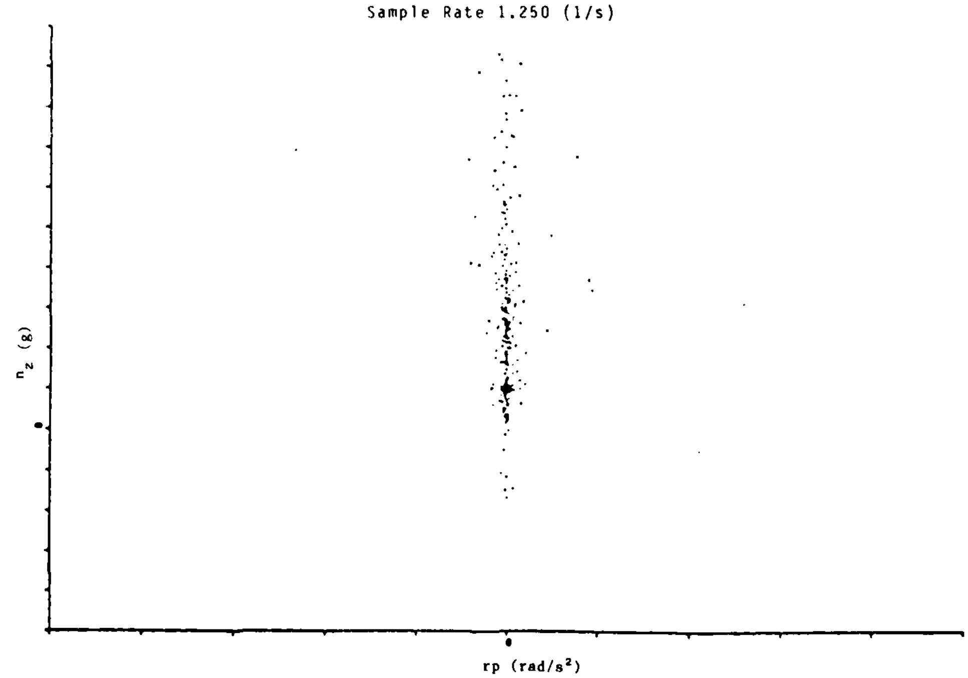


Fig. 17: FIGHTER BLUE, STRESS. MASS +/- 10 %, SUBSONIC
Sample Rate 1.250 (1/s)

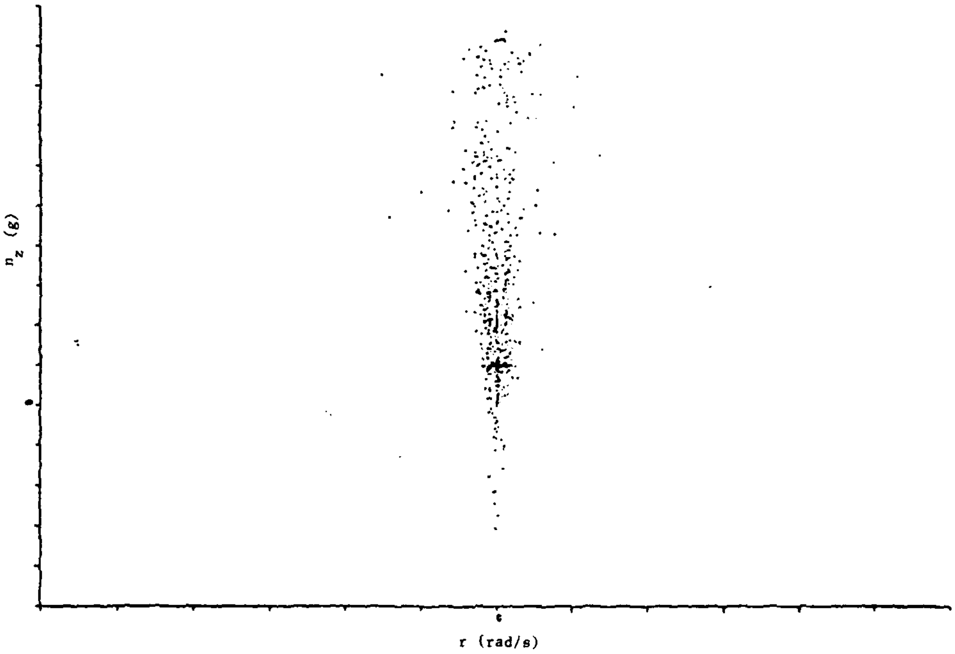


Fig. 18: FIGHTER BLUE, STRESS. MASS +/- 10 %, SUPERSONIC
Sample Rate 1.250 (1/s)

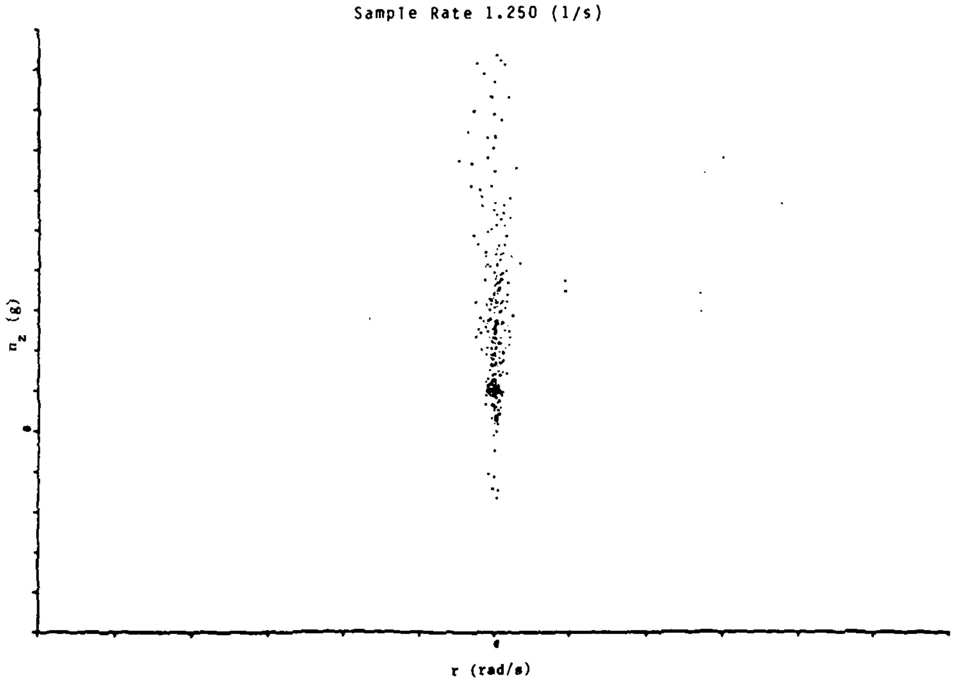


Fig. 19: FIGHTER BLUE, STRESS. MASS +/1 10 %, SUBSONIC
Sample Rate 1.250 (1/s)

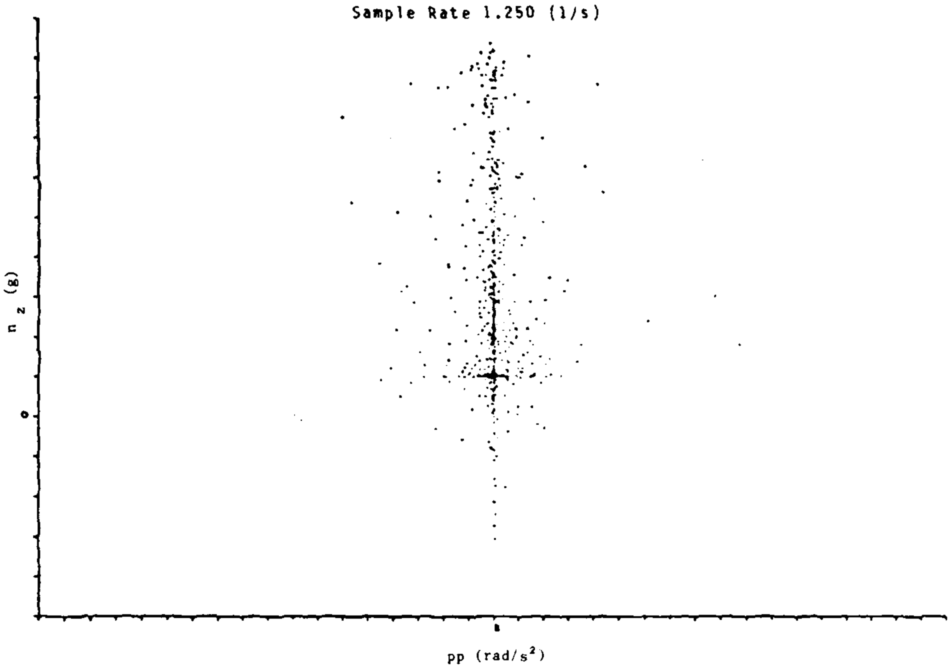


Fig. 20 FIGHTER BLUE, STRESS. MASS +/- 10 %, SUPERSONIC
Sample Rate 1.250 (1/s)

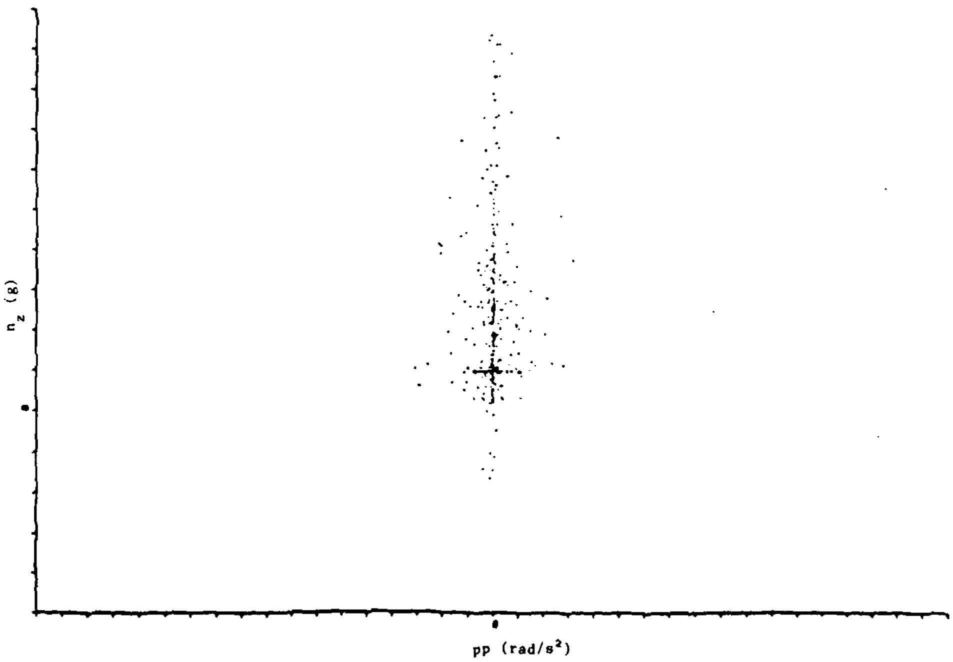


Fig. 21: FIGHTER BLUE, STRESS. MASS +/- 10 % SUBSONIC
Sample Rate 2.500 (1/s)

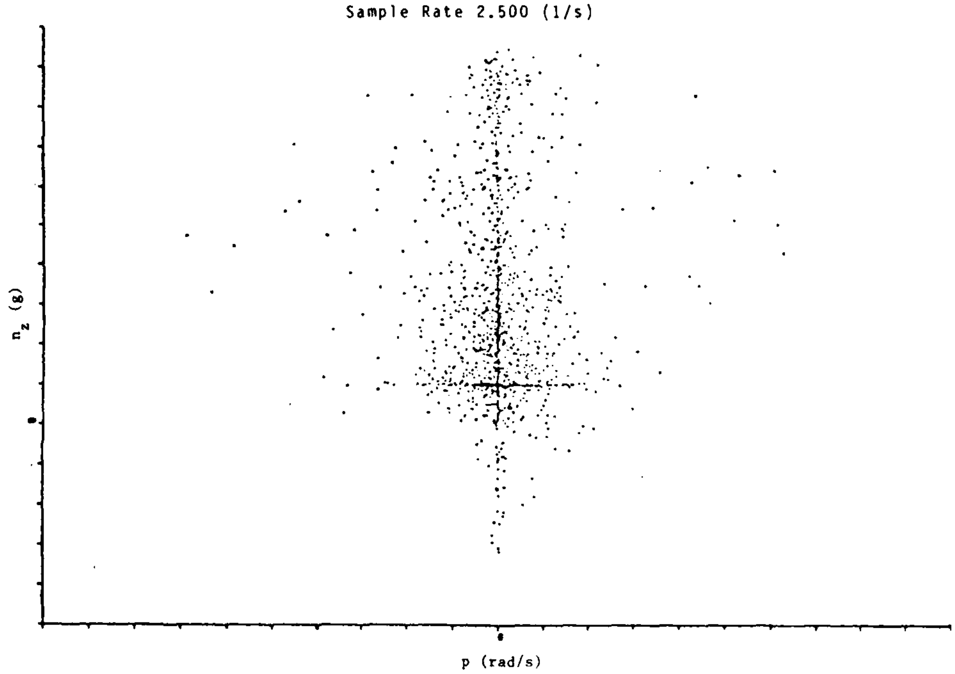


Fig. 22: FIGHTER BLUE, STRESS. MASS +/- 10 % SUPERSONIC
Sample Rate 1.250 (1/s)

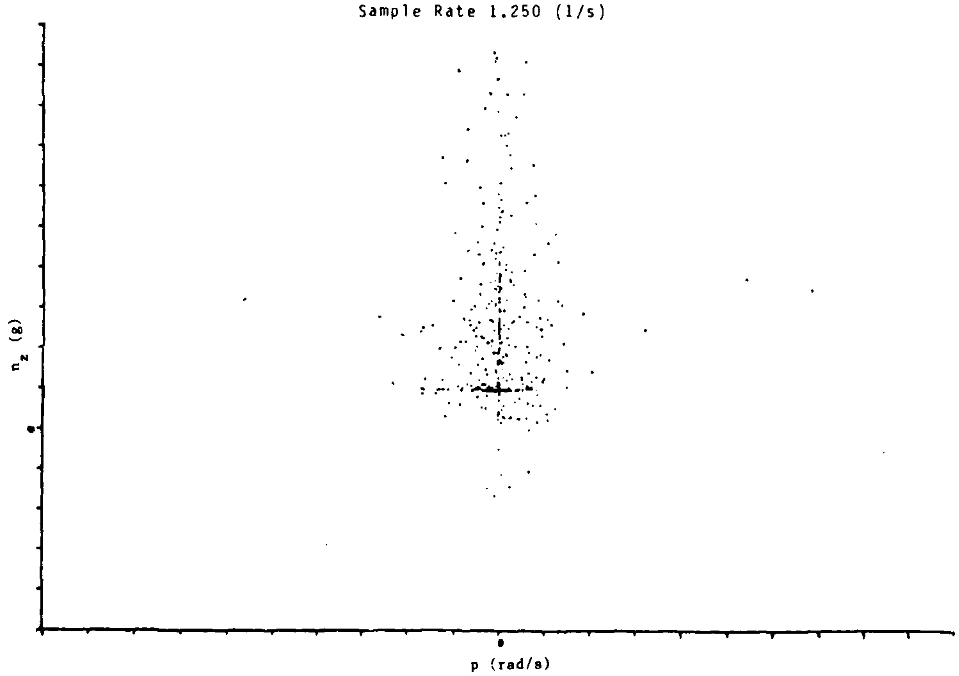
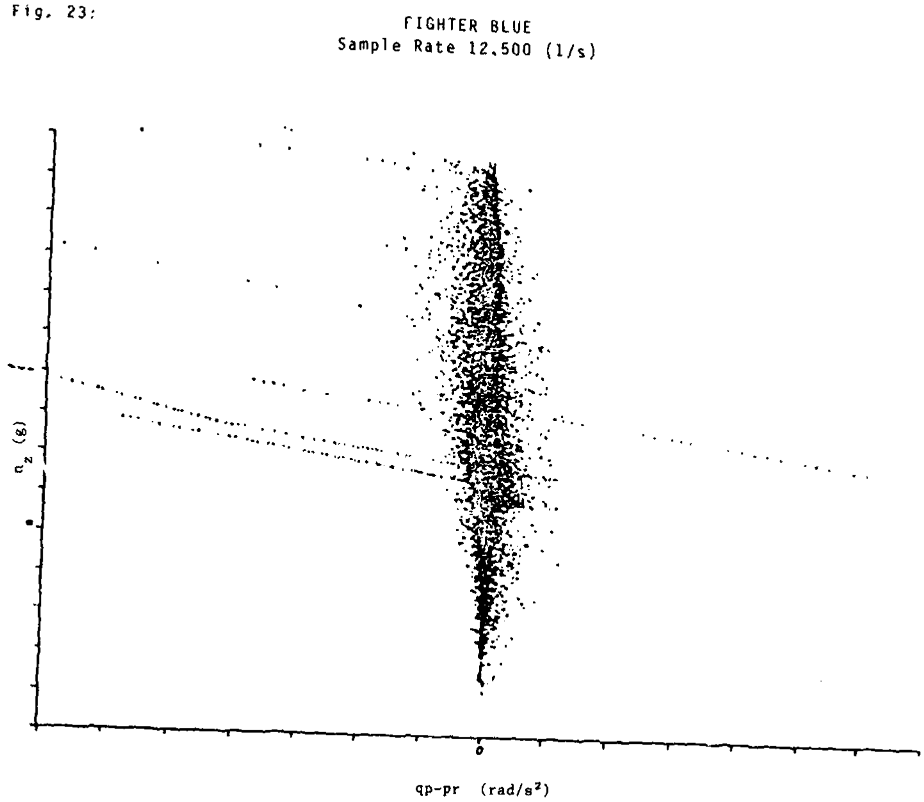


Fig. 23:



The occurrence of these parameters is the highest in subsonic combat, which agrees to the occurrence of the g loads in short range combat (figures 11 - 22).

It is also possible to identify weaknesses in the flight control laws when detecting and analysing departures from normal.

Figure 23 shows such a departure from normal. The increase in sample rate to 12.500 1/s makes these excursions better visible.

The evaluation of these excursions are necessary to optimise the flight control system for carefree handling.

Data recording in manned simulation makes it possible to find the most demanding mission part with respect to structural loads by varying the scenario and the starting situation and is able to show the accurrence of given parameters during the airfights.

4. RESTRICTIONS TO THE DFS-SIMULATION

The recorded data shown in the figures are based upon a fixed aerodynamic data set and the loads are computed at the CG. For another aircraft also aeroelastic data are available.

Evaluation has shown that simulation effects have to be expected in the area of 0 to -2 g load, because of the non existing capability to present megative g feel to the pilots.

Correlation of simulation to the real flight should to be done in order to increase confidence in the data achieved from simulations. The data should be correlated in defined maneuvers with flight trials. After correlation the manned combat simulation could provide inputs to help update the specifications.

These correlations have been initiated. The results of these are not yet evaluated.

5. CONCLUSION

The evaluated data show, that a manned simulation in a scenario with its data recording and evaluation can help to optimise the structural design load envelope, by recording the occurrence of given parameters in various types of aircombat.

It is also a means to optimise the structural envelope in relation to the operational envelope under the aspect of carefree handling.

After correlation of flight trials with manned simulation it can provide inputs to update the specifications relevant to future missions (figures 24).

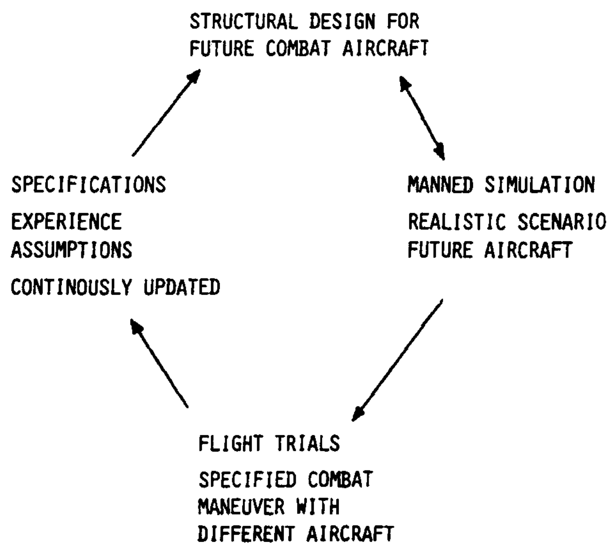

STRUCTURAL DESIGN FOR
FUTURE COMBAT AIRCRAFT
SPECIFICATIONS
EXPERIENCE
ASSUMPTIONS
CONTINOUSLY UPDATED
MANNED SIMULATION
REALISTIC SCENARIO
FUTURE AIRCRAFT
FLIGHT TRIALS
SPECIFIED COMBAT
MANEUVER WITH
DIFFERENT AIRCRAFT

Fig. 24:

Recorder's Report on the Structures and Materials Workshop on Design Loads for Advanced Fighters

by

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Grand-Duchy of Luxembourg

SUMMARY

It is the aim of this paper to summarize in a combined form the most important problem areas addressed in the discussions following the individual presentations as well as in the final discussion at the end of the workshop. Attention will also be focussed on particular parts of the content of the various papers which are directly related to the different points of discussion.

1. INTRODUCTION

In the past, design manoeuvre loads of fighter aircraft were clearly specified in "manoeuvre load regulations" which - for a given aircraft configuration - gave the designer quantitatively well defined design conditions to be considered in the structural layout process of the aircraft. In order to provide realistic loads data, the manoeuvre load regulations have been repeatedly updated to keep up with new aircraft technologies. Thus, as an example, the introduction of (irreversible) servohydraulic control surface actuation systems in combination with yaw and pitch damping control systems as well as stick filtering and artificial stick force simulation techniques entailed that - because the time histories of the pilot inputs and the control surface deflections were no longer related to one another - the design cases for manoeuvres were no longer specified in terms of control surface deflections but as a function of pilot inputs.

Even if it is agreed that the (coupled and uncoupled) manoeuvre design cases as specified in the airworthiness requirements lead to a good estimate of the boundaries of the loads envelope for a given aircraft, it cannot be guaranteed, however, that especially in combat situations these loads boundaries will never be exceeded. This is due to the fact that the pilot, in actual critical situations, does not fly the manoeuvres as specified in the requirements. This is a well-known point and it has been accepted - with a furtive glance at the safety factor between design limit and ultimate loads.

But with the implementation of most modern active control systems (ACS) into fighter aircraft to allow, as for example, uncoupled 6 - degree - of - freedom motion and thus including direct force and eventually thrust vectoring control, the entire situation has become more difficult. It is agreed that the "old" requirements are not sufficient to define all of the critical design cases for aircraft equipped with modern ACS, especially because these requirements do not consider the many unconventional manoeuvres to be flown with these aircraft. The resultant situation we are facing presently can be summarized as follows:

- We have no consistent set of airworthiness criteria which fully cover manoeuvre loads of agile ACS aircraft
- In the predesign stage of the aircraft the structural engineer does not really know which loads the aircraft will encounter in the course of its lifetime, because
  - the aircraft ACS can easily be modified at a later stage of development which can greatly affect its overall dynamic behavior and thus the manoeuvre load distribution,
  - a very inventive pilot may fly manoeuvres with agile aircraft which were not at all considered in the initial aircraft design.

The questions arising from these two points and which can be regarded as the key topics treated in the various presentations and discussions at the workshop are:

- Whence and how do we obtain the correct quantitative input to perform the structural (pre-)design of an ACS aircraft, or in other words: **how do we get the loads envelope of agile ACS aircraft?**
- Another crucial point ist **which airworthiness requirements should be established?**
- Finally a third point is related to the questions concerning the overall **safety of active control systems** and the (degraded) aircraft modes resulting from ACS failures.

In the following chapters attention will be focussed on the three points outlined above with special emphasis placed on the many questions and partly contradictory opinions raised during the discussions at the workshop.

2. MANOEUVRE LOADS

As stated in Paper (4) of the workshop proceedings, "it is not possible to complement the existing requirements by specifying specific additional design cases for ACS aircraft as they are difficult to identify because they are too multitudinous." This is especially true if we imagine that, for a given ACS aircraft, the same manoeuvres can be flown by activation of different control surface degrees - of - freedom and thus with a different manoeuvre load distribution.
During the workshop various procedures were described to approach the loads problem. One way of proceeding consists in determining and specifying an operational envelope for the aircraft under consideration, which is derived from the worst case manoeuvering conditions mostly occurring during air combat missions. This approach is based on the assumption that, once the operational envelope is known, the aircraft manoeuvre loads can be determined. Consequently this would allow the dimensioning of the aircraft structure as usual.

At the design stage of the aircraft, the relationship between the manoeuvre envelope and the loads could be established analytically. As an example, the block diagram of a computer program is shown in (5), which can be used to calculate the aircraft loads from "standardized" manoeuvres. At the present time this computer code is validated by flight test results obtained with relatively conventional aircraft. The pursued aim consists of its later application to the predesign of ACS aircraft.

The most important discussion points related to Paper (5) were as follows:

- What is a "standardized" manoeuvre for agile ACS aircraft ?
  Do we really know these manoeuvres at the design stage of the aircraft, since they will be (very) different from the "corresponding" manoeuvres of conventional aircraft.
- It was remarked that any calculations on ACS aircraft require a very correct 6 - degree - of - freedom simulation model. The difficulty of correctly predicting the principal stability derivatives was pointed out.

Another very similar approach, outlined in Paper (10) derives the aircraft loads from manoeuvre situations which are determined in manned combat simulations.

Once the prototype aircraft is available, the experimental determination of manoeuvre loads for defined manoeuvres is possible by flight testing. With regard to this matter, Paper (6) gives a detailed description of a load monitoring system for the derivation of the aircraft manoeuvre loads.

The "accuracy" of the results obtained from flight tests (to be used for confirmation of the design loads) with highly instrumented (prototype) aircraft is another crucial point. This is due to the fact that the pilot must be regarded as a very "variable" element which has a great affect on the aircraft's dynamic behavior. Paper (6) is an impressive portrayal of the pilot's influence on the loads produced when flying "defined" manoeuvres. This is also confirmed by Paper (7) in which we find the following sentence: "Three pilots performed 13 types of manoeuvres and they showed quite large variations of action in some cases." Thus it can be stated that the manoeuvre load patterns are more or less pilot dependent.

The loads determination procedure according to Papers (5) and (10) does not only yield the maximum manoeuvre loads data but moreover the load spectra which are relevant with regard to aircraft fatigue problems. Fatigue problems are also addressed in two sections of Paper (4) entitled "Fatigue Design" and "Loads Measurement". Thereby the importance of load measuring systems to confirm design loads as well as their corresponding spectra is stated.

The great concern addressed to the fatigue problem has its roots in the assumption that ACS aircraft will be operated more frequently and for a longer duration in the vicinity of maximum design loads, especially because their carefree handling qualities do encourage pilots to fly high - g - manoeuvres. Hence it can be concluded that the consideration of fatigue loads will become more important for ACS aircraft and, as mentioned in Paper (8), fatigue requirements may become the essential sizing criterion for the metallic parts of an aircraft structure.

In the following, focus is placed on the approach used at Dassault for the dimensioning of aircraft structures with regard to manoeuvre loads. The procedure, as described in (8), is unique in the sense that the airplane is no longer dimensioned by the external (manoeuvre) loads but by the flux of the interior forces. The key idea of the procedure is to determine for any manoeuvre the values of a great number (hundreds) of constraints "inside" the aircraft structure. If these constraints (stresses, hinge moments,...) at well chosen points of the aircraft structure exceed predefined limiting values, then a redesign of the aircraft has to take place envolving modifications which affect its control system and/or its structure. A lively discussion followed this presentation. A summary of the most relevant paraphrased questions is given in the Annex to this paper.

The numerous questions raised at the end of the various presentations indicated that there is no essential agreement among the specialists as to the most accurate way to determine aircraft manoeuvre loads. This underlines the fact that the prediction of the (manoeuvre) loads of agile ACS aircraft is indeed a very difficult task. Some of the remarks were not related to the various procedures of loads determination but to the question of how far these procedures could be used or integrated in the certification process of aircraft. It was noted that the process of aircraft clearance can be very different from country to country which does not only depend on the difference in the regulations but also on the coordination between aircraft designer, operator and certifying authorities.

3. AIRWORTHINESS REQUIREMENTS

It is obvious that it will not be easy to specify manoeuvre load regulations which are valid for every type of ACS aircraft. The actual question is whether a possibility exists of formulating a set of loads criteria which are specific and general enough to be applied to any (future) ACS aircraft.

Up to the present time the following 3 sets of regulations applicable to ACS aircraft have been produced: MIL - A - 87221 for the USAF, MIL - A - 8861 B for the US Navy and Chapter 208/DEF - STAN 00 - 970 for the UK. The audience heard presentations on the new USAF and UK specifications for aircraft structures.

The new USAF regulations (3) no longer consist of fixed requirements. They anticipate that loading conditions be established rationally for a typical aircraft design and aircraft environment. Thus the new specifications are not a tool comparable to the former ones (MIL - A - 008861 A). The problem areas are now defined in broad terms but not specifically. This allows the designer a high degree of flexibility. On the other hand a great deal of responsibility now rests on the designer. Starting from the operational needs expressed by the requirements the designer has to write the structural criteria report.

In the discussion it was agreed that these kinds of specifications leave a margin of error because the designer may forget "something" essential.

It was mentioned that with the issue of the new MIL - A - 87221, the former MIL - A - 008861 A were cancelled. But the information contained in the old specifications is not lost since it is included "in words" in the guidance portion of the new handbook.

Another comment concerned the "weight of paper" of the new specifications which were found to be still "heavier" than the old ones. It was agreed that MIL - A - 87221 is a hefty document. This has to be attributed to the fact that it incorporates a great deal of advice, the specification part itself being smaller than that of MIL - A - 008861 A.

The way followed by the UK to handle the specification problem is very different from that pursued by the USAF. The UK approach (4) can be regarded as being more conservative. It mainly consists in the revision of the old DEF - STAN - 00 - 970 and the inclusion of a new chapter to consider specific requirements for aircraft fitted with ACS. This new Chapter 208 includes requirements for all aspects of ACS aircraft, such as static strength, fatigue performance, aeroelasticity, loads measurement, failures and mandatory cases for structural resubstantiation.

During the discussion it came out that, despite the many topics included in Chapter 208, the document must still be considered incomplete with regard to the design of most modern ACS fighter aircraft. As for example, it was noted that the requirements only consider "active flutter suppression systems" (AFSS) which are in fact flutter margin augmentation systems. Up to now no attention has been paid to "real" AFSS suppressing flutter cases within the aircraft flight envelope. This rather conservative approach was adopted by the UK Joint Airworthiness Committee (JAC) since it was felt that the possibility of AFSS failure could not be determined. This, however, entails that the regulations as they are formulated at the present time do not provide all the information required for the design of systems which will certainly exist some day. A further updating of the requirements will be necessary.

This also applies to the specification of stability margins for ACS. In the particular case of AFSS it was felt that the definition of a margin in terms of an excess speed is an insufficient stability criterion, but that amplitude and phase margins will have to be defined as well.

It was concluded that the newly drafted Chapter 208, like any other regulation standard, must be considered as a living document which has to be updated as technology progresses.

The two sets of requirements, described in Papers (3) and (4) clearly point out (the) two possible ways of "writing" the specifications. It can be assumed that the requirements can only be formulated either in a very flexible non specific manner (like MIL - A - 87221) with regard to a tailored application to any ACS aircraft or else in a specific form (like Chapter 208) with the disadvantage of a possible lack of completeness and not necessarily being perfectly "adjusted" to each ACS aircraft design.

4. SAFETY OF ACTIVE CONTROL SYSTEMS

The length of this chapter, which deals with the safety of aircraft following failures/degradations in their ACS is inversely proportional to the concern given by the audience to this problem.

A point which was repeatedly addressed is related to proving the quantitative reliability of the ACS software. It was agreed that there is no way of quantifying software reliability. The only way to prove software integrity seems to consist in extensive testing.

The objection was made as to how a controlled drop down to lower levels of handling qualities (9) could be guaranteed if the software reliability has not been proven.

Another concern addressed the reliability of the ACS hardware such as sensors, actuating systems, electronics,etc. It was pointed out that there will always be a layout in form of quadruple chains for

ACS. Because of the redundancy inherent to such systems, a critical situation can only result from a case of multiple failures. It was also mentioned that the qualification/certification process requires the ACS to be extensively investigated in rig tests.

5. CONCLUSION

The various presentations at the workshop have clearly pointed out the many new problems which are encountered when proving the airworthiness of modern ACS aircraft. Some of the most crucial points were addressed during the different discussions. But at the end of the conference there was a general feeling among the specialists that not all of the problems are convincingly solved yet. A definitive answer could not be given to some of the most important questions, such as:

- How can companies comprehensively demonstrate the integritiy of their ACS airplanes under all operational conditions ?
- Which is the best way of writing the airworthiness requirements with the aim of being both specific and applicable to every type of future ACS aircraft.

These two basic points all alone clearly indicate the need for future work in this area.

Finally, another quite interesting point related to the future work of the structural engineer during the design phase of ACS aircraft should be addressed. It was repeatedly pointed out that due to the implementation of more and more sophisticated ACS into agile fighter aircraft, the work of the structural engineer will become less important in the entire design process of the aircraft. This has to be attributed to the fact that, in the case of ACS aircraft, a lot of structural problems can be solved by a readjustment of the very flexible ACS. It was remarked that the structural engineer´s future work will probably consist in the selection of the most critical aircraft loading cases, the sizing of the aircraft structure an the determination of the operators which are needed by the flight mechanics engineer. It was pointed out that the structural engineer will n o t have to deal with problems concerning the qualification of the ACS.

The last point which was addressed at the workshop concerned the future work of the subcommittee. The chairman raised the question if there were any needs for the subcommittee to continue its work in this area or if its activities should be stopped at the next AGARD SMP - Meeting in Fall 87. All of the specialist were urged to inform their national representative (panel member) within the subcommittee on eventual topics which could be regarded as a basis for a meaningful follow on activity.

ANNEX: Questions related to Paper (8)

Question: What is meant by a "static manoeuvre case"?

Answer: Static in this sense means that the aircraft position is regarded as being momentarily "frozen" during a manoeuvre and all the loads applied to the structure at this well defined time point are then considered as "static forces". A lot of experience and intuition is required for defining the most relevant "static manoeuvre cases".

Question: How accurate is the aircraft model which is used in the simulator tests?

Answer: The aircraft model must be very accurate. We use a 6-degree - of - freedom model with most correct stability derivatives taking into account nonlinear aerodynamics. Also in the case of ACS aircraft we do consider the entire ACS. Moreover we consider aeroelastic effects which are important with regard to the load distribution. We also use (if possible) measured aerodynamic forces from flight tests.

Question: How do you verify the aircraft finite element model?

Answer: We achieve a very correct calibration of the FEM. In the test we use about 100 basic loading conditions for verification of the FEM. The correct detection of the various loading paths is of major importance.

Question: The safety of your aircraft depends entirely on the active control system. This entails that a very complicated failure analysis is required.

Answer: We use 4 - channel control systems. One channel can fail without affecting the aircraft performance. In the case of a failure in a second channel, the aircraft performance is degraded. The pilot can fly this aircraft like a conventional aircraft, but it will no longer be "carefree".

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14. Abstract

The AGARD STRUCTURES AND MATERIALS PANEL held a Workshop at Madrid, Spain in the Spring of 1987 to discuss problems associated with defining Design Loads for Advanced Fighters. This publication includes the majority of the presentations made in the course of this Workshop, together with the Recorder's Report.

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