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MOTION SYSTEMS ROLE IN FLIGHT SIMULATORS FOR FLYING TRAINING.(U)

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MOTION SYSTEMS ROLE IN FLIGHT SIMULATORS FOR FLYING TRAINING

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By
Michael L. Cyrus

FLYING TRAINING DIVISION
Williams Air Force Base, Arizona 85224

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This report reviews the literature as it relates to the use of platform motion systems in flight simulators for flying training. Motion is discussed in terms of its effect on compensatory, pursuit, and precognitive tasks, within both the simulator and transfer contexts. Although both skilled and unskilled behaviors are addressed, the former is emphasized. The report concludes that, for most tasks, platform motion is not required to produce rapid, efficient, economical training and that other, less expensive means of imparting motion information are equally viable alternatives. The report recommends the following: (1) Whenever feasible and affordable, simulator systems should be equipped with the largest field-of-view visual system that is consistent with mission requirements, and (2) Simulators that do not include a platform motion system can be safely procured for most aircraft without compromising training effectiveness.

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PREFACE

This report is a direct outgrowth of a series of formal papers and briefings presented by the author to various scientific and military organizations on the training value and engineering characteristics of platform motion systems. The research this report represents was in support of project 1123, Flying Training Development. Mr. James Smith was the project scientist.

My deepest appreciation is extended to the many friends and colleagues whose ideas and inspiration supported this effort. I especially thank Mr. G. Reid, Capt J. Thorpe, Dr. E. Martin, Dr. W. Waag, and particularly Dr. E. Eddowes, whose theory of and contributions to the cognitive model of flying training made this report possible; and to Mr. T. F. Sun, for his incisive statistical analysis of the current motion literature.

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MOTION SYSTEMS ROLE IN FLIGHT SIMULATORS FOR FLYING TRAINING

I. INTRODUCTION

The use of motion systems for flight simulators as part of military flying training programs has, in recent years, been the subject of considerable (and often heated) debate. As early as spring 1974, scholars of varying backgrounds within the aircraft simulation community began to question the practice of automatically including large, expensive, multiple degrees of freedom platform motion systems in simulator procurements (Ref 14, 19). They pointed out several serious deficiencies associated with these devices, including increased energy costs, facility costs, and operational maintenance costs. Increased cost and complexity meant that integration of these motion systems with high fidelity, wraparound visual systems became a difficult and expensive task, a job which has not been successfully accomplished to date on any advanced simulator complex. More importantly, critics of the motion systems pointed out that currently available stationary training devices were highly effective and possessed considerable transfer value, while no known commercially affordable motion system had shown a statistically significant transfer effect, let alone one of practical value from either the cost effectiveness or training effectiveness points of view. As a result, the USAF Tactical Air Command (TAC) recently took the position of refusing to purchase platform motion systems as part of its A-10 and F-16 simulator procurement actions until such systems could be shown to exhibit significant positive transfer. This report will review the literature as it relates to the role of platform motion systems in flight simulators and will attempt to place that information in the perspective of the military flying training program.

The issue of platform motion is regarded as a function of four primary variables in the training environment: motion itself, aircraft type, pilot population experience level, and training objective. Throughout the remainder of this report, unless otherwise noted, motion will be regarded as being maneuver correlated and not as resulting from disturbances generated by a platform motion system. In this report, aircraft type refers primarily to fixed wing aircraft and not to helicopters nor space vehicles. Experience level ranges from the Undergraduate Pilot Trainee through combat qualified pilots, although the emphasis will be placed on the latter, as it is in the advanced skill acquisition and maintenance that the Air Force spends the largest portion of its training dollars. Training objective refers to the purpose of the simulator system in training the person. Simulators range from small, inexpensive part-task trainers, to highly complex (and expensive) full mission simulators theoretically capable of performing any maneuver or task that the aircraft can. Evidence on motion use comes from three areas: ground, airborne, and transfer studies. Within each of these areas, motion will be examined from the point of view of either compensatory, pursuit, or precognitive tracking.

II. GROUND SIMULATION STUDIES

Ground simulation studies, like their airborne and transfer counterparts, break roughly into three groups: single- and multi-axis compensatory tasks, single- and multi-axis pursuit tasks, and multi-axis precognitive tasks; although by far the largest volume of research results is in the area of single-axis compensatory tracking. Dependent measures vary, depending on experimental goal, but belong in two classes: time domain and frequency domain. Typical time domain measures are RMS error, moment functions, and time on target. Effective time constant, crossover frequency, pilot and pilot/machine transfer functions all exemplify frequency domain measures. This report will examine experimental information from compensatory, pursuit, and precognitive tasks.

III. COMPENSATORY TRACKING

In the typical compensatory tracking situation, the subject is provided an error signal and possibly one or more of its derivatives, by way of various displays. He then tries to minimize error by manipulating

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the available control(s). Extensive mathematical modeling of systems similar to Figure 1 has been generated (Ref 24, 25, 39). Variations of controller characteristics and the resulting effect on manual control across a broad band of dynamics have been examined. Compensatory tracking tasks are forcing functions of two major types, single sine waves and random appearing waves, although the latter are by far the most prevalent. In most cases, the input function has very low coherency, and thus the subject does not have direct information concerning either the nature of the input or the characteristics of the controlled element.

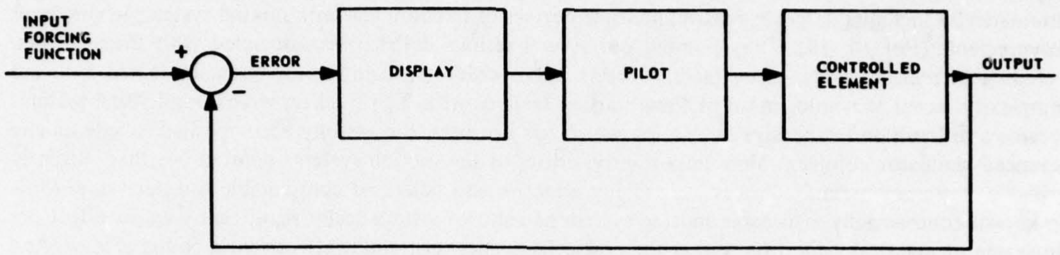

Figure 1. **Typical compensatory system.**

Viewing the subject as a primitive information processor, in such a tracking task, the sensory system that provides the most lead (or least lag) at the greatest resolution for the error signal will be the system which allows for better average control performance. It is in this regard that the vestibular system, with its generally agreed on lower stimulation thresholds (or lower reaction thresholds) (Ref 4, 8, 11, 40, 42), should provide improved tracking performance over, say, a visual presentation alone. However, the literature is restricted primarily to the tradeoff between very-small-field-of-view visual presentations and motion effects, so that the effect of a large field-of-view has only recently been addressed (Ref 40, 43). It is important that the reader understand the conceptual framework that underlies the current mathematical models of human tracking behavior[1] and why many researchers, including the author, reject its wholesale application to flying training. The primary difficulty with the present theory is that its applicability is limited to dealing with control inputs of random, random-appearing, or transient nature. Unlike actual aircraft flight, the pilot is presented with a display that essentially contains no information. A pilot's capability to "solve" a tracking problem (say a bombing run) over a series of trials and to "store it" for future reference is not addressed. Although learning of a sort will occur (specifically, learning which of the cues best help the pilot reduce the display error), the task cannot be learned in the sense that a loop, overhead pattern, or barrel roll is learned. Thus, in the presence of random, random appearing, or transient inputs, a pilot reacts like a servosystem because he has no alternative and not because his behavior can be characterized by servosystem properties. A second major drawback in the literature is that the control system dynamics studied are often very dissimilar to aircraft dynamics. Much literature has been devoted to unstable or marginal dynamics, containing substantial negative damping ratios or higher order derivatives, while most aircraft have reasonable control dynamics with excellent damping characteristics. A general rule is that the more unstable, or higher the order, a control system is, the more likely some form of motion information will be of benefit in a compensatory tracking task; however, for typical aircraft-like dynamics (Ref 12), some researchers have found that in these situations motion tends more to interfere with, than to aid, tracking performance (Ref 15, 16, 17). It is interesting to note that pilots are instructed to ignore "seat of the pants" (i.e., motion) stimuli in the instrument flying environment and rely solely on the instruments. Mathematical models of the vestibular system also show a poor correlation between perceived and actual motion, primarily due to the nonlinearities and adaptation phenomena associated with the vestibular

[1] For an excellent summary of mathematical modeling of human pilot behavior, the reader is encouraged to review Reference 25.

system (Ref 2, 43). It is instructive to examine one such experiment in detail. For this purpose, consider the one discussed in "Evaluation of Roll Axis Tracking as an Indicator of Vestibular/Somato Sensory Function" (Ref 15, 16, 17). In this experiment, subjects were asked to perform a roll compensatory task as shown in Figure 2. Zero mean, band-limited (to .5 rad/sec) Gaussian noise was used as the forcing function, and its standard deviation was set to 90° of roll. The subject was presented the error signal via a small field-of-view, inside-out visual display and additionally, when in the motion mode, through platform roll motion. A side-mounted force stick was used for operator control. Figure 3 contains the simulated dynamics and Figures 4 through 7 the results of the experiment. The reader is asked to study these figures carefully and refer to the original experiment for further information if required.

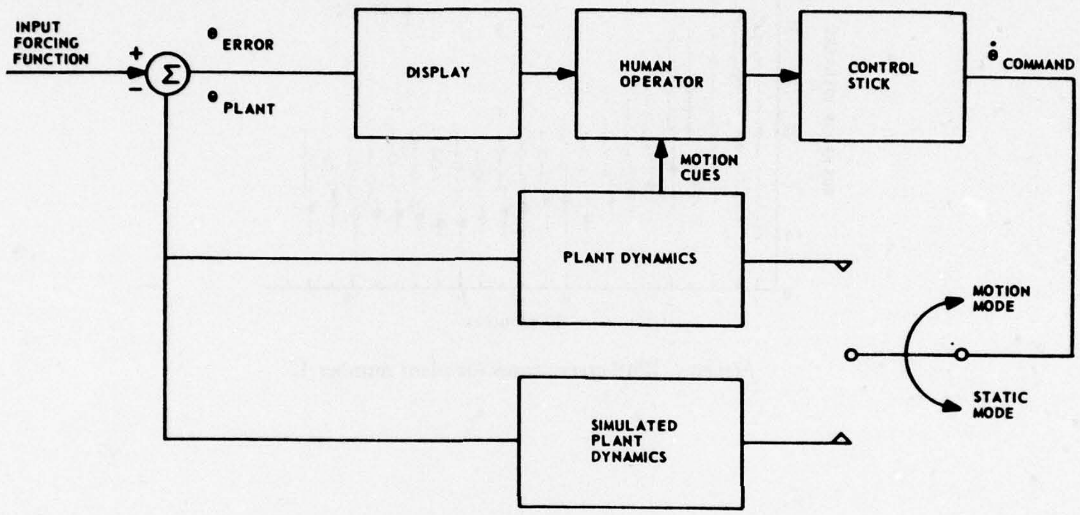

Figure 2. **Roll axis tracking simulator block diagram.**

PLANT NUMBER	
1	$\frac{K}{S(S+6)(S+127)}$
2	$\frac{K}{S(2S+1)(S+6)(S+127)}$
3	$\frac{K}{S^2(2S+1)(S+6)(S+127)}$
4	$\frac{K}{S^2(4S+1)(2S+1)(S+6)(S+127)}$

PLANT DYNAMICS USED, INPUT ≡ VELOCITY COMMAND TO PLANT; OUTPUT ≡ PLANT POSITION.

Figure 3. **Transfer function dynamics.**

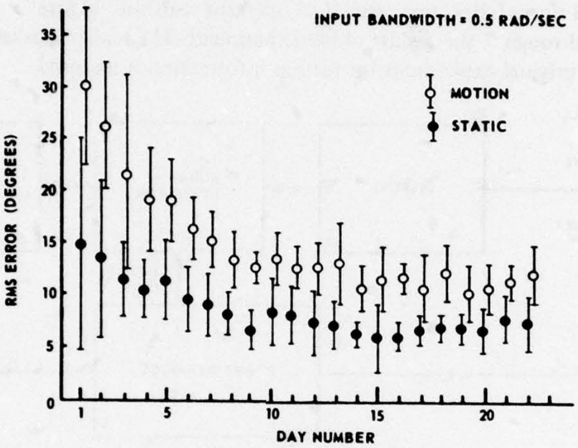

Figure 4. **RMS error scores for plant number 1.**

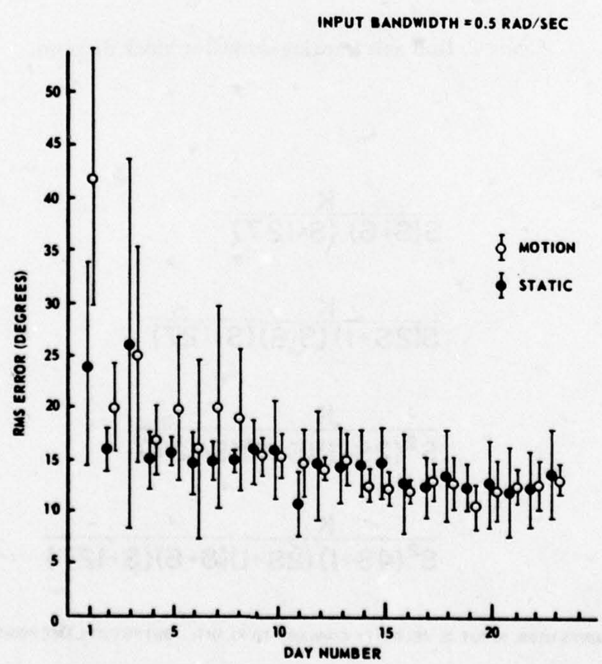

Figure 5. **RMS error scores for plant number 2.**

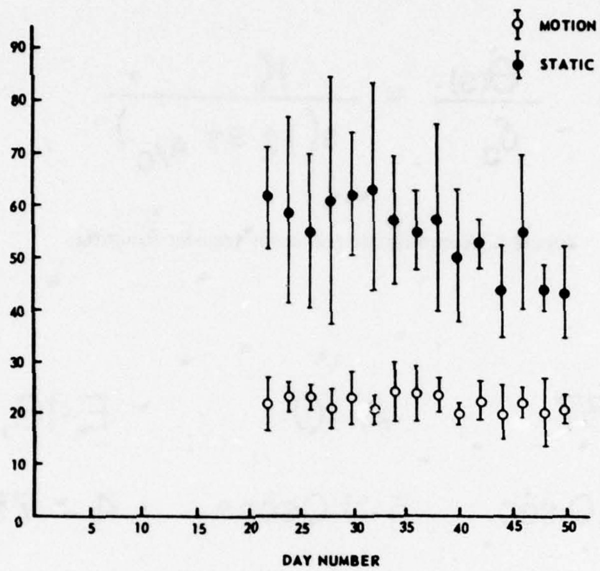

Figure 6. **RMS error scores for plant number 3.**

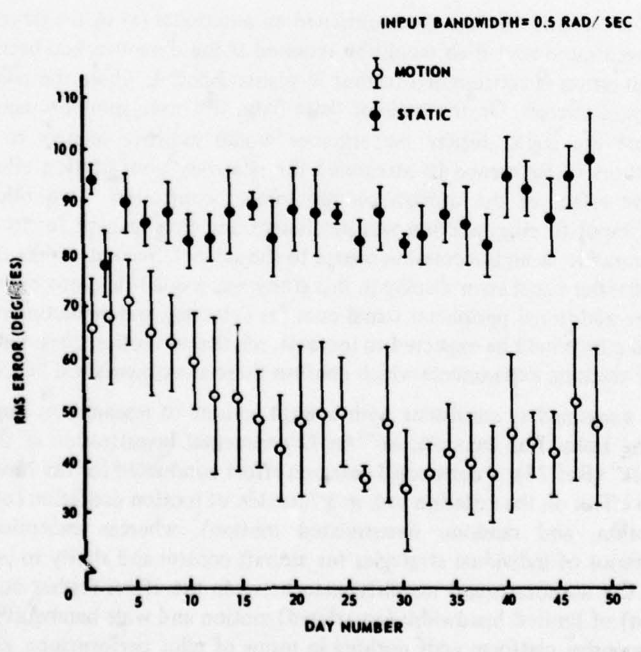

Figure 7. **RMS error scores for plant number 4.**

Before considering the data, note that the approximate roll rate to aileron displacement transfer function is a simple first-order lag (Ref 11). When this is placed in the context of the experiment, wherein the error angle is denoted θ, the resulting roll mode transfer function is as shown in Figure 8. Typical values for the aircraft time constant, tau, are shown in Figure 9.

$$\frac{\theta(s)}{\delta_a} = \frac{K}{s(1 + s\tau_{A/C})}$$

Figure 8. **Approximate roll mode transfer function.**

T-37	A-10	F-16
.15 - 1.0 sec.	.5 - 1.0 sec.	.4 - .75 sec.

Figure 9. **Typical roll mode time constants.**

In this experiment, plants one and two contained an additional (s) in the denominator, forcing the subjects to generate even more lead than would be required if the dynamics had been representative of an actual aircraft. This situation is confounded further in plants 3 and 4, where the controlled dynamics no longer represent a typical aircraft. On the basis of these data, the more similar to actual aircraft dynamics the plant is, the more the static display performance would improve relative to the motion display performance. The authors of Reference 16 attributed the relatively poor motion effect in plants one and two to the disruptive effect of the motion on the subject controllers. Two other facts need to be mentioned. First, the input forcing function was incoherent and thus, except for its magnitude and band limited nature, was unusable as an information source to the subject. Second, unlike the visual information available in actual flight, the visual error display in this study was a small-field-of-view bar-line system which could not generate the additional peripheral visual cues for detecting and predicting motion. The utility of these peripheral visual cues would be expected to increase, relative to motion cues. Later in this report, two inflight compensatory tracking experiments which confirm these assessments will be examined.

The study just examined is consistent with a large volume of research on single- and multiple-axis compensatory tracking tasks. For example, in "An Experimental Investigation of the Role of Motion in Ground-Based Trainers" (Ref 23), a contracted research effort conducted for the Navy, published in 1974, the authors found no effect on the criterion task as a function of motion condition (off, correlated low and high bandwidth motion, and random, uncorrelated motion), whereas exceptionally strong subject differences (both in terms of individual strategies for aircraft control and ability to perform the task) were noted. Additionally, the authors found no difference between the effect (either on the criterion task or pilot output measures) of limited bandwidth (correlated) motion and wide bandwidth (correlated) motion. "Thus, the more responsive platform adds nothing in terms of pilot performance, nor does it differ with respect to pilot's ratings" (Ref 23). This latter conclusion is still the subject of considerable controversy within the simulation community. As experiments involving manual tracking behavior and platform motion effectiveness moved away from the oscilloscope and side-arm controller displays of the laboratory and into cockpit trainers, investigators became aware of other, powerful variables and sources of information involved. These are summarized in Figure 10.

* Subject Differences, usually the largest single factor; includes the effect of learning and experience.

* Trial Effects, an extremely large effect on the order of magnitude of the subject effect, depending on the experience level of the subject population.

* Information source effects including:

  Control loading effects
  G-Seat effects
  G-Suit effects
  Instrument effects
  Platform motion effects
  Visual system effects

* Task variables, including information processing requirements and motor difficulty.

* Aircraft dynamic response characteristics.

Figure 10. **Experimental variables involved in a typical simulator or transfer study.**

Effect size (Ref 18), as well as statistical significance, now plays a major role in determining whether a particular variable or cueing mechanism will result in significant training transfer. However, the examination of motion effect size is difficult because of the controversy surrounding differing motion platform engineering characteristics. In these cases, although motion shows itself to be a very small effect, critics provide as an alternative explanation the possibility that the observed effect size is due to each particular motion system's characteristics. Although possessing a two-axis joystick (force type) controller, rather than a standard aircraft stick or yoke controller, and a small-field-of-view visual display, the NASA LANGLEY Visual-Motion Simulator (VMS) has the best (proven) overall motion servo characteristics known to the author (Ref 32). For that reason, data taken from the NASA-LANGLEY VMS have been selected for examination here. The VMS is a 60-inch[2] system (Figure 11) which currently represents the upper limit on commercial affordability. Data from three studies will be examined here: "Evaluation of a Linear Washout for Simulator Motion Cue Presentation During Landing Approach" (Ref 34); "Comparison

[2] A "60-inch" system is one in which the maximum hydraulic cylinder extension is 60 inches. For a discussion of the engineering limitations associated with 60-inch systems see Reference 6.

of a Linear and a Non-Linear Washout for Motion Simulators Utilizing Objective and Subjective Data from CTOL Transport Landing Approaches" (Ref 33); and "The Effect of Visual-Motion Time Delays on Pilot Performance in a Simulated Pursuit Tracking Task" (Ref 26).

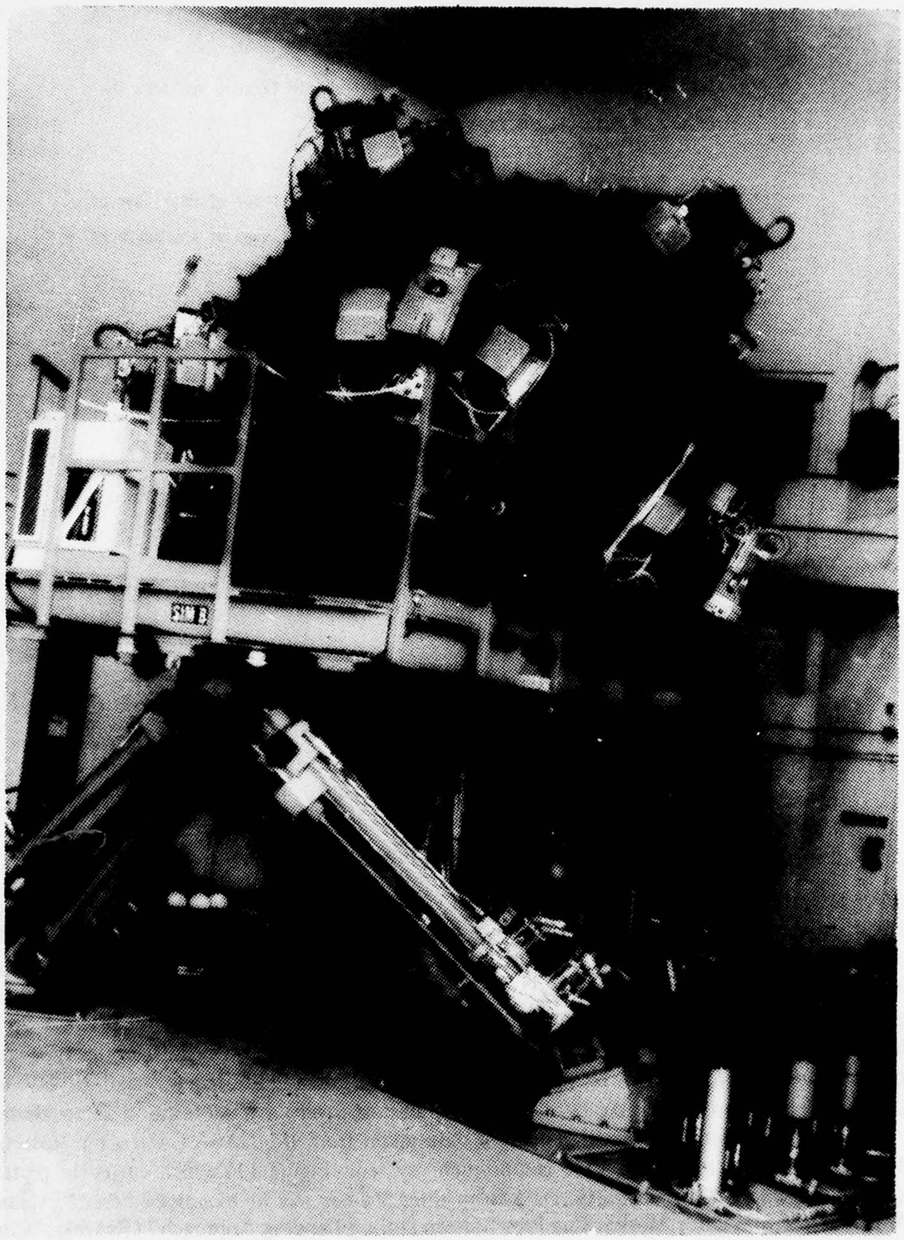

Figure 11. **Typical 60" platform motion system (Advanced Simulator for Pilot Training (ASPT)).**

The first two studies use a common experimental design, but differ in terms of the type of motion presented. The first experiment examined the effect on pilot criterion performance, (as measured by both subjective and objective measures) of a five-degrees-of-freedom (heave deleted), linear washout programmed motion system. "The task was an ILS [instrument-landing-system] landing in a simulated Boeing 737 which consisted of: (a) a transition to the localizer beam, followed by (b) a transition to the glide slope, and (c) the ensuing approach to about 76m (250 ft). Three approach conditions were provided: the standard approach previously described, the standard approach with instantaneous encounter of a weather front (a 10 knot crosswind with moderate turbulence), and the standard approach with the occurrence of an engine failure. Instrumentation consisted of an attitude-direction indicator, vertical-speed indicator, a horizontal-situation indicator, altimeter, airspeed indicator (both calibrated and true), meters for angles of attack and sideslip, and a turn and bank indicator" (Ref 34). Insofar as criterion performance is concerned, the only meaningful effects are pilots (subjects), approaches (tasks), and their interaction. The analysis of variance table in Figure 12 summarizes the results of that experiment.

		Root-mean-square performance measures									
		Deviation of –									
Factors	Degrees of freedom	Localizer		Glide slope		Speed		Pitch bar		Roll bar	
		Short duration	Long duration	Short duration	Long duration	Short duration	Long duration	Short duration	Long duration	Short duration	Long duration
Pilots, A	2	0.0578	0.0619	**11.56	**25.89	**11.08	**13.18	**15.24	**34.50	**5.343	**7.635
Motion, B	1	0.1463	0.1055	0.0199	0.0186	0.6034	0.0610	0.6817	0.1202	0.2363	3.850
Approaches, C	2	**42.55	**36.31	**9.414	**5.574	0.2739	*3.399	*3.943	1.5999	**132.0	**152.2
Replicates	4	0.7615	0.4040	0.6267	0.4790	0.3059	0.2240	1.126	0.9488	1.802	0.7457
AB	2	0.0346	0.3428	0.0334	0.2791	0.0845	0.0689	1.037	1.549	2.392	1.311
AC	4	0.4077	0.5740	*2.902	2.429	**3.734	**3.940	2.192	1.683	**5.259	**9.056
BC	2	0.0718	0.0415	0.5605	1.731	1.518	1.101	0.4292	0.8435	1.906	1.963
ABC	4	0.4217	0.6464	0.2776	0.7830	0.6870	0.2644	0.1638	0.5340	1.105	0.4287
Error	68	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------

*Indicates 5% significance level.
**Indicates 1% significance level.

Figure 12. **Computed F-distribution values for the analyses of variance.**

The second experiment (Ref 33); had nearly identical results to the first; although an improved, nonlinear motion drive algorithm was used. In the words of the authors, "Objective and subjective data gathered in the process of comparing a linear and a nonlinear washout for motion simulators reveal that there is no difference in the pilot-performance measurements used during instrument-landing-system (ILS) approaches with a Boeing 737 conventional take-off and landing (CTOL) airplane between fixed-base, linear-washout, and nonlinear-washout operations." The primary result, that of a negligible effect of platform motion on task criterion variables, is consistent with data taken from Navy (Ref 23) and Air Force studies (Ref 22) as well. Motion effect size, defined as η^2, ω^2, or ρI (as appropriate) (Ref 18) and roughly equivalent to the percentage of variance accounted for by a given treatment, is also consistent across studies conducted on other simulators. As far as motion effect on criterion variables is concerned, whenever three or more of the categories previously listed (Figure 10) are present, that effect size is very small.

The next experiment was a pursuit tracking task. Like the first two experiments, this one was conducted on the NASA LANGLEY VMS (Figure 13). Primary experimental elements of the task were as follows: (See Figures 14 through 17.)

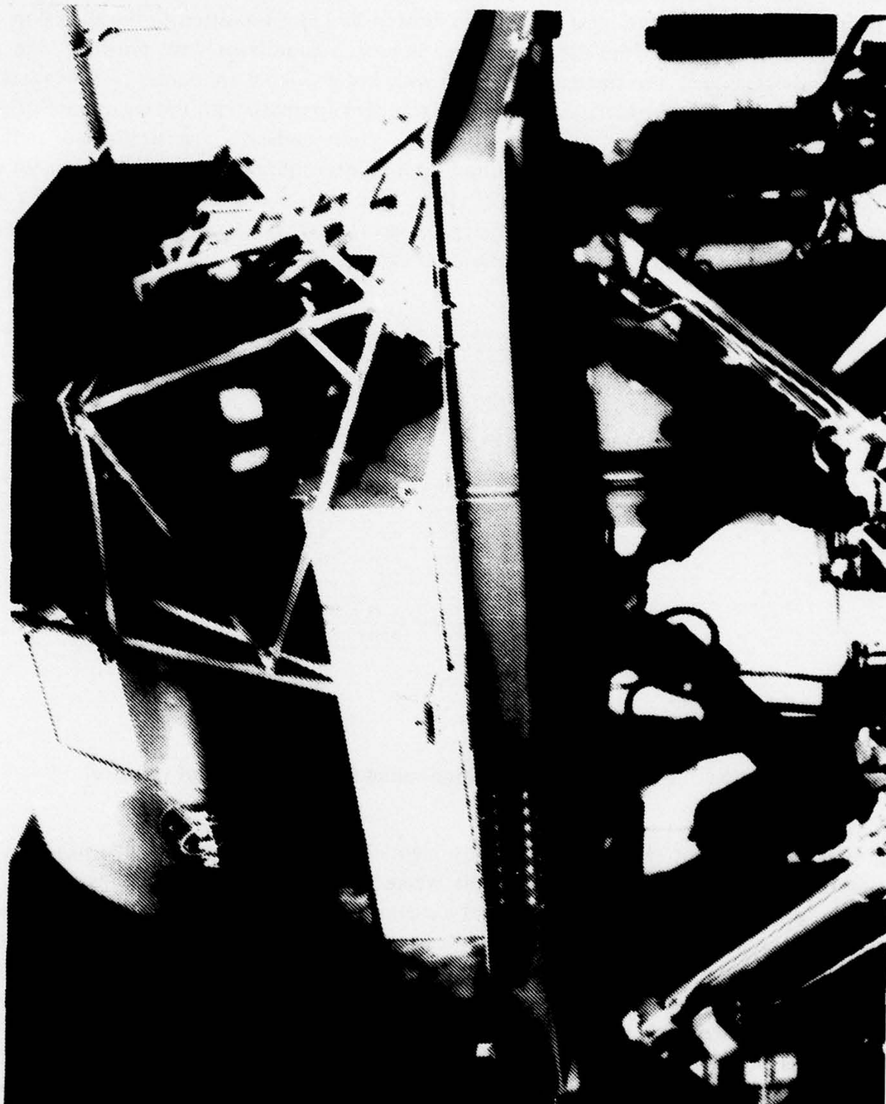

Figure 13. **NASA-Langley visual-motion simulator.**

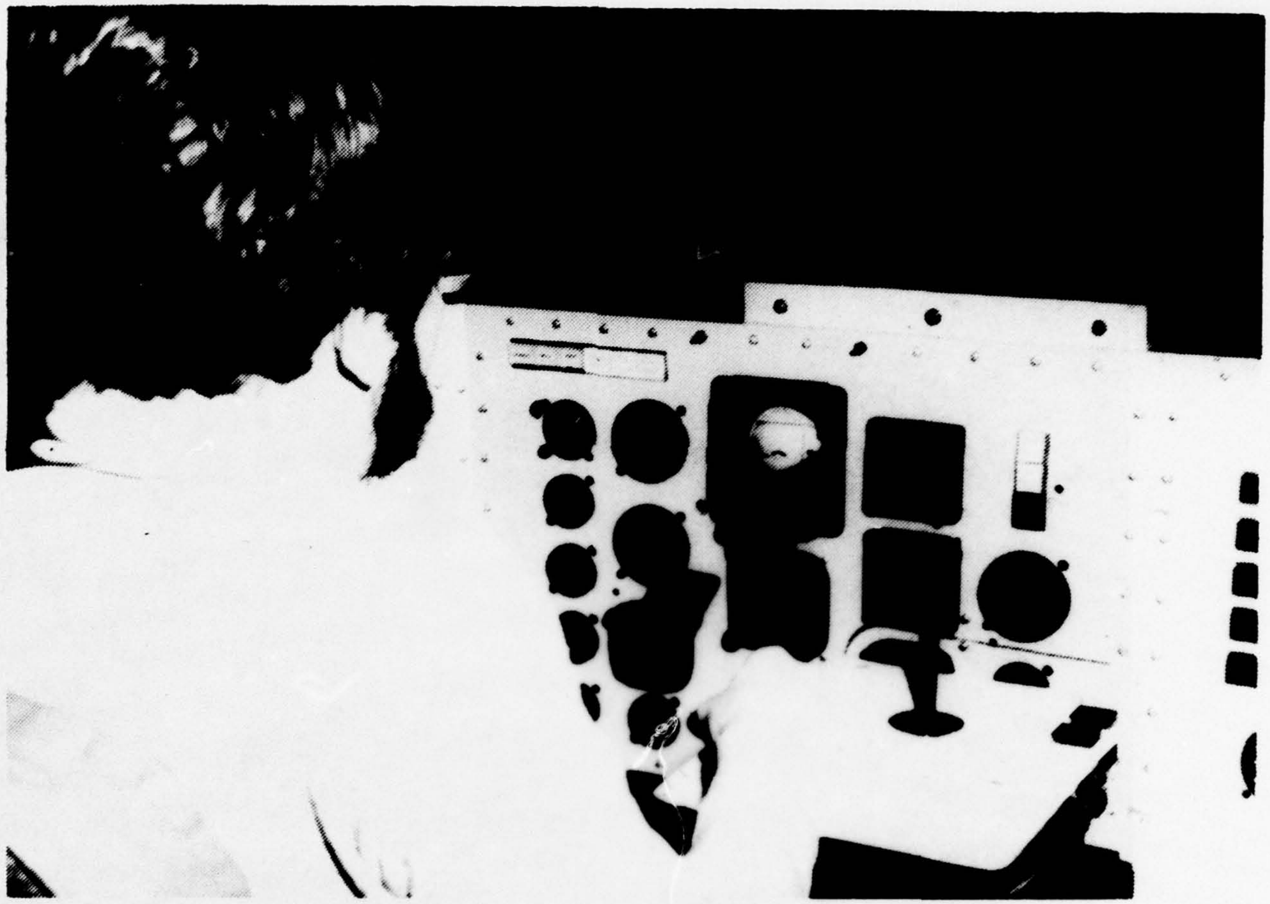

Figure 14. **Cockpit configuration for pursuit task call instruments deactivated for test.**

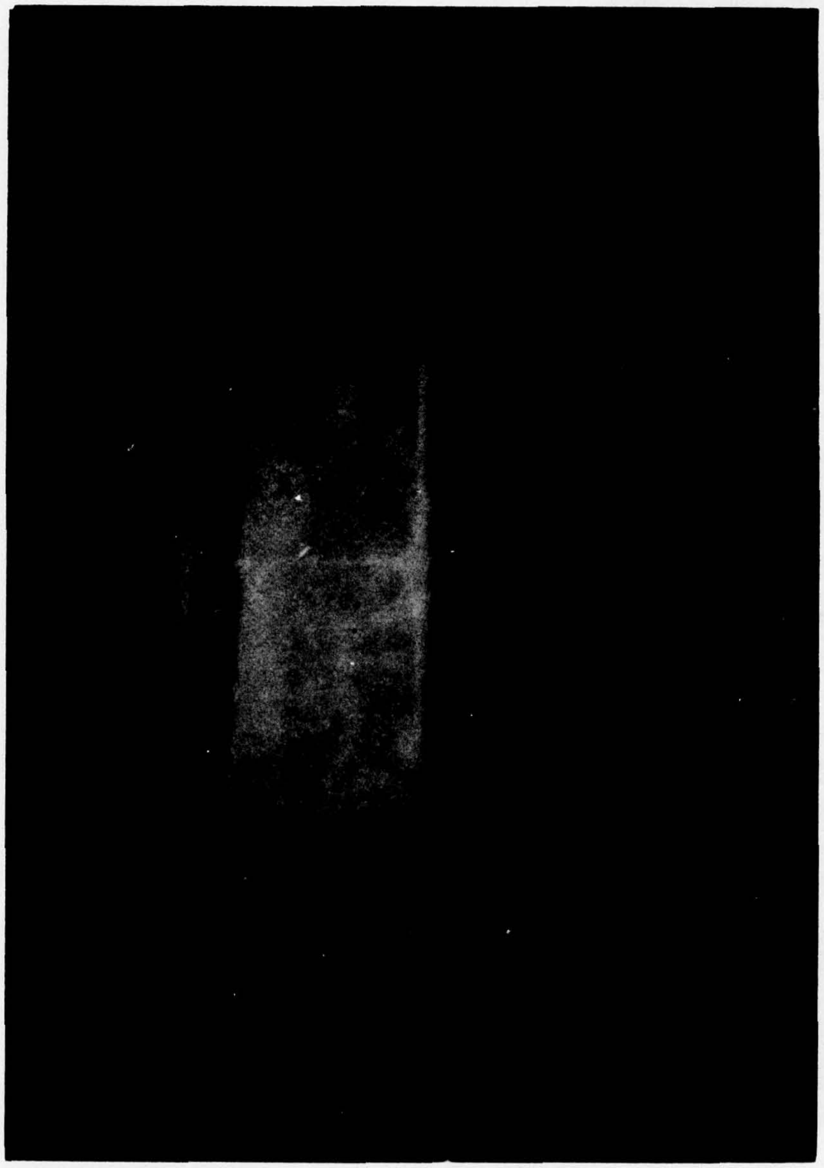

Figure 15. **Pursuit task visual display.**

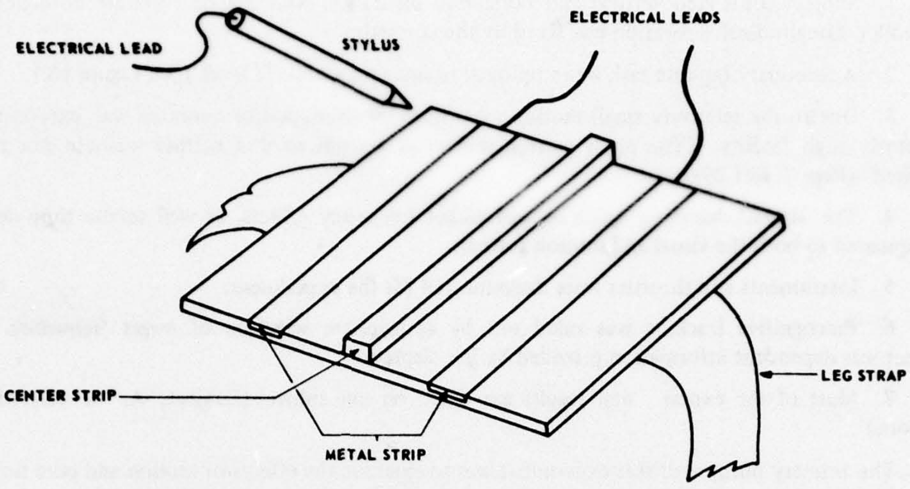

Figure 16. **Sketch of secondary task board and stylus.**

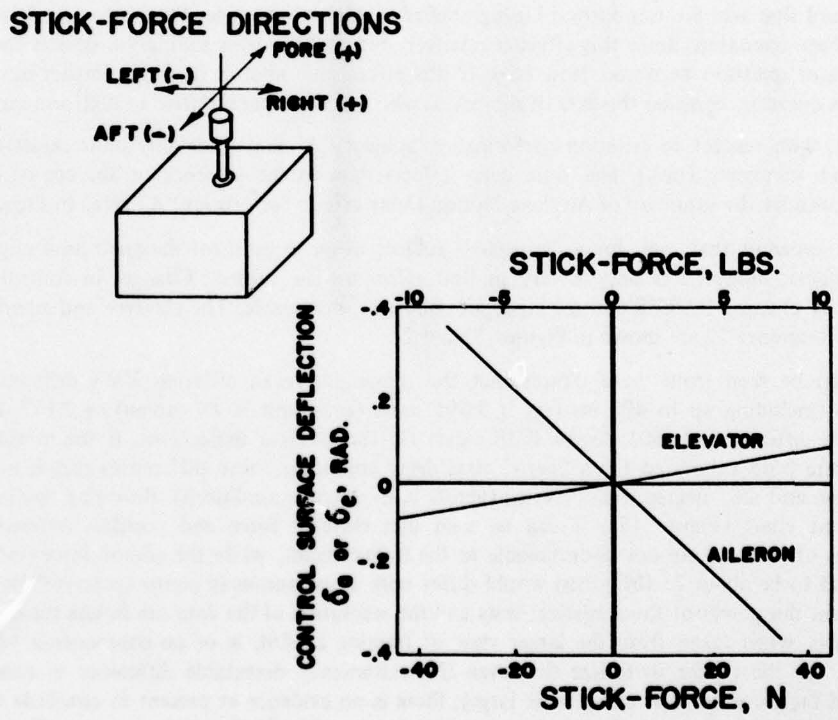

Figure 17. **Two-axis stick-force characteristics.**

1. Subject controlled vertical and horizontal separation with a target aircraft through a fingertip controller. Longitudinal separation was fixed by the computer.

2. A secondary tap-rate task was employed to increase workload level. (See Figure 16.)

3. Due to the relatively small motion excursions involved, platform motion was, except in heave, of extremely high fidelity. "The pitch motion was small enough so that neither washout nor scaling was required" (Page 7, Ref 26).

4. The aircraft handling qualities and target frequency effects, as well as the time delays, were manipulated to both the visual and motion systems.

5. Instruments and throttles were disconnected for the experiment.

6. Precognitive tracking was ruled out by appropriate selection of target frequency. Thus, the subject was dependent information provided by the displays.

7. Most of the experimental results are based on one subject (Subject "A," as referred to by the authors.)

The primary purpose of this experiment was to examine the effects of motion and pure time delay on both RMS tracking and RMS control performance. As can be seen from Figure 18, the relative motion contribution to the overall analysis of variance is very small, even though this experiment has an extremely limited number of influencing variables such as might be found in a transfer of training context. This effect is a general one. For the instrument tasks that the author examined, motion effect size was rarely greater than 10%; in the visual studies examined, less than 5% and often smaller. One effect was consistent, however, and that was the trend toward using smaller control inputs under the motion condition than with the fixed base operation. Since this effect is relatively repeatable across simulation devices for most tasks, the important question becomes: How large is this effect and what is its likely impact on training? To answer this question, consider the data of subject A, who was the *most sensitive* to platform motion.

First, with respect to criterion performance, subject "A" is considerably more sensitive to aircraft type, target frequency (task), and time delay effects than to the presence or absence of motion. For example, consider the summary of Airplane-Motion-Delay effects for subject "A" given in Figure 19.

It is apparent that even for a "sensitive" subject in an experiment designed primarily to examine motion effects, motion has only a very limited effect on the subject. Changes in control behavior as measured by changes in RMS control input are, however, noticeable. The elevator and aileron deflection data from Reference 22 are shown in Figures 20 and 21.

It can be seen from these figures that the maximum mean criterion RMS difference across all conditions (including up to 400 ms lag) is 3.695 units (each unit is .01 radian) or 2.117 degrees RMS. Similarly, a difference of .501 degree RMS exists for the elevator deflections. If the motion and visual systems were both calibrated for a "zero" time delay condition, mean differences shrink to .583 degree RMS aileron and .267 degree RMS elevator (across both aircraft conditions). Referring to the force versus displacement chart (Figure 17), it can be seen that elevator force and position differentials (a few hundredths of an inch) are not discriminable to the human being, while the aileron force (estimated from the diagram to be about 25 lb/radian) would differ only a few ounces in control pressure! Here is a classic case wherein the power of the statistical tests and the resolution of the data can isolate the existence of an effect which, when taken from the larger view of training a pilot, is of no consequence whatever. It is important for the reader to realize that even if a statistically detectable difference in control strategy existed (in fact, even if that effect were large), there is no evidence at present to conclude that any one strategy is "better" than any other strategy, given comparable RMS criterion scores. These differences simply represent different ways of solving the tracking problem. The more sophisticated the task, the larger the class of acceptable strategies, and the less likely a detected difference has any interpretable meaning.

(a) Total error in meters

Interaction	Time delay	Motion	Pilot	Delay motion	Delay pilot	Motion pilot	Delay-motion pilot	Replicates	Error
d.o.f.	2	1	3	2	6	3	6	9	207
F	[a]35.3	[a]18.8	[a]98.8	[a]4.5	[a]3.3	[a]12.6	[a]5.4	1.12	
ω^2	9.76%	2.53%	41.74%	1%	1.96%	4.95%	3.76%	.15%	

(b) Vertical error in meters

Interaction	Time delay	Motion	Pilot	Delay motion	Delay pilot	Motion pilot	Delay-motion pilot	Replicates	Error
d.o.f.	2	1	3	2	6	3	6	9	207
F	[a]42.2	[a]37.4	[a]135.9	[a]12.1	[a]4.9	[a]11.7	2.0	1.25	
ω^2	9.7%	4.29%	47.64%	2.61%	2.75%	3.78%	.71%	.26%	

(c) Horizontal error in meters

Interaction	Time delay	Motion	Pilot	Delay motion	Delay pilot	Motion pilot	Delay-motion pilot	Replicates	Error
d.o.f.	2	1	3	2	6	3	6	9	207
F	[a]8.8	[a]13.4	[a]41.6	[a]5.2	1.22	1.6	1.7	1.32	
ω^2	3.82%	3.04%	29.82%	2.06%	.32%	.44%	1.03%	.71%	

Figure 18. **Analysis of variance for four pilots. (This figure shows the analysis of variance and omega square calculations for the motion, pilot, and time delay factors in a pursuit tracking task study conducted on the NASA-Langley Visual-Motion Simulator (VMS) (Ref 26). Although the motion effect is statistically significant at the .05 level, its relative effect size is very small.)**

	Total error in meters for units of time delay[a] of -									Total error in meters for units of time delay[a] of -					
	0	1	2	3	4	5	8	12	16	0	4	6	8	12	16
	Basic airplane - no motion									Good airplane - no motion					
	6.684	6.715	9.568	8.608	10.375	10.339	13.856	9.604	9.653	6.785	8.452	6.024	7.044	7.163	7.541
	6.264	7.541	8.181	8.903	8.196	9.418	10.866	9.485	11.485	7.138	6.812	7.012	7.087	7.900	8.656
	6.099	6.242	6.925	7.602	8.547	6.468	10.342	9.894	9.860	6.087	8.062	6.427	7.657	8.678	8.531
	7.370	6.078	7.602	8.708	7.678	8.193	8.595	11.189	8.629	6.008	7.410	6.492	7.175	13.350	9.034
	5.752	8.111	8.760	6.465	9.327	9.147	8.394	14.624	12.524	4.901	5.505	6.487	6.258	7.269	6.962
	8.111	8.089	7.276	9.083	7.757	8.092	7.903	8.809	11.384	5.319	6.593	6.035	7.675	6.026	5.877
	7.239	8.303	8.476	7.480	7.443	9.309	7.279	8.888	10.214	5.270	5.392	7.220	8.562	8.443	7.306
	7.583	7.343	5.685	7.279	8.861	12.674	9.946	15.222	11.585	4.386	7.361	7.498	5.870	7.507	7.306
	7.230	6.111	7.995	6.224	7.556	5.816	9.720	8.970	10.266	5.453	6.294	8.014	11.939	6.453	6.523
	7.498	6.422	5.611	5.364	6.468	6.885	9.050	9.360	11.777	7.154	5.855	7.520	6.309	7.199	8.605
$\bar{\epsilon}_v+\bar{\epsilon}_h$	6.983	7.095	7.608	7.572	8.224	8.634	9.595	10.605	10.738	5.850	6.773	6.873	7.561	7.999	7.634
$\bar{\sigma}$	.751	.886	1.276	1.266	1.104	2.020	1.869	2.380	1.195	.951	1.047	.681	1.730	2.047	1.041
t(time delay)	Control	.12	.91	.84	1.82	[b]2.77	[b]3.89	[b]5.40	[b]5.61	Control	[b]1.54	1.71	[b]2.86	[b]3.59	[b]2.98
t(airplane)										[b]3.10	[b]3.01		2.53	[b]2.62	[b]6.21
	Basic airplane - full motion									Good airplane - full motion					
	7.446	6.322	5.697	7.861	6.806	7.114	7.004	8.217	7.977	6.632	6.242		6.020	7.849	7.745
	7.175	6.245	6.861	7.254	6.379	7.065	6.764	7.148	10.394	5.855	6.072		6.139	6.291	8.291
	6.187	5.867	6.550	6.215	7.105	6.660	6.733	8.236	10.747	5.806	7.132		6.907	7.239	5.742
	7.330	5.428	5.806	6.654	7.081	5.965	5.297	7.714	8.498	7.135	7.647		6.550	6.032	8.842
	5.276	5.285	5.270	5.051	5.901	6.956	6.069	11.421	13.219	5.919	5.816		5.703	5.672	7.588
	5.666	6.117	5.499	6.507	5.566	6.130	6.130	10.144	6.837	4.874	4.813		6.069	6.904	9.095
	6.215	6.184	5.938	6.611	6.779	5.816	6.709	8.220	7.928	5.904	5.136		5.907	6.011	5.358
	7.337	6.242	4.703	6.035	7.132	7.565	6.608	8.501	9.991	5.404	5.374		5.733	5.316	6.615
	7.772	7.044	6.035	6.251	8.867	9.336	7.693	7.958	7.443	6.767	6.404		5.230	6.224	6.075
	5.718	6.517	7.007	5.791	7.093	5.715	8.915	7.724	9.824	5.218	5.901		5.364	6.212	7.916
$\bar{\epsilon}_y+\bar{\epsilon}_h$	6.612	6.128	5.937	6.423	6.871	6.832	6.792	8.529	9.286	5.952	6.054		5.962	6.375	7.348
$\bar{\sigma}$	.896	.507	.716	.772	.888	1.081	.978	1.282	1.920	.712	.868		.505	.754	1.297
t(time delay)	Control	1.01	1.40	.39	.54	.46	.32	[b]3.98	[b]5.56	Control	.26		.03	1.09	3.59
t(motion)	.76	[b]3.00	[b]3.08	[b]2.45	[b]3.01	[b]2.94	[b]4.06	[b]2.58	1.53	.27	1.67		[b]2.80	2.26	[b].55
t(airplane)										1.83	2.08		[b]2.38	[b]4.59	[b]2.65

Interaction	Airplane	Motion	Time delay	Airplane-motion	Airplane-delay	Motion-delay	Airplane-motion-delay	Replicates	Error
d.o.f.	1	1	4	1	4	4	4	9	171
ANOV[c] F	[b]80.05	[b]41.80	[b]20.38	[b]3.93	[b]3.00	[b]4.37	0.36	0.98	
ω^2	18.86%	9.74%	18.50%	.7%	1.91%	3.22%	0	0	

[a]Each unit of time delay equals 0.03125 sec.
[b]Significant difference at 5 percent level.
[c]ANOV denotes analysis of variance.

Figure 19. **Summary of data for airplane-motion-delay interaction with subject A. (t-tests performed treating each factor separately) (This figure, adapted from reference 26, shows the relative effect size platform motion has on the RMS total error performance of a subject "sensitive" to platform motion as a function of both aircraft type and time delay. Of special importance are the mean differences between the basic aircraft, with and without motion, at zero time delay, and the "good airplane," with and without motion, again at zero time delay (that is, with motion, aerodynamic and visual information approximately syncronized). In the case of the basic aircraft, a difference of only .371 meter error RMS total exists between the full and motion cases. Likewise, for a "good" aircraft, this difference dwindles to .102 meter. Differences of this magnitude are of little consequence in a training situation, as they are dwarfed by other, more powerful variables.**

	Aileron deflection (* 10^2), radians, for units of time delay[a] of -									Aileron deflection (* 10^2), radians, for units of time delay[a] of -					
	0	1	2	3	4	5	8	12	16	0	4	6	8	12	16
	Basic airplane - no motion									Good airplane - no motion					
	2.968	2.124	3.546	3.044	3.297	2.406	3.453	2.933	3.460	1.901	3.379	2.481	3.084	3.541	2.906
	2.363	2.394	1.991	2.035	2.583	2.458	3.070	2.878	4.803	3.036	2.371	3.547	2.419	2.556	2.811
	2.013	3.612	2.025	2.030	2.709	2.096	2.507	3.138	3.692	2.922	3.016	2.123	2.946	2.824	3.605
	2.070	1.685	2.426	2.091	1.661	2.269	2.931	3.942	2.762	2.055	2.561	2.539	2.340	5.512	4.328
	2.162	2.248	1.877	1.662	2.337	1.486	2.061	3.935	3.778	2.229	3.226	2.684	2.350	2.213	2.929
	1.662	1.726	2.186	2.054	1.800	1.995	2.579	4.280	4.241	1.815	3.626	2.904	2.643	1.480	1.814
	2.334	2.635	2.689	2.131	2.898	2.393	2.115	2.674	2.069	2.163	2.319	2.293	4.530	2.214	1.758
	3.644	1.867	2.241	2.046	3.267	3.366	2.685	2.341	2.895	1.905	3.548	2.859	1.566	3.118	1.758
	3.233	2.129	2.834	2.364	3.552	2.449	3.208	1.897	2.910	1.738	3.187	3.391	4.589	1.865	2.416
	2.734	1.855	3.023	2.396	2.424	2.324	2.743	2.450	3.302	2.900	1.824	3.429	2.049	2.925	1.633
$\bar{\delta}_a$	2.518	2.228	2.484	2.186	2.653	2.324	2.735	3.047	3.391	2.266	2.907	2.825	2.825	2.825	2.596
σ	.615	.572	.533	.363	.626	.471	.448	.780	.788	.497	.609	.495	.997	1.124	.897
t(time delay)	Control	1.10	.13	1.25	.51	.73	.82	1.99	[b]3.29	Control	1.77	1.54	1.62	1.54	.91
t(airplane)										1.01	.92		.34	.51	[b]2.10
	Basic airplane - full motion														
	1.328	1.369	1.531	1.684	1.732	1.541	1.758	2.404	2.468	1.555	1.764		1.859	1.679	1.346
	1.563	1.632	1.638	1.462	1.207	1.803	1.583	2.497	2.470	1.787	1.840		1.352	1.910	2.111
	1.441	1.746	1.814	1.899	1.461	1.539	1.842	3.099	2.799	1.653	1.357		1.969	1.547	1.764
	1.618	1.321	1.297	1.600	1.573	1.351	1.886	2.147	2.386	1.515	1.626		1.522	1.878	1.822
	1.108	1.926	1.337	1.560	1.723	1.999	1.424	2.253	3.022	1.115	1.478		1.630	1.131	1.557
	1.213	1.812	1.357	1.929	1.417	1.640	1.951	2.281	2.659	1.488	1.754		1.932	2.009	2.119
	1.977	2.077	1.611	1.769	1.844	1.849	2.253	2.634	2.472	1.750	1.169		1.389	1.895	1.916
	2.608	2.383	2.536	1.275	3.002	1.575	2.826	2.404	2.727	1.174	1.441		1.376	1.891	1.627
	2.708	2.350	1.162	1.386	2.955	1.449	2.516	1.793	1.477	1.720	1.504		1.214	1.885	1.692
	1.290	1.487	1.539	1.412	1.752	.982	3.070	1.184	1.415	1.255	1.424		1.774	1.663	2.410
$\bar{\delta}_a$	1.685	1.810	1.582	1.597	1.867	1.573	2.111	2.275	2.389	1.501	1.536		1.602	1.749	1.836
σ	.568	.377	.386	.221	.616	.285	.542	.508	.533	.244	.209		.270	.259	.313
t(time delay)	Control	.60	.49	.42	.87	.54	2.04	[b]2.82	[b]3.37	Control	.22		.64	1.58	1.73
t(motion)	[b]3.61	1.93	[b]4.33	[b]4.38	[b]3.62	[b]4.31	[b]2.81	[b]2.98	[b]2.77	[b]4.37	[b]6.85		[b]3.79	[b]2.99	[b]2.42
t(airplane)										.94	1.60		[b]2.66	[b]2.92	[b]2.41

Interaction	Airplane	Motion	Time delay	Airplane-motion	Airplane-delay	Motion-delay	Airplane-motion-delay	Replicates	Error
d.o.f.	1	1	4	1	4	4	4	9	171
ANOV[c] F	[b]12.23	[b]104.18	[b]4.30	2.23	1.41	0.38	0.84	0.57	
ω^2	3.47%	31.90%	4.08%	.38%	.51%	0	0	0	

[a]Each unit of time delay equals 0.03125 sec.
[b]Significant difference at 5 percent level.
[c]ANOV denotes analysis of variance.

Figure 20. **Aileron data for subject A. (This figure shows the effect of platform motion on joystick aileron commands for a motion sensitive subject in a pursuit tracking task conducted on the NASA Langley Visual-Motion Simulator. Although the motion effect is statistically significant, with a relatively large omega square, the actual joystick RMS movement ranges from .01501 radian (about .86 degree) to .02518 radian (about 1.44 degrees) for the zero time delay (motion, visual, and aerodynamic systems synchronized) case. The total workload effect, or resulting effect on training of difference this small is negligible.**

	Elevator deflection (* 10^2), radians, for units of time delay[a] of -									Elevator deflection (* 10^2), radians, for units of time delay[a] of -					
	0	1	2	3	4	5	8	12	16	0	4	6	8	12	16
	Basic airplane - no motion									Good airplane - no motion					
	0.843	1.060	1.074	1.253	1.288	1.341	1.297	0.766	0.771	0.568	0.665	0.530	0.696	0.750	0.767
	.996	1.090	1.159	1.132	.986	1.339	1.243	.853	.906	.573	.584	.607	.529	.732	.807
	.975	.854	.734	.925	.928	.946	1.186	.954	1.103	.546	.628	.553	.638	.763	.780
	.883	.736	.948	1.090	1.105	1.003	.900	.905	.935	.629	.564	.714	.724	1.006	.991
	.749	.955	1.009	.958	1.091	1.116	1.080	1.056	1.048	.489	.729	.670	.564	.635	.782
	.908	1.146	.983	1.252	1.118	1.149	.967	1.262	1.051	.543	.647	.517	.609	.612	.614
	.980	.743	.926	.505	.675	.810	.736	.572	.865	.677	.603	.704	.916	.971	.636
	.771	.630	.728	.724	.945	.967	.938	.825	.976	.597	.694	.725	.643	.742	.636
	.852	.514	1.024	.782	1.140	.776	1.068	.995	.837	.616	.658	.738	.754	.572	.645
	1.066	.601	.484	.562	.723	1.050	.809	.701	.987	.605	.683	.558	.495	.640	1.038
$\bar{\delta}_a$	0.902	0.833	0.916	0.924	1.000	1.050	1.022	0.889	0.948	0.584	0.646	0.631	0.657	0.722	0.770
σ	.102	.223	.208	.260	.191	.193	.185	.194	.105	.052	.051	.088	.123	.123	.149
t(time delay)	Control	.70	.14	.22	1.00	1.49	1.22	.14	.46	Control	1.32	1.01	[b]1.56	[b]2.96	[b]3.98
t(airplane)										[b]8.74	[b]5.68		[b]5.22	[b]2.30	[b]3.10
	Basic airplane - full motion									Good airplane - full motion					
	0.525	0.528	0.543	0.529	0.632	0.596	0.583	0.710	0.602	0.550	0.433		0.387	0.526	0.487
	.566	.623	.586	.612	.634	.611	.580	.632	.540	.475	.396		.465	.514	.500
	.535	.681	.624	.639	.651	.665	.644	.599	.642	.409	.486		.439	.421	.509
	.712	.574	.592	.070	.725	.706	.622	.626	.610	.416	.471		.427	.497	.552
	.601	.634	.678	.659	.712	.788	.782	.722	.600	.401	.421		.552	.488	.536
	.568	.643	.608	.064	.649	.722	.664	.592	.637	.378	.409		.458	.525	.461
	.603	.552	.529	.657	.609	.560	.638	.585	.629	.427	.403		.454	.493	.502
	.675	.630	.609	.574	.665	.594	.712	.606	.663	.402	.408		.440	.551	.525
	.604	.542	.484	.521	.694	.665	.684	.596	.514	.445	.465		.430	.543	.522
	.454	.438	.517	.522	.553	.545	.684	.566	.521	.455	.388		.482	.531	.596
$\bar{\delta}_a$	0.584	0.585	0.577	0.599	0.653	0.646	0.659	0.623	0.596	0.436	0.428		0.453	0.509	0.518
σ	.074	.072	.058	.069	.051	.077	.061	.052	.053	.050	.035		.043	.038	.037
t(time delay)	Control	.01	.25	.55	[b]2.39	[b]2.15	[b]2.63	1.37	.40	Control	.43		.96	[b]4.01	[b]4.53
t(motion)	[b]6.86	[b]3.36	[b]4.95	[b]3.83	[b]6.41	[b]3.26	[b]5.54	[b]4.22	[b]4.60	[b]6.51	[b]10.87		[b]4.96	[b]5.33	[b]5.19
t(airplane)										[b]5.30	[b]12.20		[b]8.58	[b]5.73	[b]3.87

Interaction	Airplane	Motion	Time delay	Airplane-motion	Airplane-delay	Motion-delay	Airplane-motion-delay	Replicates	Error
d.o.f.	1	1	4	1	4	4	4	9	171
ANOV[c] F	[b]222.31	[b]334.36	[b]3.34	[b]16.71	[b]5.75	1.00	0.45	0.90	
ω^2	27.82%	41.90%	1.18%	1.97%	2.39%	0	0	0	

[a]Each unit of time delay equals 0.03125 sec.
[b]Significant difference at 5 percent level.
[c]ANOV denotes analysis of variance.

Figure 21. **Elevator data for subject A. (This figure shows the effect of platform motion on joystick elevator commands for a motion sensitive subject in a pursuit tracking task conducted on the NASA Langley Visual-Motion Simulator. Although the motion effect is statistically significant, with a relatively large omega square, the actual joystick RMS movement ranges from .00436 radian (about .25 degree) to .00902 radian (about .52 degree) for the zero time delay (motion, visual, and aerodynamic systems synchronized) case. The total workload effect, or resulting effect on training of a difference this small, is negligible.**

IV. AIRCRAFT STUDIES

Of all the experimentation relative to motion cuing performed to date, inflight experimentation is the least well developed, however, one of the striking differences between inflight and many previous laboratory and simulator results is the profound difference between visual and instrument flight control behavior. These differences are characterized by higher gain and less phase lag across the flight control frequency range (Ref 29, 41). The gain difference between contact and instrument flight is a little over 10 dB in the mid frequency regime, with 10° or greater phase lead (contact, relative to instrument, flight). These same studies show very little difference between fixed base (instrument) behavior and actual aircraft behavior for experienced pilots on compensatory tracking tasks. Several authors have attributed the increased power of the visual effect to two contributory factors:

1. The high resolution of "real" visual information, together with peripheral cues.

2. The capability of the experienced human operator to generate highly complex, organized sequences of control actions based on partially complete information patterns.

Kuehnel (Ref 20) found that experienced pilots could detect changes in pitch disturbance and initiate correcting responses faster than would be expected from vestibular sensing alone. The reaction time given for pitch was everywhere below that expected from laboratory data for roll and yaw. Figure 22, adapted from Newell (Ref 29), summarizes this information. In his review, Newell (Ref 29) concludes that it is superior visual motion discrimination which accounts for the decreased latency:

> In summary, it appears that visual sensing can be of finer resolution than vestibular or tactile sensing and that it can operate for small motion perception without phase lag or time delays up to a frequency of 0.4 cps and with small phase lag but no great loss of information up to a frequency of 1.6 cps.

Whatever the explanation for these data, it is clear that a motion sense more refined than vestibular sensing, as it is presently understood, is at work. Since this information will always be available for use to the pilot in the aircraft whether or not he is trained on a simulator that employs platform motion, the utility of such a platform motion system appears marginal.

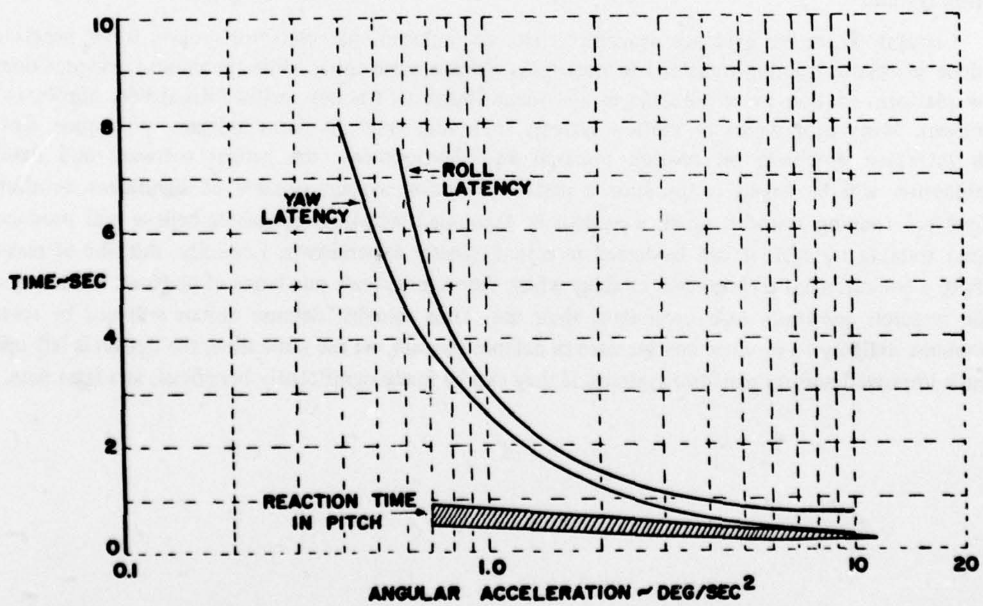

Figure 22. **Latency and reaction time versus angular acceleration.**

One of the difficulties remaining with inflight experimentation deals with problems in the computation of human transfer functions. Often insufficient power exits at the high end of the forcing function spectrum to permit a meaningful analysis of motion/no motion effects. In other cases, instrument lag (or resolution) makes comparison difficult.

The next study was an inflight simulation study conducted at the NASA Flight Research Center to determine roll-mode simulation motion requirements (Ref 41). White noise was passed through two second-order filters and used to create separate error command runs. Three values of roll-mode time constants were selected, to provide a range of aircraft performance from fighter to transport. Figure 23 shows the forcing function input function, and the results of the experiment for each of the roll-mode time constants. In this instance, in excess of 99% of the total input power is below 4 rad/sec. In this region, not only is visual performance considerably better than either fixed base or instrument flight (with actual aircraft motion), but fixed base performance is better than moving base, as measured by higher gain and lower phase lag over the mid and low frequency regimes! Considering the number of data runs made, comparison beyond frequencies of 2 to 3 rad/sec is not meaningful. (For a discussion of error analysis involving transfer function estimation see Bendat and Piersol (Ref 3) or Otnes and Enochson (Ref 31)). Therefore, for experienced pilots on compensatory tasks, the case for motion is extremely weak. Even full fidelity (actual aircraft) motion differs scarcely from fixed base operation. With such a minor differential for full fidelity motion, a platform motion system, with its numerous known deficiencies (Ref 6), cannot be expected to provide a significant transfer-of-training effect.

The subject of Flying Training transfer is an area which, by research standards, has been only modestly developed, but from an experience viewpoint it is voluminous. Every aircraft to aircraft, simulator to aircraft, or training course to aircraft is considered as a data point for transfer. Thus, the questions arise: Are platform motion systems necessary for training? If not, what is the training effectiveness of their less costly alternatives? Fortunately, in this area, the data are not at all ambiguous. For example, at the Flying Training Division of the Air Force Human Resources Laboratory (AFHRL/FT), almost all possible maneuvers and tasks for Instrument, Navigation, Formation, Contact, Air-to-Air, and Air-to-Surface flight, have been examined, and as yet not a single one has been found that is not trainable without a platform motion system.

Certainly from the evidence available it can be deduced that platform motion is *not* necessary to produce successful training transfer for most tasks. At the same time, while the present evidence does not show platform motion to be valuable as an enhancement to training, neither has it been shown to be a detriment. Many proponents of motion systems, including some simulator industry spokesmen, feel that with increased emphasis on motion research and development, the proper software and hardware combination will be found to produce a platform motion system capable of significant, economical, differential training transfer. Once a system is developed which investigators believe will produce the desired training transfer, it can be tested in actual transfer experiments. Logically, this line of reasoning leads to a procurement and research strategy which defers large scale purchases of platform motion systems while research continues into optimizing their use. Thus valuable defense dollars will not be spent on equipment unlikely to produce any increase in defense posture. At the same time, the option is left open to include improved motion platform systems, if they can be made significantly beneficial, at a later date.

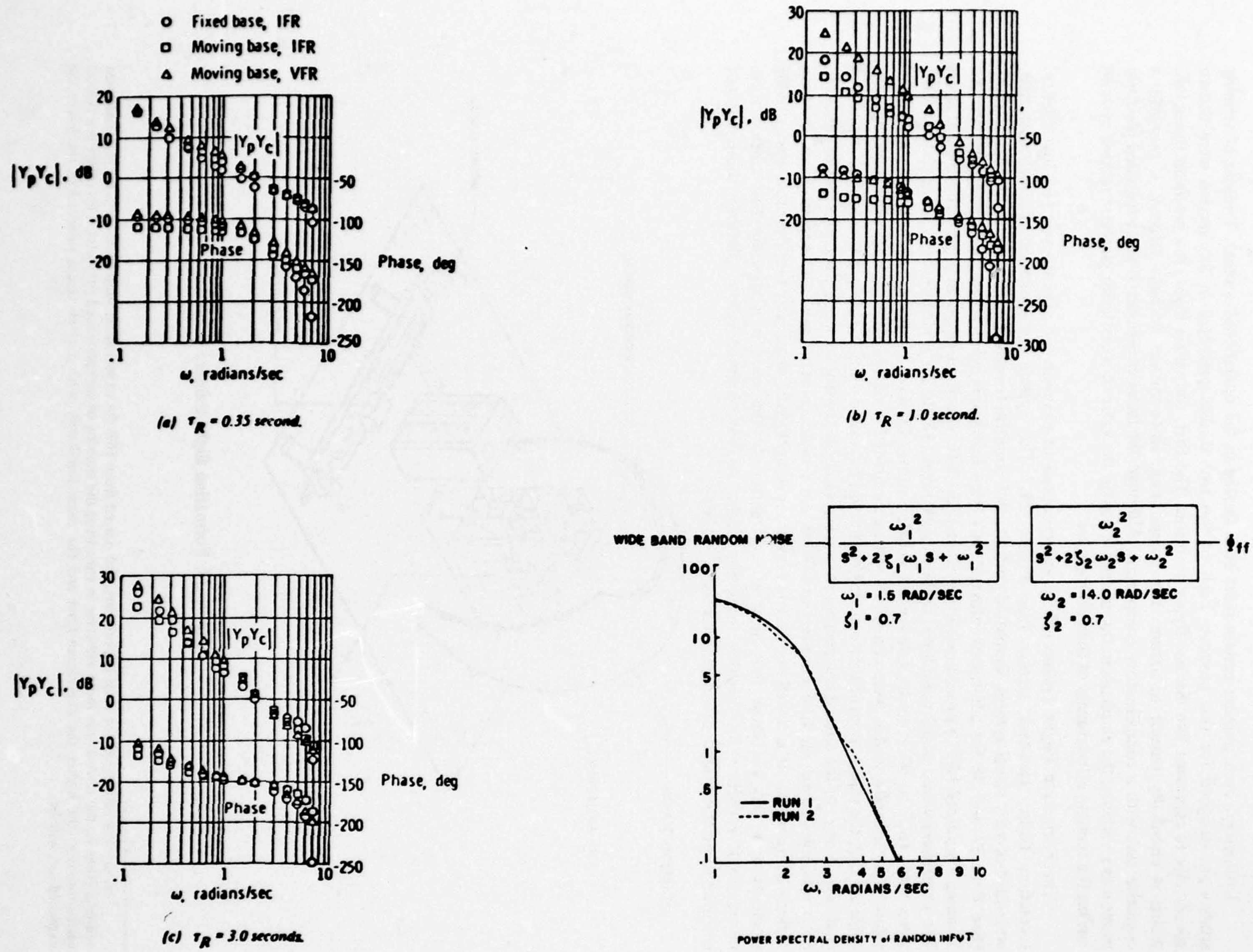

Figure 23. **Man machine transfer functions and disturbance input power spectrum for NASA in-flight simulation experiment.**

V. TRANSFER OF TRAINING STUDIES

Ultimately, each training system must be evaluated in the operational context. Transfer of training studies are designed for this purpose. Each of the two studies presented in this section were chosen specifically to represent two distinct flying problems. The first, formation flight, is a precision flying task which is essentially pursuit in nature. The second task, air-to-surface weapons delivery, is primarily a cognitive task with a compensatory component. Although the latter experimental study included platform motion as a variable, the emphasis in this section is not on the value of a particular platform motion system, but on the training effectiveness of their alternatives.

The Formation Flight Trainer (FFT) was procured to examine the effectiveness of a low fidelity, formation flight, part-task trainer (see Figure 24). The system consisted of a low resolution, wide-field-of-view visual system, simplified cockpit, and primitive (constant spring) control loading system. (See Refs 37 and 38 for additional information.) Nine maneuvers were taught in accordance with Air Training Command (ATC) procedures and evaluated by ATC check pilots on an expanded 12-point scale. The maneuvers were: straight-and-level, shallow bank turns (15° to 20°), medium bank turns (30° to 40°), steep turns (60° to 90°), route, crossunder, echelon turns (45° bank), turning rejoin, and straight-ahead rejoin. Two separate studies were conducted with a combined N of 111. Both studies provided conclusive evidence that the trainer is an effective device, significant beyond $p = .05$.[3] This was true in spite of the fact that few, if any, of the critical engineering parameters (such as control stick gain, aircraft transfer function, etc.) resembled their physical counterparts. What did remain constant were the cognitive and decision making components. It is a well known and important characteristic of transfer that the most generalizable elements of a task are those that most affect transfer. In this case, it is apparent that control form invariance is sufficient for teaching formation flight. As was observed before, platform motion is not essential to produce rapid, effective, economical training.

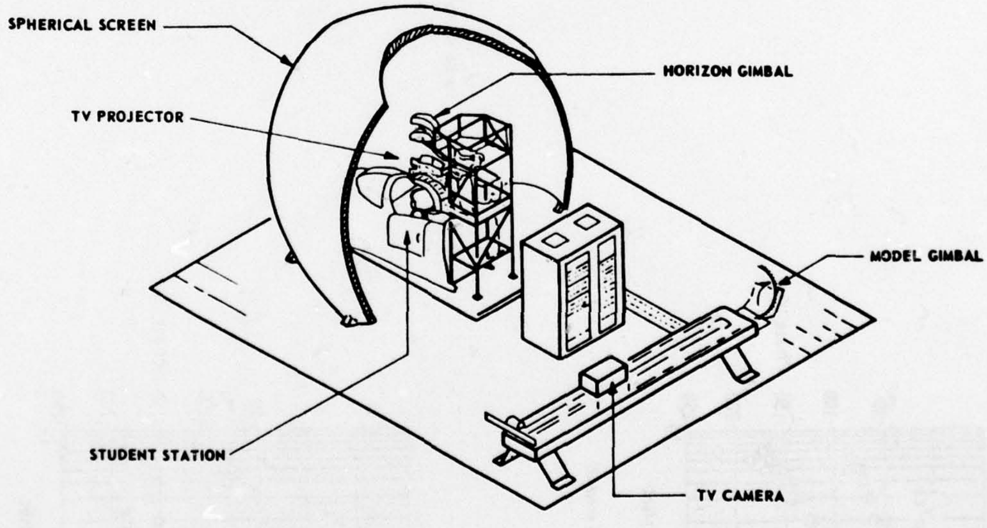

Figure 24. **Formation flight trainer.**

[3]An ω^2 was calculated for each experiment, and ranged from 16% for experienced subjects to 39% for inexperienced subjects (that is, the device was more effective in enhancing the training of inexperienced subjects). This effect is a typical one; moreover, the higher the experience level and the more familiarity with a given task a subject has, the lower the expected ω^2 will be.

The next study (Ref 10) examined a more general transfer effect, that of air-to-surface weapons delivery training. In this experiment, 24 undergraduate pilot training graduates were intercepted just prior to F-5B fighter lead-in training and given instruction (eight 1-hour sorties) in air-to-surface weapons delivery techniques in the Advanced Simulator for Pilot Training (ASPT). The ASPT, a full mission simulator with wraparound computer generated visual capability located at Williams AFB, Arizona, was configured as a T-37, not an an F-5B, for this study. After training, each group dropped ordnance from the F-5B on the Air Force Gila Bend Gunnery Range. The resulting distributional differences between the simulator trained groups and the control group were visually distinct.

Bear in mind, this was the first F-5B aircraft sortie ever flown by these subjects. Their error scores and range performance were representative of graduates of Combat Crew Training School with considerable range experience. There were no motion effects (positive or negative) of any kind. At this point, it is important to consider the training ramifications of this experiment. First, from the fidelity viewpoint, very few of the critical simulation engineering parameters are similar to their aircraft counterparts. The control dynamics are unrealistic, the range pattern and airspeeds were much slower in the simulator than in the actual aircraft, and the instruments, mil-settings, in fact, even the basic shape of the lift/drag curves are dissimilar. Yet, in spite of these differences, transfer was exceptionally high. Again, what is "similar" is what matters the most: the cognitive components, for precisely the same reasons, namely, that they are invariant under the translation from simulator task to aircraft task. Teaching "judgement," or more precisely the building a strategy of flying based on experience, is the critical problem.

Air-to-surface training and experimentation have now been extended to A-10 transition and air-to-surface research using a simplified A-10 flight model developed at AFHRL/FT. Both phases of training (through two classes) have been extremely successful. In some cases, the novice pilots transitioning to the A-10 have actually outperformed their instructor pilots in terms of bomb scores on the Air Force Gila Bend Gunnery Range (dropping practice bombs from the A-10 aircraft). For the A-10 study (being conducted for TAC), platform motion is not used. Instead, motion cues are supplied by a G-seat system and, to a large degree, by the wraparound visual system. The effect on within-simulator performance of experienced pilots of the visual field-of-view is exponential (see Figure 25).

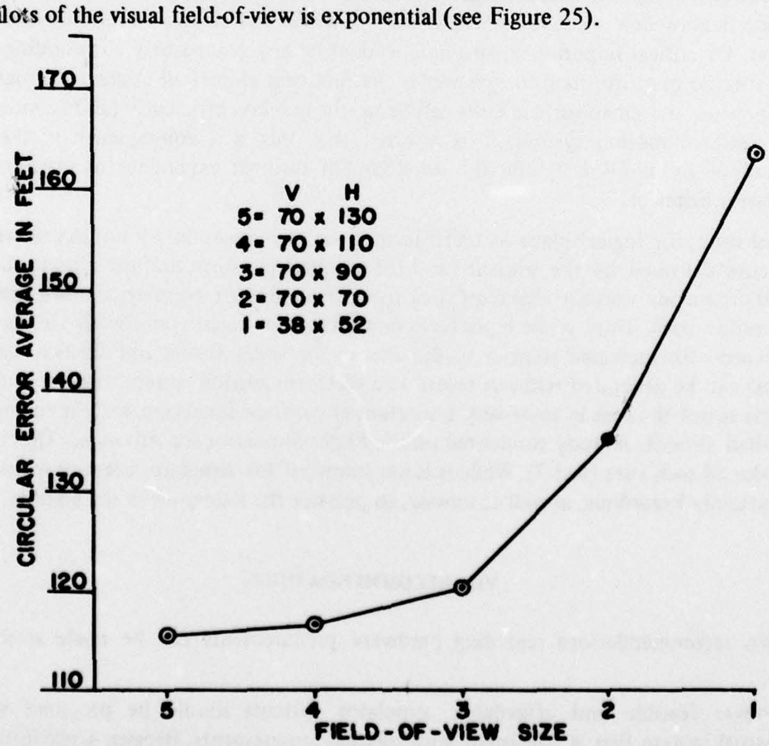

Figure 25. **Field-of-view effect on simulator bomb deliveries.**

It would be misleading to imply that strong visual effects apply only to experienced pilots. In the first of a series of contact flight studies conducted on ASPT, eight novice subjects were taught basic aircraft control in the simulator including takeoff, straight-in approach and landing, 360° overhead pattern and landing, configuration change, turns to heading, and airspeed control. Subjects were advanced on a proficiency basis in the simulator. Of the eight subjects, seven were successful in landing the aircraft on their first aircraft sortie (the test flight for this experiment). The very fact that the instructor pilots felt confident enough about the student's ability to allow the student to complete the landing is indicative of the training value of the simulator. The wide-field-of-view visual display is a key element here because an overhead pattern simply cannot be practiced without one.

VI. ANALYSIS

In reviewing the data relative to platform motion and flying training for fixed wing aircraft, several salient points arise. The earlier experiments were small-sample compensatory or pursuit tracking tasks wherein the operator was asked to nullify the effect of an incoherent signal forcing function, displayed visually on an oscilloscope or similar device. The typical control dynamics were not generally representative of operational aircraft, often having substantial negative damping ratios or an extraordinarily high number of poles in the denominator of the control element transfer function. Subject population and controller characteristics were also dissimilar to the operational environment. In subsequent simulator experiments, as well as in later transfer experiments the addition of platform motion had little, if any, noticeable effect on criterion performance in standard aircraft flying tasks; operator output behavior, however, was affected, although that effect was seen to be small in absolute terms. Other variables were demonstrated to have an equal or more profound effect on training (effect size) than the presence or absence of platform motion. These include individual subject differences, (e.g., experience and ability), practice effects, task variables, aircraft and control loading response characteristics, and other information sources; most particularly high resolution, wide-field-of-view visual systems, G-seats, G-suits, buffet and vibration systems, and aircraft instrumentation. Of critical importance, and independent of any controversy surrounding the engineering limitations of specific platform motion systems, is the fact that almost all contact, formation, navigation, instrument, air-to-air, and air-to-surface tasks can be taught quickly, efficiently (and economically) without employing a platform motion system. It is asserted that this is a consequence of the fundamentally cognitive nature of flying (Ref 9) and the development through experience of open-loop, hierarchical control over motor behavior.

As a final note, the logical place to teach proper use of motion cues is not in a simulator, but in the aircraft. The cues delivered by the present (and foreseeable) platform motion systems differ radically in both time and frequency domain characteristics from their aircraft counterparts, except in the case of buffet and vibration cues. Thus, while a platform motion system might conceivably aid performance in the simulator, prospects for increased transfer to the aircraft are small. Buffet and vibration cues (often termed "alerting" cues) can be generated without resort to a platform motion system through some less expensive alternative. This is not the case in some very important emergency situations, such as engine-out on takeoff for a wide bodied aircraft. A study conducted on the Flight Simulator for Advanced Aircraft demonstrated the positive value of such cues (Ref 7). While it is not known if this simulator practice would transfer to the aircraft, it is certainly hazardous, as well as unwise, to practice the maneuver in the aircraft.

VII. RECOMMENDATIONS

Only two recommendations regarding hardware procurements can be made as the result of this report:

1. Wherever feasible and affordable, simulator systems should be procured with the largest field-of-view visual system that is consistent with mission requirements. Because a platform motion system

has a considerable impact on visual system design alternatives and these will eventually affect training effectiveness, platform motion should be carefully scrutinized prior to its inclusion.

2. Until research can develop a significantly improved platform motion system (one capable of enhancing training) simulators may safely be procured without a platform motion system, (without compromising training effectiveness). Naturally, the option to buy a platform motion system can always be held open at some cost.

Since the early 1950's, considerable research efforts have been spent on analyzing compensatory and pursuit tracking tasks. The result has been a collection of descriptive mathematical models which can, on a trial-to-trial and pilot-to-pilot basis, be made to fit observed data. The mathematical models treat the human pilot essentially as a passive servo-system, while ignoring his cognitive and decision making processes. Attempts to model skilled, open-loop monitoring behavior is unfortunately limited at present to general block diagrams. Some excellent work has occurred in the area of cognitive sets and workload estimation using maximum likelihood estimators (Ref 5). This work should be continued and extended.

It has long been known that human controllers can and do develop hierarchical control over skills even in "unsolvable" tasks (Ref 35, 36). Invariably, this skill acquisition results in behavior that is superior to a strictly error-feedback strategy, giving the impression that the human operator is processing information at a higher rate than would be expected on the basis of even continuous feedback alone, let alone time-sampled feedback. Research is required to determine both the mechanism for this remarkable behavior and the means for instilling it into pilot trainees. Perhaps some of the conceptual models offered by nonlinear information processing theory (maximum likelihood (Ref 21) or maximum entropy (Ref 13, 28)) will point the way. Determining the pilot's cognitive and decision process is necessary to understand and optimize flying training.

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