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**USAAVLABS TECHNICAL REPORT 67-55**

**V/STOL GROUND-BASED SIMULATION TECHNIQUES**

By

J. B. Sinacori

November 1967

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**U. S. ARMY AVIATION MATERIEL LABORATORIES  
FORT EUSTIS, VIRGINIA**

**CONTRACT DA 44-177-AMC-462(T)  
NORTHROP CORPORATION  
NORAIR DIVISION  
HAWTHORNE, CALIFORNIA**

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DEPARTMENT OF THE ARMY  
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FORT EUSTIS, VIRGINIA 23604

This report has been reviewed by the U. S. Army Aviation Materiel Laboratories and the Human Engineering Laboratories, and is considered to be technically sound. The work was performed under Contract DA 44-177-AMC-462(T).

Various kinds of simulators were studied to determine their capability of producing data representative of visual flight for V/STOL aircraft. The resulting data were compared and correlated with flight data from the same aircraft. The simulators used different displays, motion modes, and instrumentation, and the results are discussed in the light of the characteristics of each simulator. To eliminate the necessity for correlating pilot performance, only one subject pilot was used to generate the simulator and aircraft data required for this study.

The report is published for the dissemination and application of information and the stimulation of ideas in the area of simulation technology with emphasis on handling qualities research.

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by

J. B. Sinacori

Prepared by

Northrop Corporation  
Norair Division  
Hawthorne, California

for

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FORT EUSTIS, VIRGINIA**

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## SUMMARY

A study of various kinds of simulators has been made to determine their capability to produce data representative of visual flight. Four simulations of a jet-lift V/STOL aircraft were conducted using the same pilot. Control characteristics and airframe parameters were maintained constant (as closely as possible), and the same tasks were used by the pilot in each evaluation. The resulting data were compared with flight results from the same aircraft. The simulators used different displays, motion modes, and instrumentation, and the results are discussed in the light of the characteristics of each simulator.

The results show clearly that in order to produce quantitative data representative of flight results, the display must have a quality level compatible with the task being performed. Specifically, a precision hovering task requires a high resolution display, while a translation (or transition task) can be performed with a display of much less resolution. The display content is important, particularly for the precision hovering task where height holding is required. For flight simulation of large translational movements, cockpit motion did not appear to affect the results; however, for precision hover and small, quick position changes, cockpit motion appears to be important in that it assists the pilot in detecting small drift and improves his ability to control vehicle attitude. The absence of cockpit motion when using a point source visual display for the presentation of visual information can cause vertigo and loss of performance.

The study shows that valid V/STOL flight simulation can be accomplished and that quantitative and subjective data which closely compare with flight results can be obtained.

## FOREWORD

This final technical report covers the work performed by Northrop Corporation, Norair Division, under Contract DA 44-177-AMC-462(T) during the period 27 June 1966 to 27 May 1967. It was sponsored by the USAAVLABS, Fort Eustis, Virginia, and was monitored by Mr. Robert P. Smith of the Aeromechanics Division.

The program at Northrop Norair was performed under the direction of Mr. J. T. Gallagher, Supervisor of Vehicle Dynamics and Control Branch, with Mr. J. B. Sinacori serving as Principal Investigator. Report number NOR 67-85 has been assigned for internal control.

The author gratefully acknowledges the assistance of the following: Mr. Ronald M. Gerdes, research pilot for the National Aeronautics and Space Administration, during the final experiment; Messrs. L. S. Rolls and R. K. Greif, also of NASA, for their contribution of essential data; and Mr. John D. Waugh of the U.S. Army Human Engineering Laboratories for his assistance during the final experiments.

The following are among the many Northrop Corporation personnel who contributed significantly to this effort:

Mr. D. S. Patton - Simulator Development  
Mr. R. B. Wilson - Computer Programming  
Mr. L. C. Pickett - Data Analysis  
Mr. E. D. Onstott - Data Analysis  
Mr. J. T. Gallagher - Data Correlation and Critique  
Dr. H. J. Coleman - Human Factors  
Mr. W. T. Richardson - Human Factors

All constructive comments, suggestions, and recommendations are solicited and should be forwarded to USAAVLABS, Attn: SAVFE-AM.

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## SYMBOLS

G	simulator actuator position - ft
g	acceleration of gravity - 32.2 ft/sec <sup>2</sup>
Hz	frequency, cycles per second
I <sub>x</sub>	rolling moment of inertia - slug-ft <sup>2</sup>
I <sub>y</sub>	pitching moment of inertia - slug-ft <sup>2</sup>
I <sub>z</sub>	yawing moment of inertia - slug-ft <sup>2</sup>
j	$\sqrt{-1}$
K <sub>P<math>\phi</math></sub>	pilot gain in bank - in./rad
K <sub>P<sub>y</sub></sub>	pilot gain in lateral displacement - in./ft
L	rolling moment - lb-ft
M	pitching moment - lb-ft
m	vehicle mass - slugs
N	yawing moment - lb-ft
P	probability density function
p	vehicle roll rate - rad/sec
q	vehicle pitch rate - rad/sec
r	vehicle yaw rate - rad/sec
R.M.S.	root-mean-square value

### SYMBOLS (Continued)

<b>S</b>	visual display transparency scale; ratio of real-world dimension to transparency dimension
<b>s</b>	Laplace transform variable
<b>T</b>	thrust - lb
<b>T<sub>L</sub></b>	pilot lead time constant - sec
<b>t</b>	time - sec
<b>u</b>	vehicle inertial velocity along X body axis - ft/sec
<b>v</b>	vehicle inertial velocity along Y body axis - ft/sec
<b>w</b>	vehicle inertial velocity along Z body axis - ft/sec
<b>X</b>	longitudinal force along vehicle X axis - lb
<b>X'</b>	longitudinal displacement in earth axis system - ft
<b>X<sub>u</sub></b>	longitudinal force due to longitudinal velocity - lb/ft/sec
<b>Y</b>	lateral force along vehicle Y axis - lb
<b>Y'</b>	lateral displacement in earth axis system - ft
<b>Y<sub>v</sub></b>	side force due to side velocity - lb/ft/sec
<b>Z</b>	vertical force along vehicle Z axis - lb
<b>Z'</b>	vertical displacement in earth axis system - ft
<b>Z<sub>w</sub></b>	vertical force due to vertical velocity - lb/ft/sec
<b>δ<sub>TP</sub></b>	pilot's throttle deflection - in.
<b>δ<sub>SP</sub></b>	pilot's stick deflection in pitch - in.

### SYMBOLS (Continued)

$\delta_{SR}$	pilot's stick deflection in roll - in.
$\delta_{RP}$	rudder pedal deflection - in.
$\phi$	vehicle bank angle - deg (except where noted)
$\phi_B$	phase angle - deg
$\theta$	vehicle pitch angle - deg (except where noted)
$\psi$	vehicle yaw angle - deg (except where noted)
$\xi$	damping ratio
$\epsilon_\phi$	error, commanded bank angle - actual bank angle - rad
$\epsilon_Y$	error, commanded side position - actual side position - ft
$\tau$	time constant - sec
$\Phi$	power spectral density function
$\omega$	frequency - rad/sec
$\sigma$	real part of a root or root-mean-square value
<b>Subscripts</b>	
pitch	denotes pitch axis
roll	denotes roll axis
yaw	denotes yaw axis
RC	reaction control
T	thrust
c	command
p	body axis attitude rate - roll

SYMBOLS (Continued)

q	body axis attitude rate - pitch
r	body axis attitude rate - yaw
x	denotes simulator X axis
y	denotes simulator Y axis
z	denotes simulator Z axis
ss	steady state

**NOTE:** A dot over a quantity indicates differentiation with respect to time.

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## INTRODUCTION

The solution of the problems resulting when attempts are made to conduct valid pilot-in-the-loop simulation centers on one point: the transmission of all the essential cues to the pilot and the effective extraction of his control movements. All other aspects of the problem are secondary in the sense that they are mathematically describable to whatever degree is necessary or desired. In Figure 1, a generalized description of the various components of a simulator is shown. Several distinct subsystems are evident, and each can provide only an approximation to the real world.

The results of this study are discussed in light of the performance of these subsystems in providing the pilot with a real-world representation. The vehicle used in this study was the NASA X-14A jet-lift VTOL aircraft. This aircraft as presently configured is capable of only visual flight. Therefore, throughout this study only visual simulations were attempted. Cockpit instrumentation was not seriously considered. Also, the aural and olfactory cues were not deliberately included and as such are probably incorrect. The force feel system in all the simulators was adjusted so that the feedbacks to the pilot were identical to those in the aircraft.

Studies of the motion and outside visual display subsystems comprise the major portion of this investigation. Some effects of the force feel and instrumentation subsystems are indicated, however.

Two tasks were employed in each evaluation: (1) the precision hover at an altitude of 15 feet in which aircraft position in the horizontal plane is held to a root-mean-square value of 1 foot or less, and (2) the lateral quick-start and -stop maneuver. This is a lateral change of aircraft position starting from a dead hover, and moving to a laterally displaced hover position, with a return to the initial point with altitude held at about 15 feet. The position amplitude of the lateral quick-stop maneuvers varies from 20 feet to about 50 feet. Heading is held constant for both tasks. These are the standard tasks employed by NASA pilots when evaluating a lateral (roll) control system designed for low-speed operations.

The simulators employed the full range of possible variations. They are listed broadly in the following:

Simulator A: poor display, good cockpit motion

Simulator B: fair display, fixed cockpit

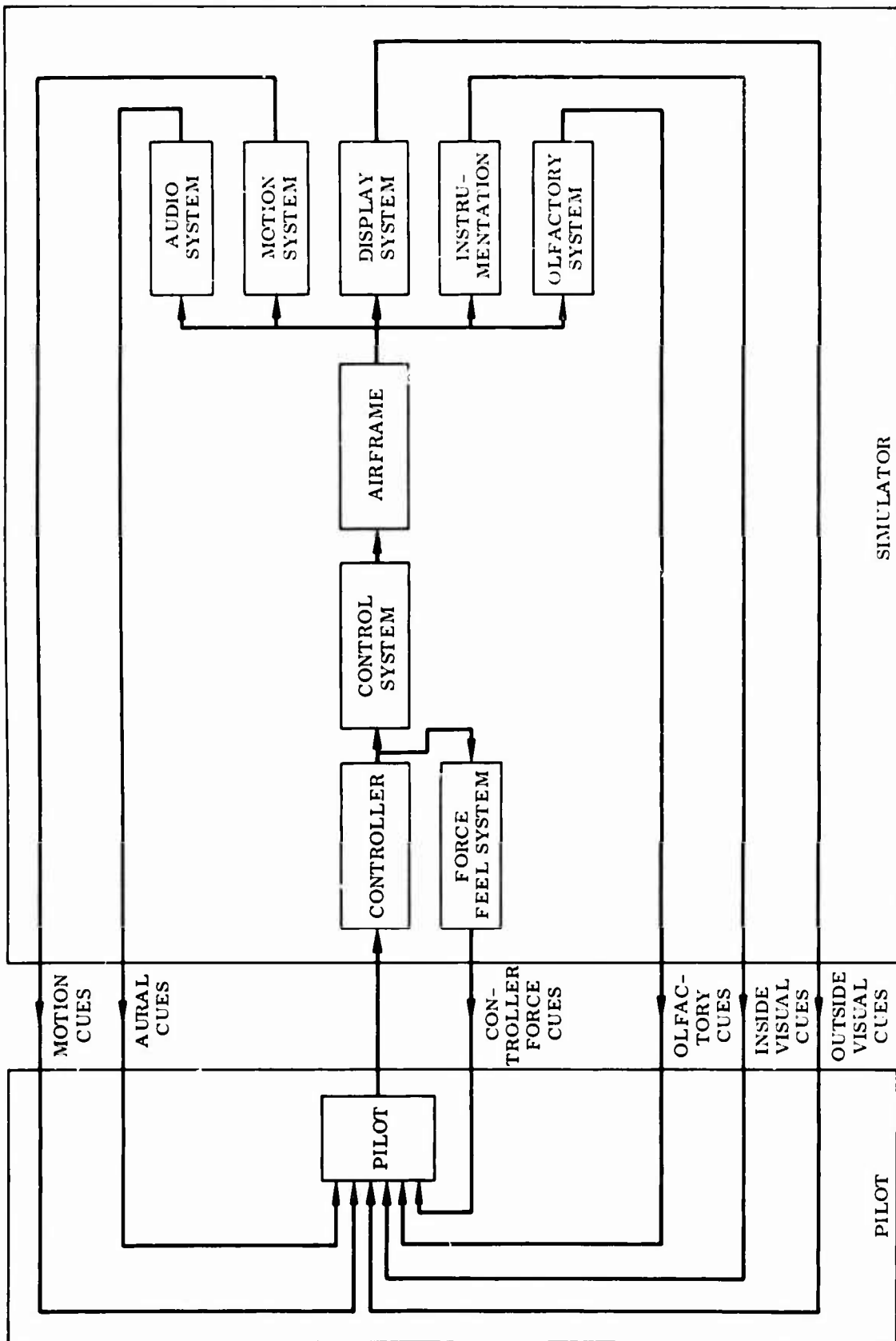


FIGURE 1. BLOCK DIAGRAM OF FLIGHT SIMULATOR

Simulator C: good display, fixed cockpit

Simulator D: good display, six degrees of motion

Power spectral and probability density analyses were carried out on selected variables including the pilot's stick movement,<sup>1</sup> and subjective pilot opinions were obtained.

Only the roll axis variables were analyzed because only roll axis data were available from flight test for the particular conditions considered.

With the exception of a limited number of tests in Simulator C, all the tests were made with the same pilot. The conclusions are based upon the comparison of the pilot's activities and performance in the simulators and in flight.

The flight tests are reported in reference 1, and numerous descriptions and excellent test results of the X-14A vehicle may be found in reports by the Flight Test Staff of NASA-Ames Research Center. Operations performed on the X-14A flight test data consisted of the following:

1. Calculation of the effective transfer function of bank angle from lateral stick for hover from oscillograph records and digital computer techniques.
2. Calculation of the effective transfer function of side position from bank angle (all other variables constant) from 16 mm motion picture films using analog computer techniques.
3. Conversion of the oscillograph records to magnetic tape signals using a manually operated optical tracker.
4. Generation of power spectral and probability density function of selected time histories from the magnetic tape using an electronic wave analyzer.
5. Calculation of control system frequency response from taped data using the electronic wave analyzer.

The sample of flight data used as a reference was one of several recorded in two flights and is believed to be typical of all the records. Variation in magnitude of any of the variables, such as stick position and control

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<sup>1</sup>All power spectral density plots of lateral stick movements are normalized such that 100% = 3 inches travel.

moment can be large, depending on pilot activity. This is part of the reason why two maneuvers which require a high and low level of pilot activity were chosen for analysis. The variations in levels among all the maneuvers are small compared to the levels themselves.

Recommendations for future work required to complete the solution of the problem are included. It is felt that the findings reported herein offer one solution to the problem of conducting valid V/STOL simulation. It is recognized that other valid approaches exist which are not covered by this study.

## PROBLEM DESCRIPTION

The objective of any flight simulation is to produce data representative of flight. When this cannot be done easily, it becomes necessary to understand why and to learn what can be done to the simulator to cause the data to resemble flight results.

As might be expected, the pilot interfaces present the greatest obstacles to analysis or interpretation. Specifically, this means that subsystem elements such as cockpit instrumentation and motion, visual displays, and stick feel characteristics, if not provided correctly, can create confusion when the data are interpreted. For reasons of cost and complexity, research simulator fidelity has historically been low and the interpretation of the results has thus been qualified.

Out of necessity, the simulator data have been extrapolated to the corresponding flight conditions and the appropriate analyses made. Fortunately, pilot opinion has been used extensively as a quantitative pilot output and has therefore lent some consistency to the mass of simulator data available. Whereas pilot opinion has been used with great benefit, it has also been misused, with highly questionable data resulting. Some discrepancies due to incorrect pilot integration are discussed below.

### DISCREPANCIES RELATED TO TASK

When a pilot is called upon to "rate a system" after first familiarizing himself with its dynamics and "flying" several missions or tasks, he is usually aware of the limitations of the simulator and consequently modifies his reactions and rates accordingly. Thus, he may rate the simulator, not the selected dynamics of the aircraft that the simulator imitates. To attempt, therefore, to compare absolute pilot opinion requires careful examination of the task and the fidelity of the simulator approximation to the real dynamics.

Other aspects of pilot integration in the VTOL simulation are apparent when simulator results from tests with one or two axes of rotary motion are compared with single-axis results, or those from simulators with translatory motion. The exact degree of correlation cannot be determined simply because the pilot is required to control more loops and the task becomes different.

### DISCREPANCIES DUE TO PILOT EXPERIENCE AND PREJUDICE

The VTOL problem during low-speed maneuvering is peculiar because the bulk of handling quality data is based on an attitude-change task, although the real task is to maneuver the vehicle over the ground. Unless the maneuver task is well-defined, the pilot will select a task consistent with his abilities and thereby insert pilot experience as a variable into the problem. The question of previous pilot training and experience enters all phases of simulation in another way also. It is well-known that a pilot will compare aircraft dynamic response to that of vehicles that he is familiar with and often use descriptive expressions involving parameters of a totally different system. Such "second-guessing" affects pilot opinion and introduces another unknown factor into the result.

In some instances, the limitations of the simulation require that the pilot project his simulator sensations to the real world. For example, he compares his experience of changing attitude in a conventional aircraft to that in the VTOL aircraft at low speeds and comments, "I wouldn't wish to fly this aircraft in gusty air." The projection was made, but since some VTOL aircraft have low gust susceptibility at low speeds (out of ground effect), the projection is incorrect and the pilot rating too critical.

### DISCREPANCIES DUE TO DISPLAYS

A poor display can seriously limit or alter the assigned task. For the VTOL aircraft being simulated during day VFR hover operations, this is a critical point. Since, again, the loop with which the pilot is most concerned is the position loop, failure to provide correct position information may cause him seriously to limit his maneuvering, or revert to an attitude stabilization task. Cockpit displays are often inadequate and responsive to cockpit motions in a manner different from real instruments. Outside visual displays offer only a few of the real cues present. The question arises of how much is enough. This is an important point for studies requiring low-level ground tracking tasks.

### DISCREPANCIES DUE TO MOTION

It has been observed by Northrop Norair that during a five-degree-of-motion simulation, the pilot expressed increasing difficulty in flying the assigned task after the addition of degrees starting from zero. Yet pilot comments on tests with only two rotary degrees of motion consistently disclosed that the simulator was easier to fly with motion than without (using only attitude information via an oscilloscope). One must

conclude loosely that motion cues are always distracting but sometimes offer useful information which enables the pilot to close loops more satisfactorily.

In the case of VTOL hovering, or low-speed maneuvering, the question arises regarding the usefulness of the relatively high frequency attitude cues compared to the low frequency translation cues. When the aircraft becomes large enough so the pilot station is considerably off the center of gravity, the linear acceleration resulting from the rotational motion is significant and could have a strong influence on pilot performance.

These discrepancies are pointed out to emphasize the lack of knowledge of integrating the pilot with a simulator. They show that while pilot opinion alone is helpful, considerable inaccuracy may result.

## APPROACH

Since a major contributing factor to the problem of conducting a valid simulation is proper control and documentation of simulator tests, a five-part approach was taken:

1. Past test data were screened carefully and only credible data were selected for study corresponding to the same test conditions.
2. These data were augmented by performing additional tests which compensated for deficiencies found in the original data.
3. Selected variables such as pilot stick deflection, control moment, bank angle, and side position were analyzed. The analyses consisted of calculation of root-mean-square, power spectral density, and probability density of these variables. In addition, pilot opinion was obtained where applicable. This consisted of the Cooper Pilot Rating.
4. The data from each simulation were compared with similar data taken from flight tests.
5. Each simulator type was examined and criticized in the light of the comparison and the characteristics of each type.

## CHRONOLOGY OF EVENTS

Data from various simulations and flight tests were used in this study program. These simulations and flight tests are described briefly below.

### SIMULATION A

Under sponsorship of the Navy (references 1 and 2), Northrop Corporation completed a simulation in October 1964 to verify the design of an all-mechanical rate command attitude control for the X-14A vehicle. The system was verified and hardware was fabricated.

### FLIGHT TESTS

Flight tests were conducted by NASA personnel at Ames Research Center during December 1965. In all, thirteen flights were performed, data were taken, and an analysis of these data was made. Attitude controllability in roll was acceptable with a Cooper Pilot Opinion of 3-1/2 (reference 1).

### SIMULATION B

In fulfillment of contractual obligations for this study, a final complementary experiment was designed and performed during April 1967. The objective was to explain certain observations gathered from an intensive study of Simulation A and the flight tests.

### SIMULATION C

This is a modified form of Simulation B, and was performed during the same period.

### SIMULATION D

This work was performed by NASA personnel at Ames Research Center during February 1967. These data were taken using the Ames six-degree-of-freedom-motion simulator. These data were kindly provided by NASA to serve as a check case for the present study. Details of the simulator may be found in reference 3.

## EXPERIMENTAL RESULTS AND CRITIQUE

The four simulations, A, B, C, and D, are discussed in the following paragraphs. For each simulation, the salient features are outlined, the experimental results are described, and an evaluation is made.

### SIMULATION A

#### Salient Features

A full description of Simulation A may be found in reference 1. To clarify some of the experimental results, the following salient features of this simulation are provided:

1. Cockpit yaw motion illusion was produced by a mixture of cockpit motion and opposite display movement. Pitch and roll were used one to one.
2. Outside visual display consisted of a runway outline (white), earth (dark), and sky (blue). All were projected on a flat screen which was about 10 feet from the pilot's eyes. The horizon was held fixed, and the runway outline changed perspective in response to vehicle position changes in space. A photograph of the cockpit and display is shown in Figure 2.
3. Stick feel characteristics were adjusted to match those in the X-14A.
4. Minimum cockpit instrumentation was used.
5. Control system (roll axis) matched flight except for time constant. For a first-order rate control,

$$\left. \begin{array}{l} \frac{p}{\delta_{SR}} \Big|_{ss} = .27 \text{ rad/sec-in.} \\ \text{and} \\ \tau = 0.135 \text{ sec} \end{array} \right\} \text{ Simulator}$$

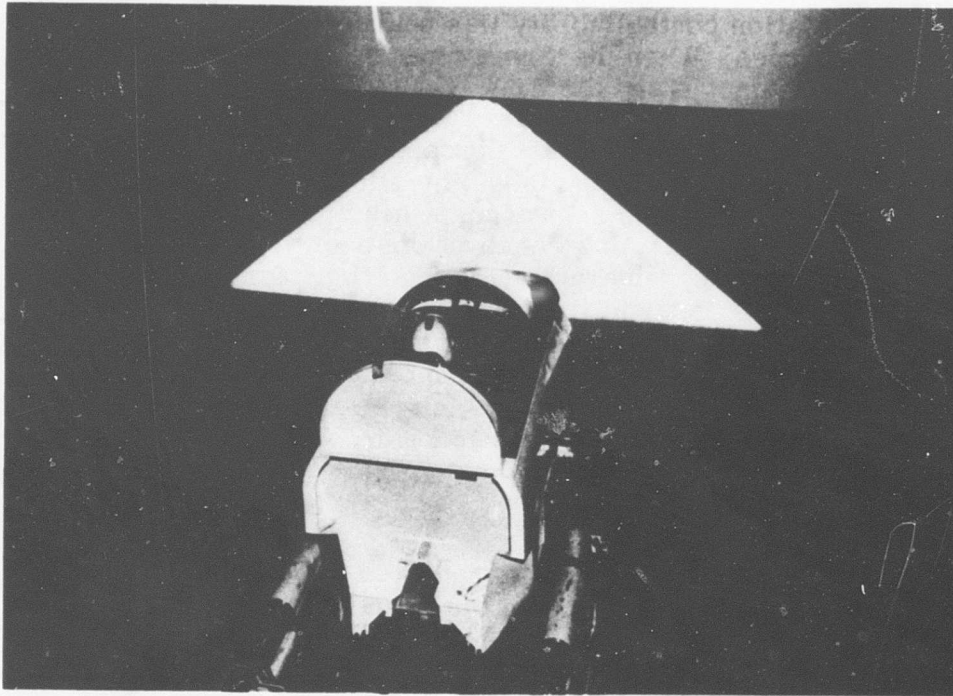


FIGURE 2. VISUAL DISPLAY AND COCKPIT OF SIMULATOR A

$$\left. \begin{array}{l} \frac{p}{\delta_{SR}} \Big|_{ss} = 0.28 \text{ rad/sec-in.} \\ \text{and} \\ \tau = 0.4 \text{ sec} \end{array} \right\} \text{Flight}$$

6. The airframe equations of motion are given in reference 1.

### Experimental Results

The results of Simulation A are outlined briefly below:

1. Control of altitude was impossible because of insufficient altitude cues.
2. Flights were possible with the vertical degree of freedom fixed.
3. Attitude controllability was good. A Cooper Pilot Rating of 3-1/2 was achieved for pitch, roll, and yaw.

4. Translation controllability was unacceptable because of poor visual cues. When the runway was near, runway movement was not smooth and the runway could not be seen because the nose of the simulator blocked visibility. At far distances, runway motion was barely perceptible and therefore unusable. For a general hovering task, the pilot reported the visual cues similar to those as seen at night near the end of and slightly above a runway. As a result of the poor visual cues, pilot stick activity was considerably less than flight for maneuvering and comparable to flight for hover. Bank angles were lower than flight except for hover, and hover accuracy was not less than 10 feet (R.M.S.). A comparison of performance may be seen in Tables I and II, and lateral stick power spectral and probability density functions are shown in Figures 3 and 4.

### Critique

1. Attitude controllability was reported to be good because the basic control was good and the visual and kinesthetic cues of the simulator were accurate. Roll control time histories (reference 1) revealed no overcontrol tendencies. No pilot vertigo tendencies were discovered. The power spectral density of the stick inputs in roll, shown in Figure 3, shows no lightly damped poles at frequencies of 0.5 Hz (the approximate closed loop root for attitude), verifying that a good attitude closure was being effected by the pilot.
2. Insufficient translational cues existed which caused the pilot to perform poorly in this respect. Hovering more nearly resembled uncontrolled drifting, and attempted maneuvering appeared ill-defined. Both the content and the dynamics of the display prevented the pilot from producing a good position closure. The difference in the control system dynamics (flight versus simulator) would normally indicate that pilot lead required for good control should be less in the simulator than in flight; therefore, stick activity should be less. However, insufficient evidence exists to substantiate this point. The power spectral density of pilot lateral stick inputs can be seen in Figure 3 and the probability density of the same variable in Figure 4. A comparison of the data from this simulator with flight results shows that the energy for the simulated flight is lower than that in actual flight at nearly all frequencies for the lateral quick-stop maneuver. However, the energy levels are comparable for hover.

**TABLE I**  
**SUMMARY OF IMPORTANT RESULTS FOR EACH SIMULATION AND FLIGHT**

R. M. S. Test		Root-Mean-Square Values of Roll Axis Quantities for Various Simulators and Flight Time												
		Hover Task			40-Ft Lateral Quick Start and Stop Task *									
		$\delta_{SR}$	$\dot{p}$	$\phi$	$Y'$	$\delta_{SR}$	$\dot{p}$	$\phi$	Percent Full Travel	Rad/Sec <sup>2</sup>	Degrees	Percent Full Travel	Rad/Sec <sup>2</sup>	Degrees
Simulator A cockpit motion in pitch, roll, yaw; poor visual display		4.35	.053	0.5	~10	7.8	.079	1.5	7.8	.079	1.5			
Simulator B cockpit fixed fair visual display		6.05	.088	1.8	~9	7.3	.095	3.0	7.3	.095	3.0			
Simulator C cockpit fixed good visual display		2.90	.042	1.0	~2.4	9.6	.136	3.0	9.6	.136	3.0			
Simulator D all moving cockpit		3.60	.086	0.6	~0.5	21.0	.316	4.6	21.0	.316	4.6			
Flight Test		4.25	.220	1.0	~1.0	11.5	.330	3.6	11.5	.330	3.6			

\* For Simulator D, only a 15-foot lateral quick-stop maneuver was possible due to limited travel.

TABLE II

SUMMARY OF IMPORTANT SIMULATOR CHARACTERISTICS, FLIGHT TEST PARAMETERS FOR THE LATERAL AXIS, AND GENERAL SIMULATOR AND PILOT PERFORMANCE

Subsystem	Subsystem Description					Pilot Comments**	
	Affiliation	Stick Force Feel System*	Airframe Transfer Functions	Motion System	Display System		Cockpit Instrumentation
System			$\frac{\phi(s)}{SR(s)} = \frac{0.7}{s(s+2.5)}$ rad/in. $\frac{\psi(s)}{SR(s)} = \frac{32.2}{s(s+1)}$ ft/rad $\frac{\delta(s)}{SR(s)} = \frac{32.2}{s(s+1)}$ ft/rad	Cockpit Only: Pitch Roll Yaw	Runway Outline and Horizon	Minimum Day Visual Flight Rules	Attitude performance good. Translation performance poor. Attitude holding impossible only without vertical degree of freedom.  Attitude performance fair. Overcontrol tendency. Translation performance fair. Excellent for large translations.
Simulator A Pilot A	Northrop	P 1/2 lb friction, $\pm 3''$ max R 2 lb friction, $\pm 3''$ max Y 6 lb friction, $\pm 3''$ max Z 3 lb friction, $\pm 8''$ max	$\frac{\phi(s)}{SR(s)} = \frac{2}{s(s+7.4)}$ rad/in. $\frac{\psi(s)}{SR(s)} = \frac{32.2}{s(s+1)}$ ft/rad $\frac{\delta(s)}{SR(s)} = \frac{32.2}{s(s+1)}$ ft/rad	Fixed Base	DeFlores Type: Airport Transparency 750 to 1 Scale	None	Attitude performance fair. Overcontrol tendency at times. Translation performance good. Excellent for precision hover.
Simulator B Pilot A	Northrop	P 1/2 lb friction, $\pm 3''$ max R 1.8 lb friction, $\pm 3''$ max Y 6 lb friction, $\pm 3''$ max Z 3 lb friction, $\pm 8''$ max	$\frac{\phi(s)}{SR(s)} = \frac{0.7}{s(s+2.5)}$ rad/in. $\frac{\psi(s)}{SR(s)} = \frac{32.2}{s(s+1)}$ ft/rad $\frac{\delta(s)}{SR(s)} = \frac{32.2}{s(s+1)}$ ft/rad	Fixed Base	DeFlores Type: Detail on Airport Transparency 80 to 1 Scale	None	Attitude performance fair. Overcontrol tendency at times. Translation performance good. Excellent for precision hover.
Simulator C Pilot A	Northrop	P 1/2 lb friction, $\pm 3''$ max R 1.8 lb friction, $\pm 3''$ max Y 6 lb friction, $\pm 3''$ max Z 3 lb friction, $\pm 8''$ max	$\frac{\phi(s)}{SR(s)} = \frac{0.7}{s(s+2.5)}$ rad/in. $\frac{\psi(s)}{SR(s)} = \frac{32.2}{s(s+1)}$ ft/rad $\frac{\delta(s)}{SR(s)} = \frac{32.2}{s(s+1)}$ ft/rad	Six Degrees of Motion	Real World	Minimum Day Visual Flight Rules	Attitude and translation performance excellent. No overcontrol tendency.
Simulator D Pilot A	NASA Ames Research Center	P 1/2 lb friction, $\pm 3''$ max R 1 lb friction, $\pm 3''$ max Y 6 lb friction, $\pm 2.5''$ max Z fighter type quadrant	$\frac{\phi(s)}{SR(s)} = \frac{0.7}{s(s+2.5)}$ rad/in. $\frac{\psi(s)}{SR(s)} = \frac{32.2}{s(s+1)}$ ft/rad $\frac{\delta(s)}{SR(s)} = \frac{32.2}{s(s+1)}$ ft/rad	Real World	Real World	Minimum Day Visual Flight Rules	Overall controllability acceptable with PR-3-1/2. No vertigo tendency.

\*P - Pitch, R - Roll, Y - Yaw, Z - Throttle \*\*PR - Cooper Pilot Rating

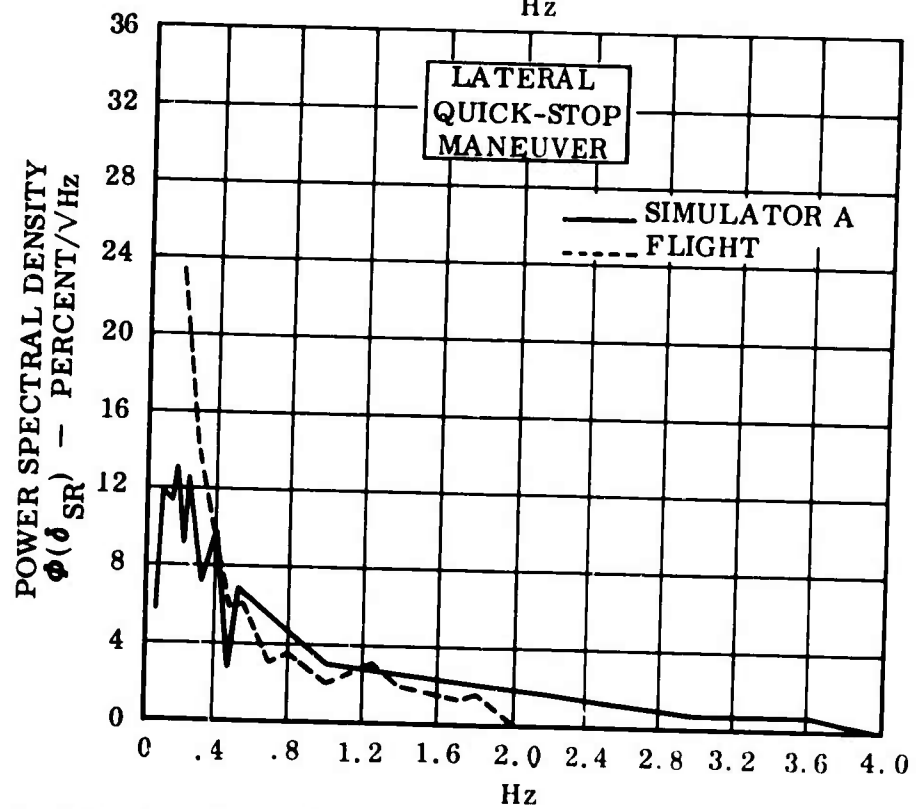
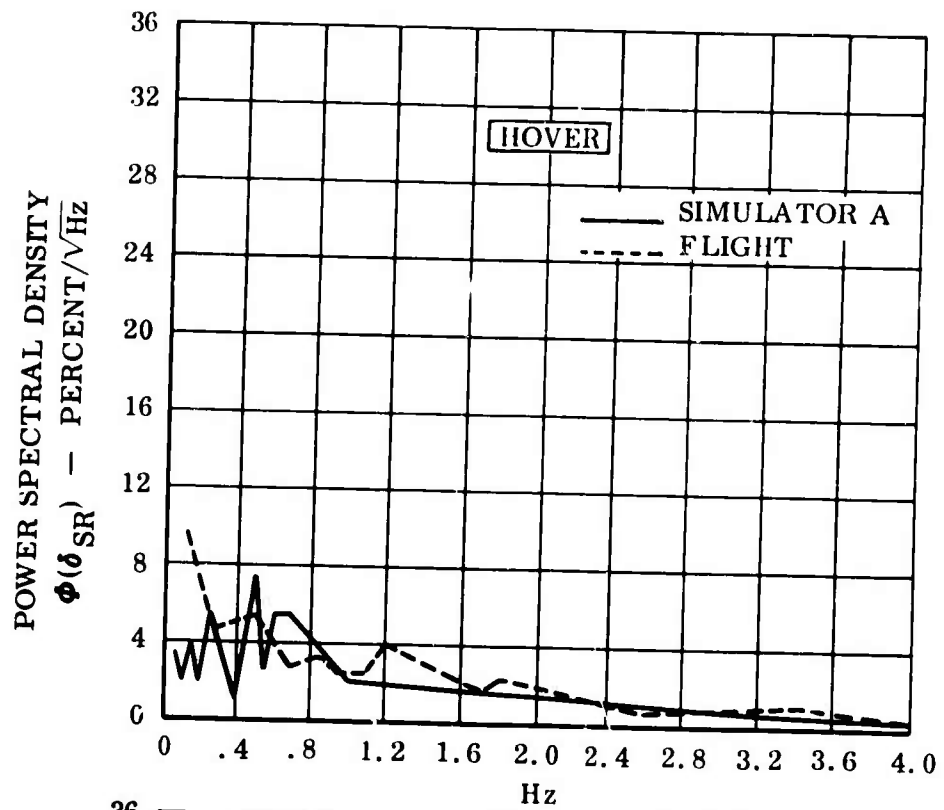


FIGURE 3. POWER SPECTRA OF LATERAL CONTROL INPUT, SIMULATOR A

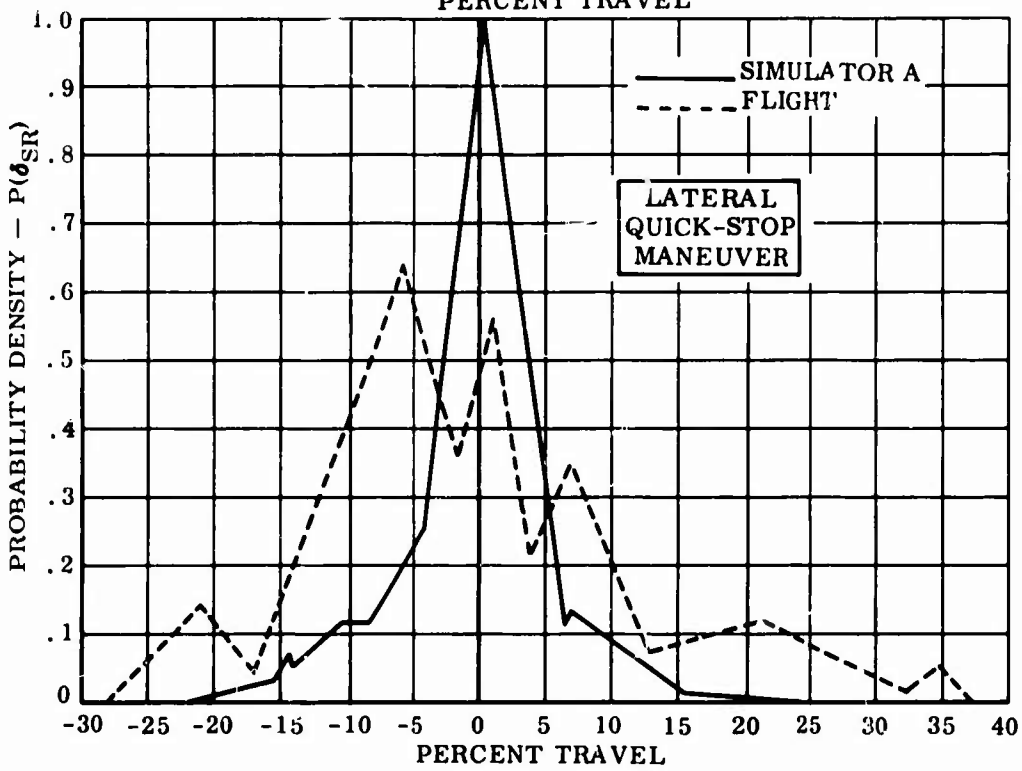
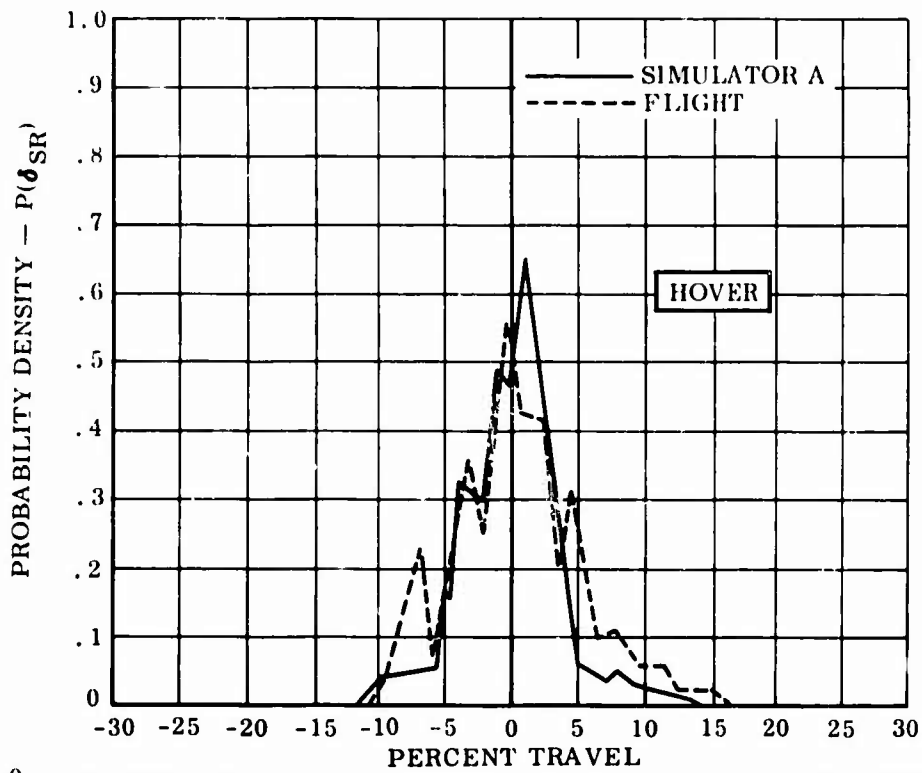


FIGURE 4. PROBABILITY DENSITY OF LATERAL CONTROL INPUT, SIMULATOR A

## SIMULATION B

### Salient Features

A full description of Simulation B is contained in Appendix I. The salient features are outlined below:

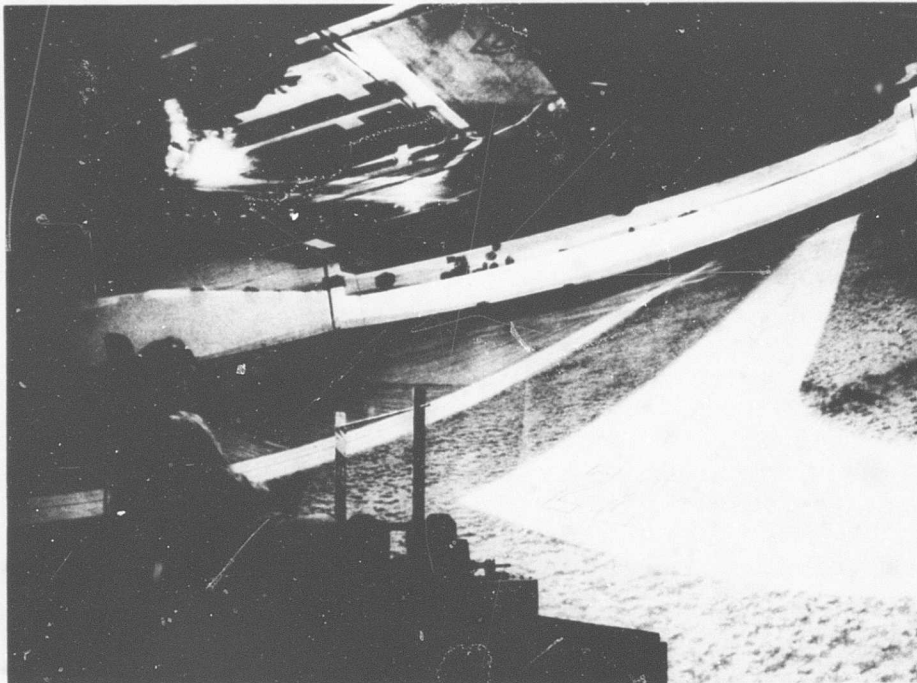
1. The simulator is fixed base.
2. Outside visual display was of the DeFlorez type and consisted of an airport scene projected on a  $180^\circ$  wide by  $30^\circ$  high spherical screen, as shown in Figure 5. The illusion of six degrees of motion was created by introducing the proper motion to the transparency. The scene was in full color and the 4-foot-square area of the transparency was scaled at a ratio of 750 to 1 ( $S = 750$ ). The following thresholds were measured for each degree of freedom at this scale:

Pitch	Roll	Yaw	X'	Y'	Z'
.026°	.017°	0.70°/sec	4.5 ft	3.0 ft	3.7 ft

3. Stick feel characteristics were adjusted to match those in the X-14A.
4. No cockpit instrumentation was used. A horizontal bar was installed at shoulder height about one arm's length in front of the pilot.
5. Control system (roll axis) was identical to flight.

### Experimental Results

1. Attitude controllability was unacceptable for hovering or close maneuvering. Attitude performance was similar to results of Simulation A, and R.M.S. values of stick position and bank angle were less than flight values, as can be seen on Tables I and II.
2. Translational control was acceptable for large movements such as translating down the runway or for making approaches to a landing.
3. The position controllability was unacceptable near the ground due to several factors:



**FIGURE 5. VISUAL DISPLAY AND COCKPIT OF SIMULATOR B**

- a. The position thresholds at a scale of 750 to 1 precluded precision hovering. The R.M.S. of lateral position during an attempted precision hover at an altitude of 30 feet was 10 feet where the threshold was 3 feet.
- b. Occasional excitation of the transparencies' natural frequency of 8 Hz destroyed the display illusion momentarily and was slightly annoying to the pilot.
- c. Near the ground, the scene becomes less clear due to the finite dimension of the light source, and consequently resolution decreases.
- d. The content of the display, particularly near the horizon, was not realistic, and occasionally the pilot would confuse altitude and pitch attitude changes.
- e. Position control was characterized by "drift" type motions during attempted hover and inaccurate position changes during maneuvering near the ground.

- f. Pilot vertigo was induced as the time duration of a particular flight increased. Vertigo was especially annoying to the pilot during attitude reversals or hovering. The pilot felt he could do better with cockpit motion cues.
- g. The pilot felt that he could not perceive small drift motions and therefore down-rated the controllability accordingly.
- h. Power spectral and probability density distributions of the pilot's stick inputs are presented in Figures 6 and 7. Note that they are lower than the flight values except during attempted hover where the energy at 0.6 Hz in the simulated flight is larger than flight.

### Critique

1. The unacceptability of the attitude control is the result of the pilot's not being able to bring the vehicle to an acceptable hover either at high or at low altitude. At high altitude, hover is difficult anyway; but at low altitude, the realism of the display was destroyed by the excitation of the transparencies' natural frequencies and the loss of resolution. The large relative position thresholds which exist at this scale also prevent an acceptable hover. If a hover cannot be achieved, then a lateral maneuver is not possible.
2. The control is acceptable for large translations away from the ground because the errors generated during attempted hover are not serious when applied to a large translation maneuver such as translating down the runway at an altitude of 100 feet. This is because the longitudinal plane assumes importance during the maneuver and the lateral excursions resulting from poor roll control are small compared to the large longitudinal motion. In other words, sideslip angles are maintained within acceptable limits.
3. The reduced pilot activity (see Table I) is caused by the inability of the pilot to perceive small motions, thereby causing him to adapt a "loose" control technique. In other words, he sees little and therefore does little.
4. Pilot vertigo may be caused by the conflict between the sometimes "fair" visual cues acquired during attempted hover and the highly trained kinesthetic sensations which are expected but not felt because the cockpit is fixed. Inadvertent pilot head motions were observed frequently.

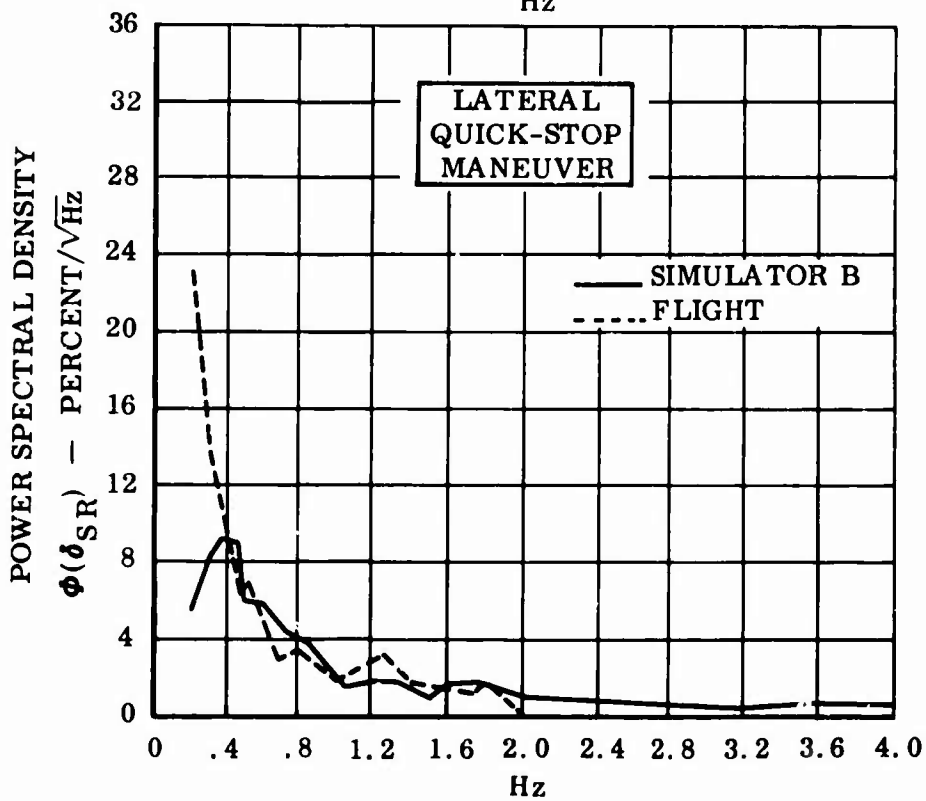
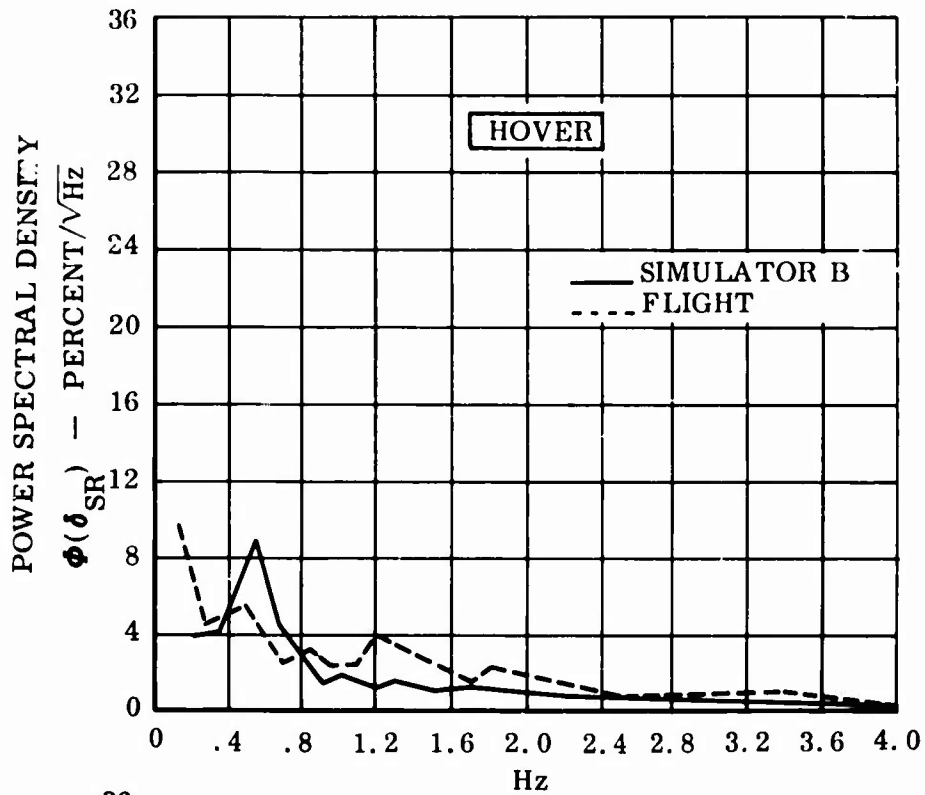


FIGURE 6. POWER SPECTRA OF LATERAL CONTROL INPUT, SIMULATOR B

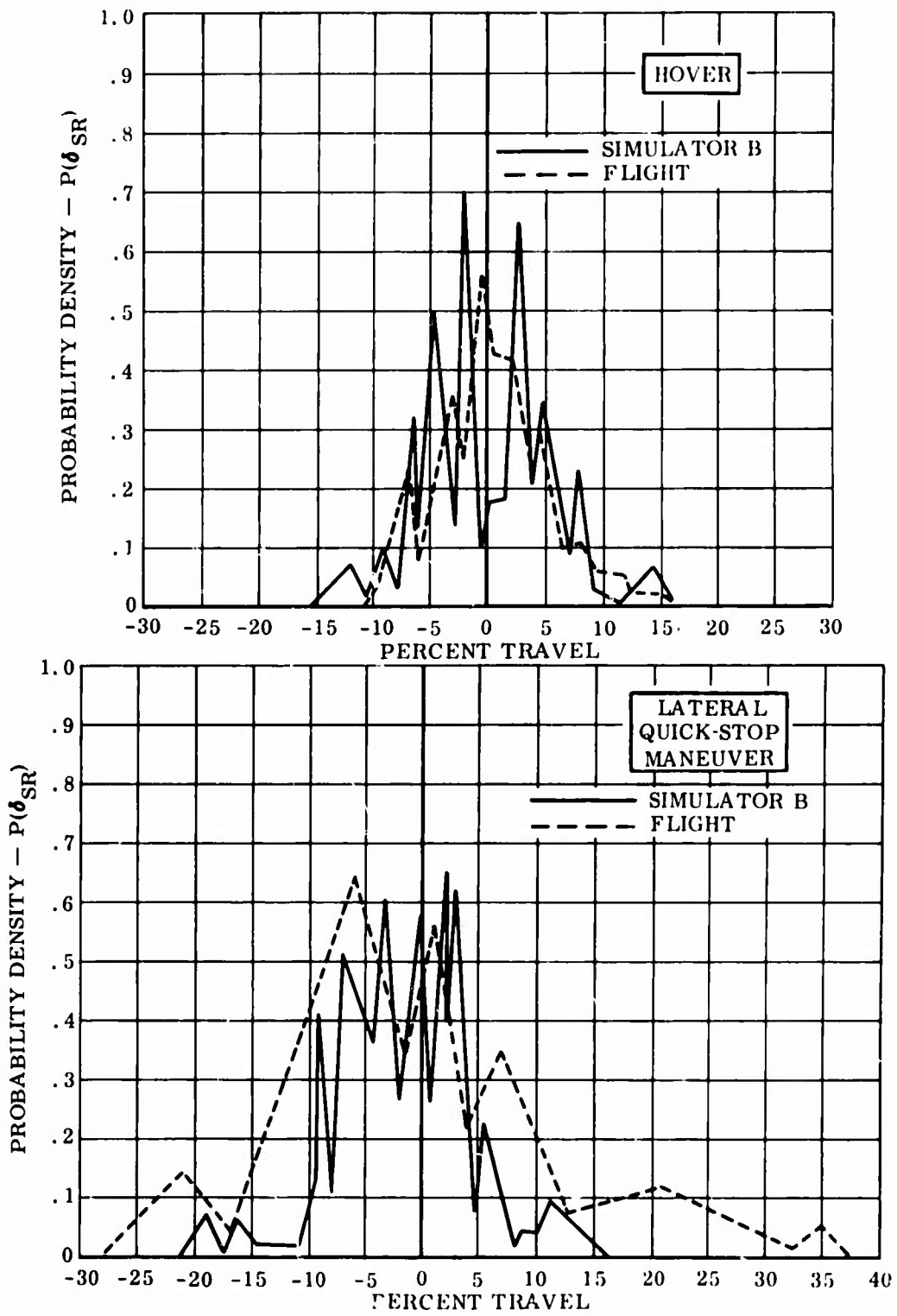


FIGURE 7. PROBABILITY DENSITY OF LATERAL CONTROL INPUT, SIMULATOR B

5. The increased R.M.S. of lateral stick during attempted hover over the flight value is probably caused by the additional energy in the attitude closure resonance at 0.6 Hz, as can be seen on Figure 6. This is a consequence of the lightly damped closure that the pilot is producing.
6. Altitude holding near the ground was considered to be difficult by the pilot because of the absence of vertical references.

### SIMULATION C

#### Salient Features

A full description of this simulation is contained in Appendix I. Salient features are outlined below:

1. The simulator is fixed base.
2. Outside visual display was of the DeFlorez type similar to that of Simulator B with the exception that transparency scale was 80 to 1 ( $S = 80$ ) and the content of the display was different as shown in Figure 8. This display consisted essentially of a modified blowup of a portion of the 750-to-1 transparency.

A helicopter pad was represented containing towers for altitude reference and a grid system. The grid scale was 10 feet per square and the towers were 30 feet high with a horizontal reference line halfway up. Measured resolutions at a scale of 80 to 1 are given below:

Pitch	Roll	Yaw	X'	Y'	Z'
.026°	.017°	0.7°/sec	0.48 ft	0.32 ft	0.40 ft

3. Stick feel characteristics were adjusted to match those in the X-14A.
4. No cockpit instrumentation was used. A horizontal bar was installed at shoulder height about one arm's length in front of the pilot.
5. Control system (roll axis) was identical to that in the airplane.

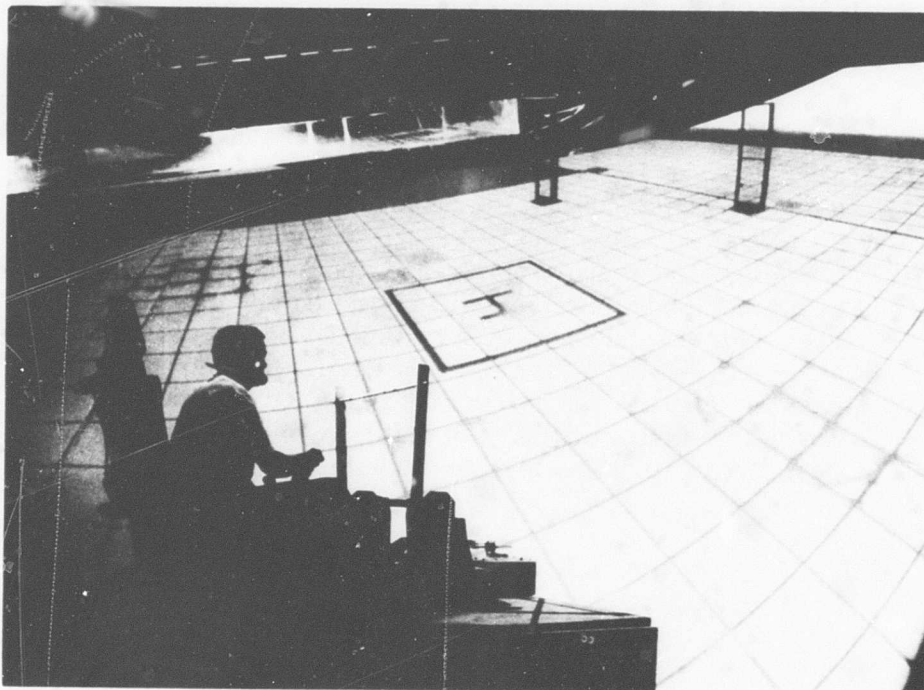


FIGURE 8. VISUAL DISPLAY AND COCKPIT OF SIMULATOR C

### Experimental Results

1. Attitude controllability was acceptable for hovering with a Cooper Rating of 3 to 3-1/2. Precision hovering could be maintained by all the pilots with an R.M.S. lateral position of 2 feet (threshold = 0.32 ft) and an R.M.S. bank angle of 1 degree, as indicated on Tables I and II.
2. Attitude controllability was unacceptable for the lateral quick-stop maneuver with a Cooper Rating of 6 to 6-1/2. Overcontrol in attitude occurred frequently, and overshoots in lateral position were common.
3. Altitude control was good. The pilot could consistently hold altitude and was able to estimate altitude to an accuracy of less than 1 foot.

4. Smooth lift-offs and touchdowns were possible, and the pilot could easily estimate his touchdown altitude.
5. Stick activity generally compares with flight results. Power spectral and probability density plots of lateral stick position are shown in Figures 9 and 10. A time history of lateral quick-stop maneuvers is shown in Figure 11.
6. The pilot constantly complained about the onset of vertigo, which occurred during position or attitude changes, and the overcontrol tendency. Other aspects of the display were annoying, such as the lack of a good horizon. Display definition and content were described as good for the precision hovering task, and the pilot felt that the addition of motion cues would improve his performance.

### Critique

1. Attitude controllability during hover was acceptable because the control is basically reasonable for the small motions required for hover. The pilot, in rating the attitude controllability, is nevertheless judging it on the basis of his ability to maintain small position errors. Since now, as compared with Simulation B, the position cues are good, he is able to rate attitude controllability with respect to the position holding task.
2. Attitude controllability for the lateral quick-stop maneuver was unacceptable because of the inability of the pilot to lead attitude, i.e., detect roll rate, with consequent overcontrol and position overshoot. This may be due to several factors, which are discussed in the General Critique. Again, inadvertent external pilot head movements were observed occasionally.
3. The general increase in pilot performance is due mainly to the transparency scale which is more compatible with the precision hover task. The transparency resonances are not so apparent at this scale, and the addition of two vertical towers for height cues enabled the pilot to estimate altitude accurately.
4. The pilot experienced moderate vertigo after a period of only 10 minutes in the simulator. The vertigo tendency seemed to be most acute during attitude reversals. The decrease in pilot lead and his complaints of vertigo during attitude reversals are evidence which supports the hypothesis that kinesthetic

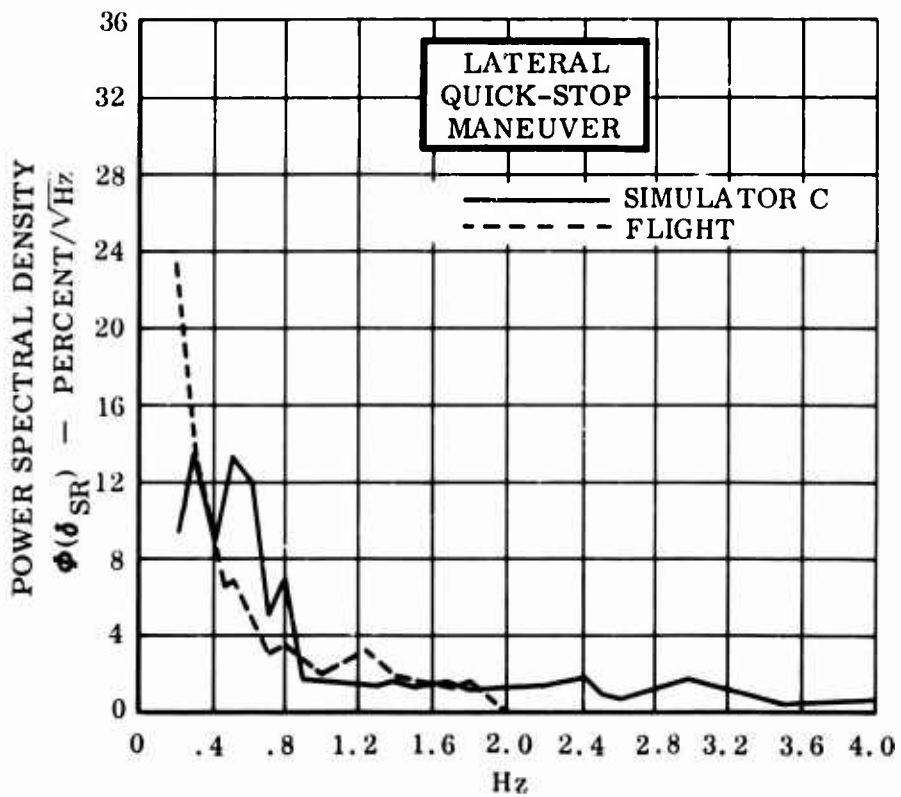
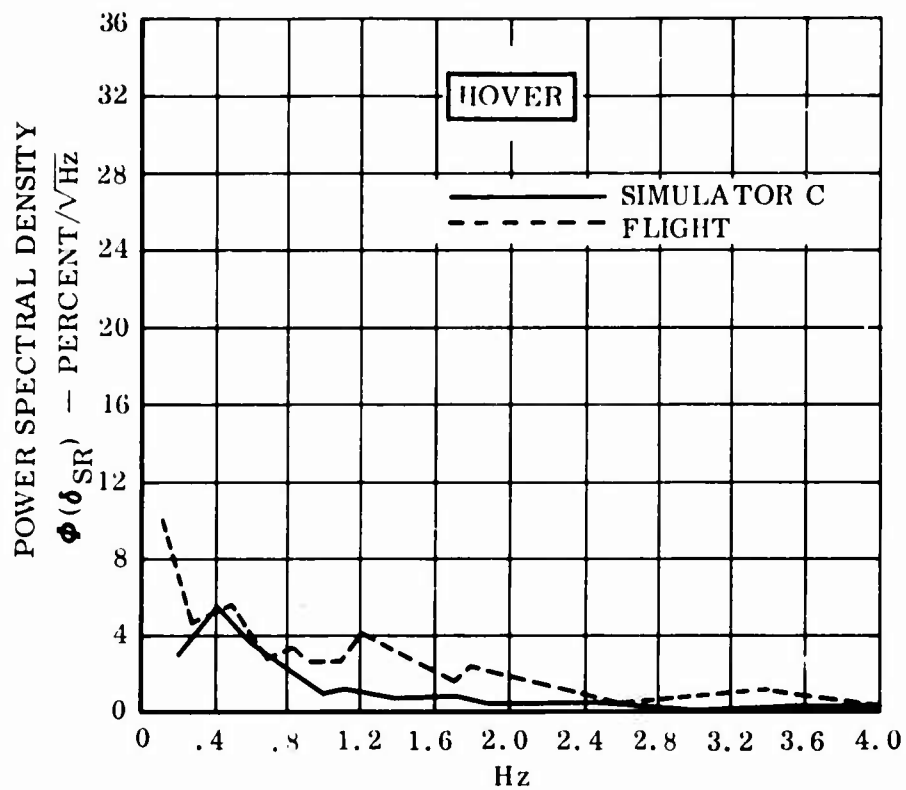


FIGURE 9. POWER SPECTRA OF LATERAL CONTROL INPUT, SIMULATOR C

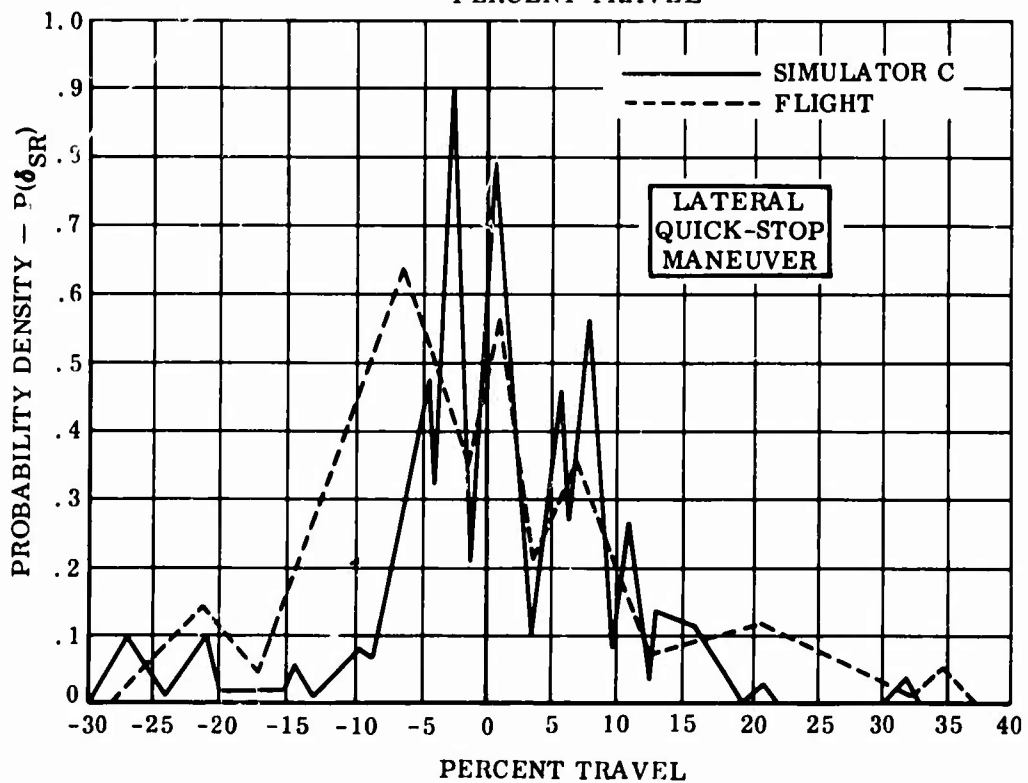
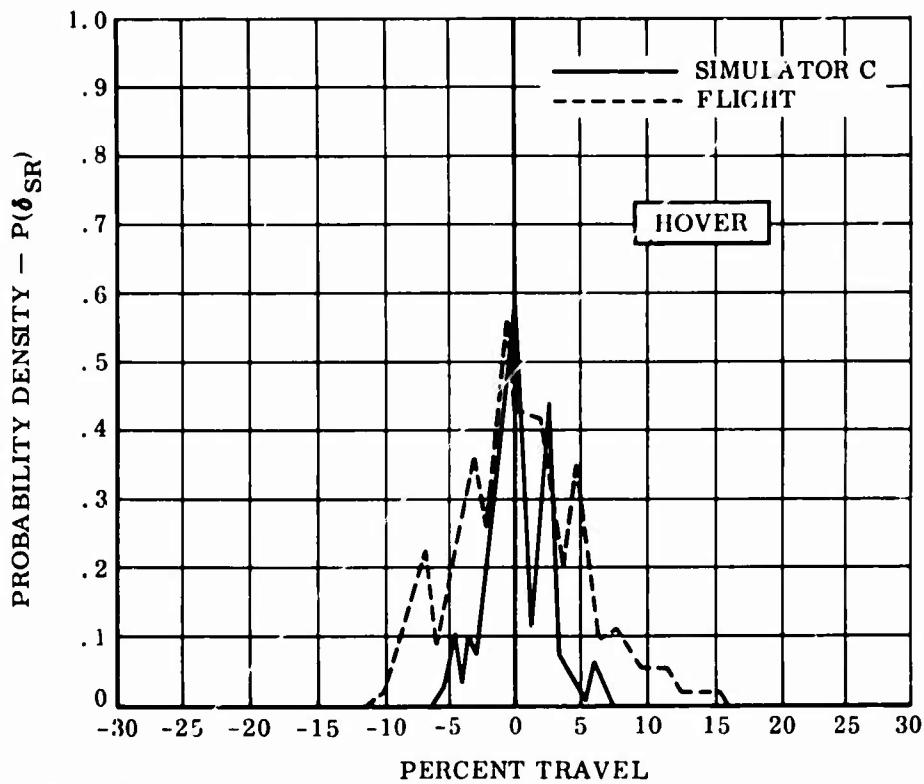


FIGURE 10. PROBABILITY DENSITY OF LATERAL CONTROL INPUT, SIMULATOR C

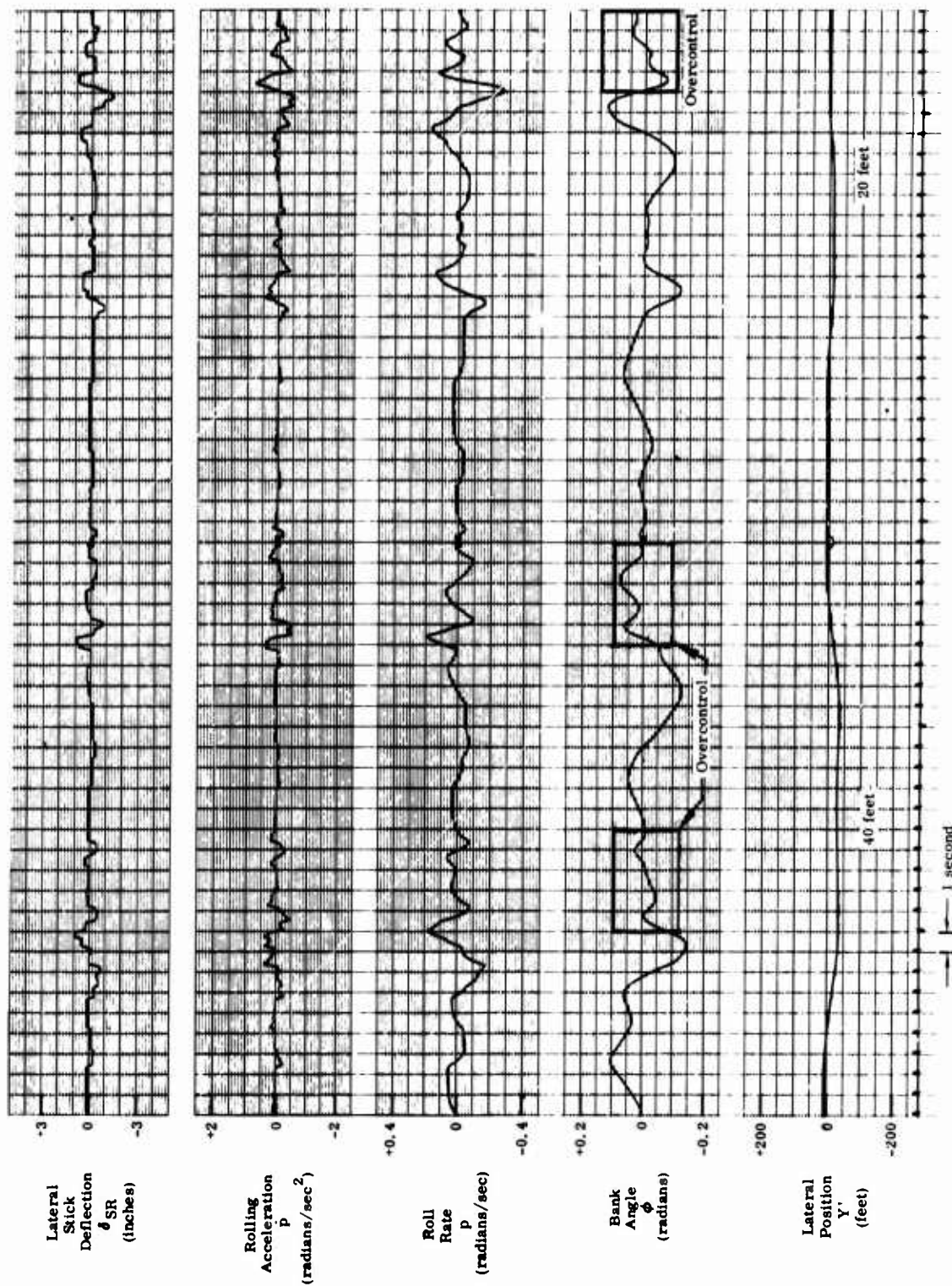


FIGURE 11. TIME HISTORY OF LATERAL QUICK-STOP MANEUVERS, SIMULATOR C

cues, while not dominant, are nevertheless important, especially to a highly skilled pilot.

## SIMULATOR D

### Salient Features

A full description of this simulator and the results of many tests conducted with it are contained in reference 3. Salient features are outlined below:

1. This simulator has six degrees of motion.
2. The surrounding room and a portion of an outside ramp are visible from the cockpit and are used for visual cues. Markers are installed in the room for position reference. The simulator has a maximum translational travel of  $\pm 10$  feet in the three linear degrees of freedom. A photograph of the simulator is shown in Figure 12.

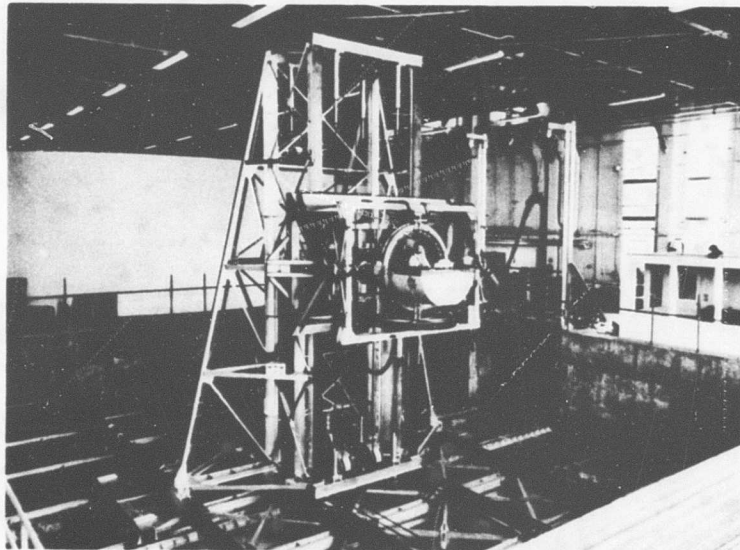


FIGURE 12. SIX-DEGREE-OF-FREEDOM  
SIMULATOR D

3. Stick feel characteristics were adjusted to match those in the X-14A.
4. Minimum cockpit instrumentation was used.
5. Control system was matched to flight.

### Experimental Results

1. Control was good on all axes. Pilot opinion matched that from flight. Hovering performance was better than flight, with a lateral position R. M. S. of only 0.5 foot. (See Tables I and II.)
2. No overcontrol tendency existed, and pilot vertigo was non-existent.
3. Lateral quick-stop maneuvers were performed at slightly higher frequencies than flight.
4. Bank angle, roll velocity, and control moment were slightly higher than flight for the 20-foot lateral quick-stop maneuver and were close to flight for hover.
5. Lateral stick R. M. S. was close to flight for hover but double that of flight for a series of 20-foot lateral quick-stop maneuvers. Power spectral and probability density plots are shown in Figures 13 and 14. A time history of a series of lateral quick-stop maneuvers is shown in Figure 15.

### Critique

1. The superior pilot performance observed in this simulation is, of course, due to its faithful reproduction of flight conditions. The simulator's frequency response is sufficiently better than that of the airframe and control system so that its dynamics are not felt by the pilot.
2. The greater levels of pilot activity observed during the lateral quick-stop maneuvers reflect the pilot's confidence in the simulator. The greater levels are due to the pilot's maintaining maneuver onset conditions similar to or greater than flight while increasing the frequency at which he performs these maneuvers so as to remain within the linear limitations of the simulator.

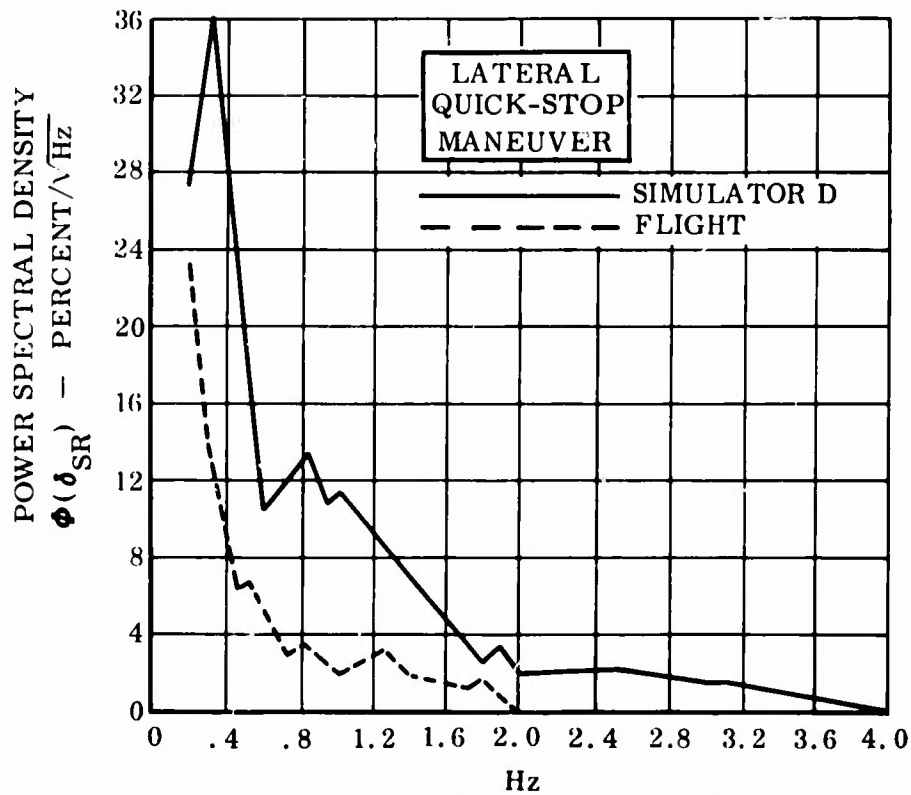
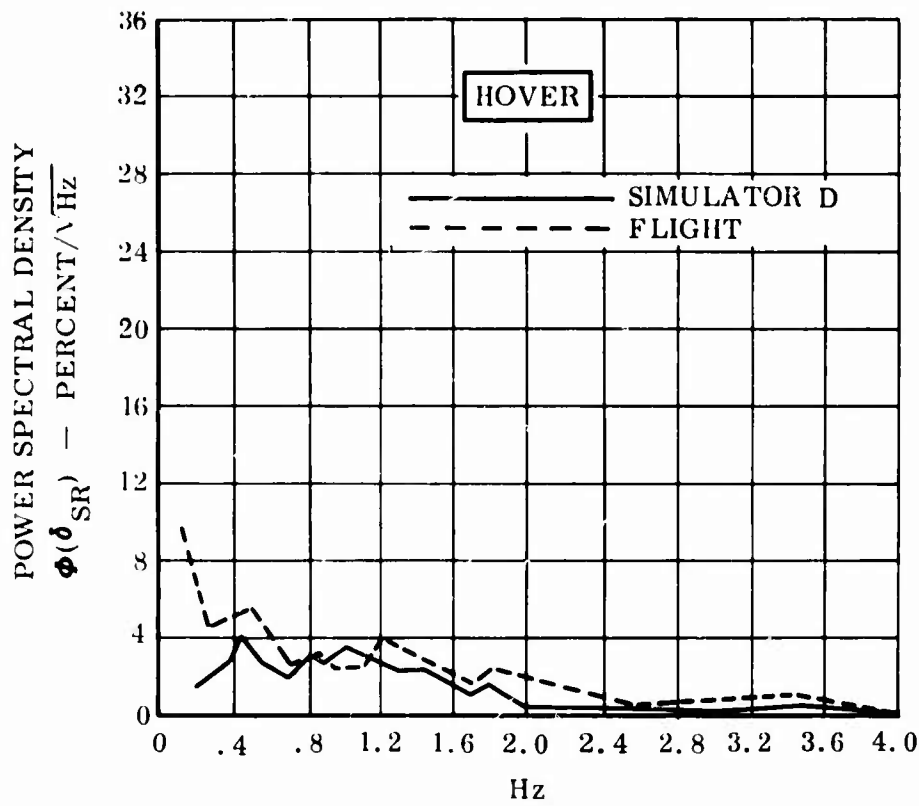


FIGURE 13. POWER SPECTRA OF LATERAL CONTROL INPUT, SIMULATOR D

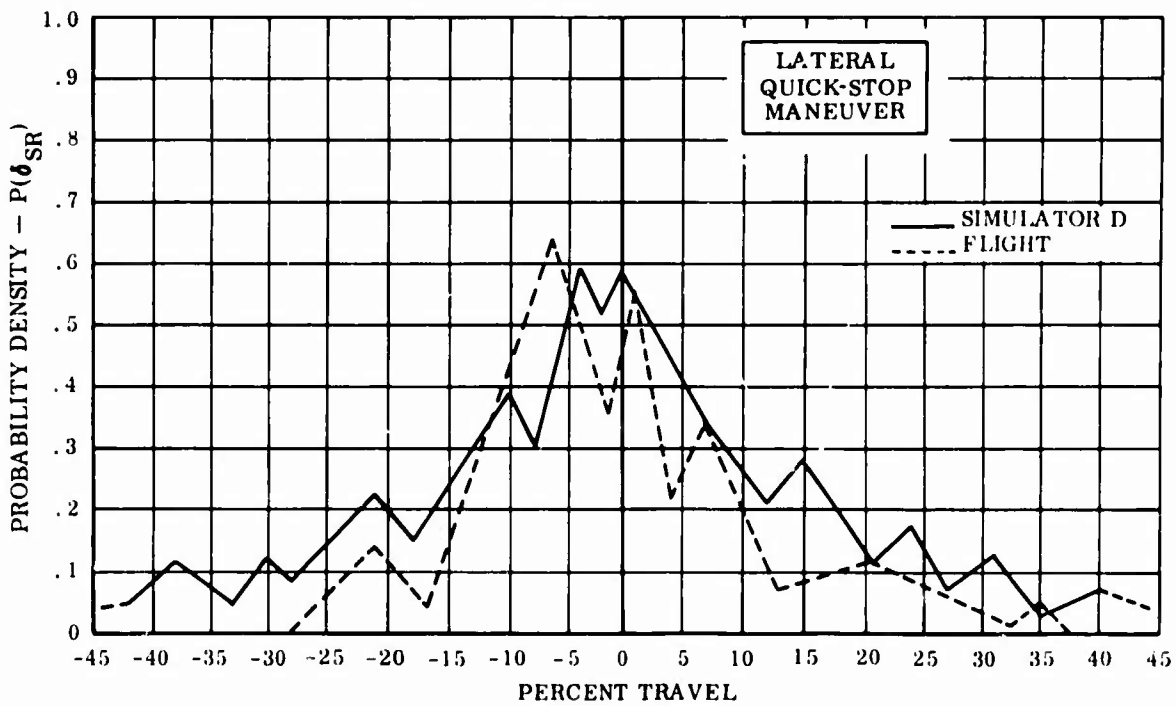
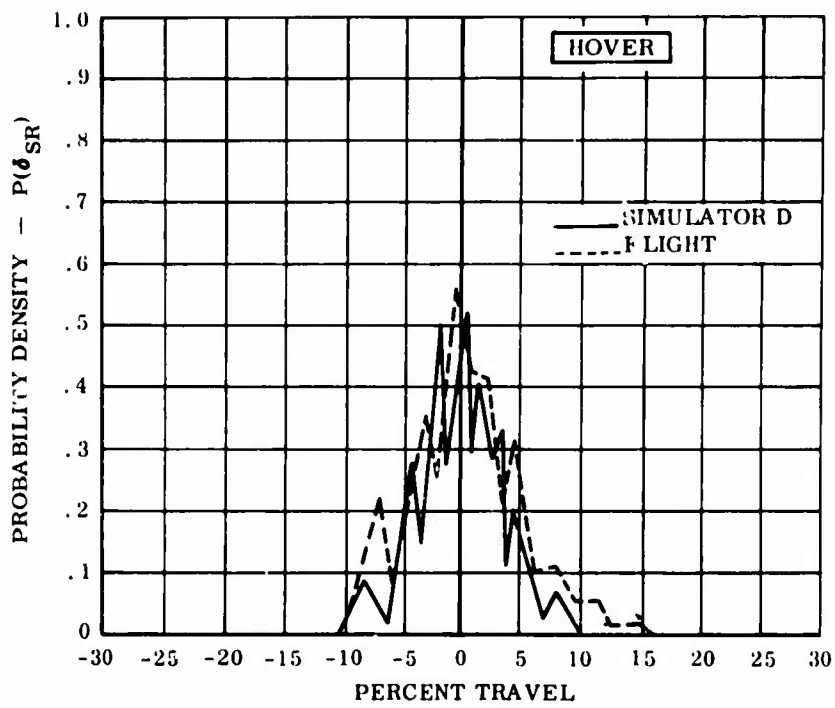


FIGURE 14. PROBABILITY DENSITY OF LATERAL CONTROL INPUT, SIMULATOR D

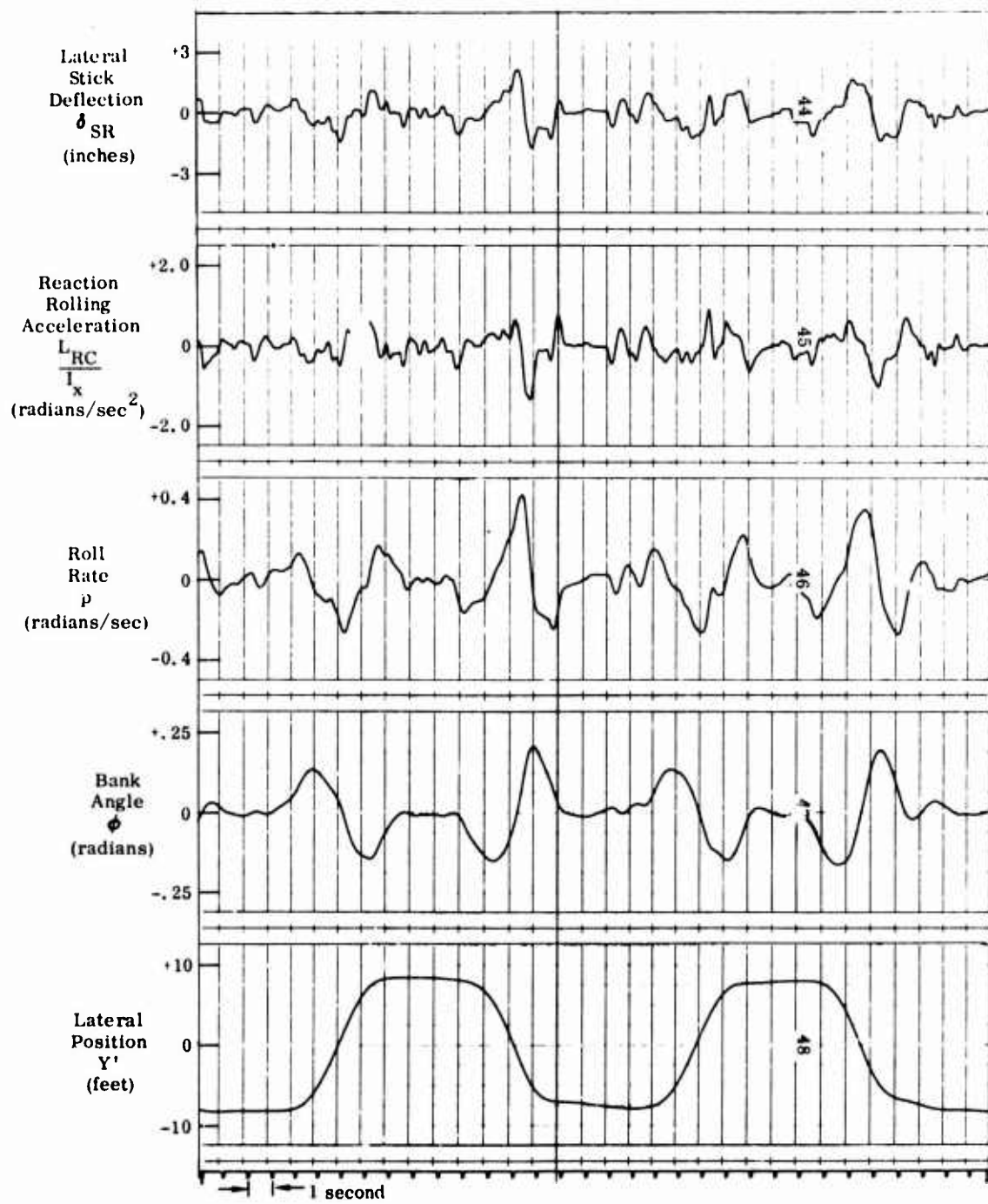


FIGURE 15. TIME HISTORY OF LATERAL QUICK-STOP MANEUVERS, SIMULATOR D

3. The power spectral density of the pilot's lateral stick deflection verifies this point, as the attitude closure was being effected at frequencies of 1.0 Hz. The closures for flight occur at frequencies of 0.5 Hz, while the various other simulators' closures are between these values but closer to the lower one.

## GENERAL CRITIQUE

### Effect of Motion

It has been observed that overcontrol tendencies exist with the fixed-base simulators, while for all other quantities constant, this does not occur in the moving-base simulators or flight. The visual display frequency response of the fixed-base simulators is sufficiently high that this is not a factor in the overcontrol problem (see Appendix I). The onset of vertigo for the fixed-base simulators using the point light source type of display is established. The indications are, therefore, that significant pilot lead can be generated through the rotary motion cues. This is illustrated in Figure 16, which contains several root loci of pilot attitude closures. A pilot model consisting of lead and a time delay represented by a first-order Pade' approximation (reference 4) is included. Note that varying pilot gain can produce closed loop roots which may vary considerably in damping ratio at nearly the same frequency and pilot gain. The observations from the fixed-base simulation indicate that closed loop roots exist at frequencies of 3.5 radians per second with a damping ratio of 0.1 to 0.3. Such a closure would be represented by the dark crosses on Figure 16. The root locus shows, however, that the complex roots may be moved to the left if the pilot lead time constant  $T_L$  is increased to 0.4 second at constant pilot gain. The resulting damping ratio is then 0.5. This is approximately what is observed in flight. Compare the time histories of Figures 11, 15, and 17. The same absence of motion which results in decreased pilot lead could cause the conflict between the visual and kinesthetic cues which can cause vertigo (reference 5). Note that in all the simulators with motion, no overcontrol or vertigo tendencies have existed.

Figure 18 serves to illustrate the effect of introducing another closure. In this figure, the effective closed loop transfer function of the pilot-attitude controller is combined with the additional airframe transfer function relating side position and bank angle. Pilot attitude gain  $K_{p\phi}$  and lead time constant are fixed, and the locus is plotted for various values of the linear pilot gain  $K_{p_y}$ .

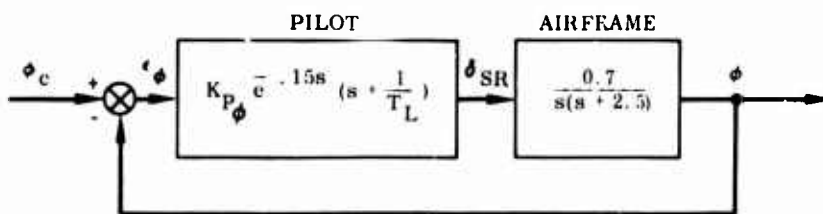
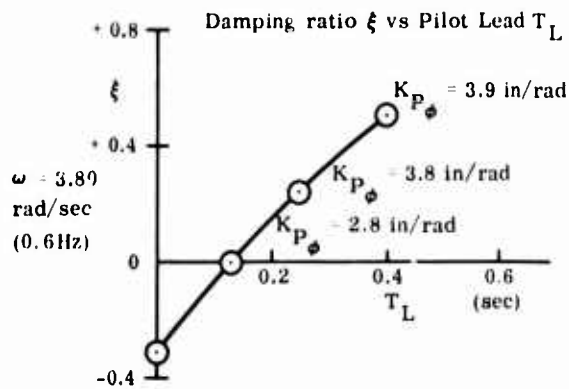
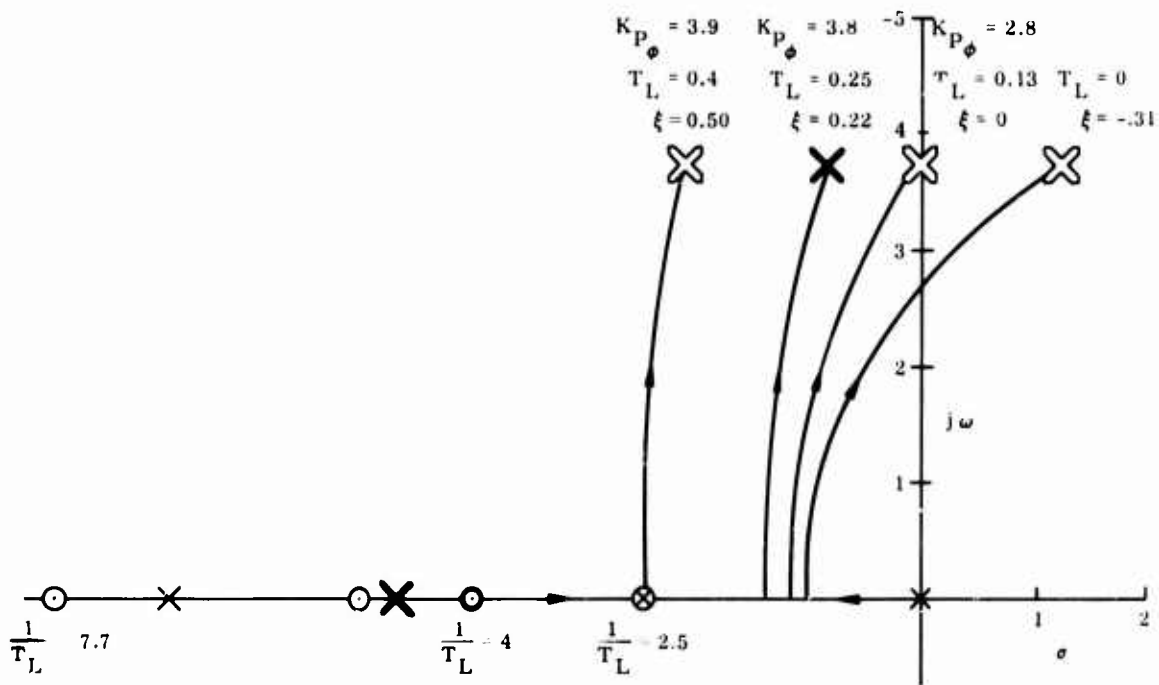


FIGURE 16. ROOT LOCUS OF PILOT'S ATTITUDE CLOSURE

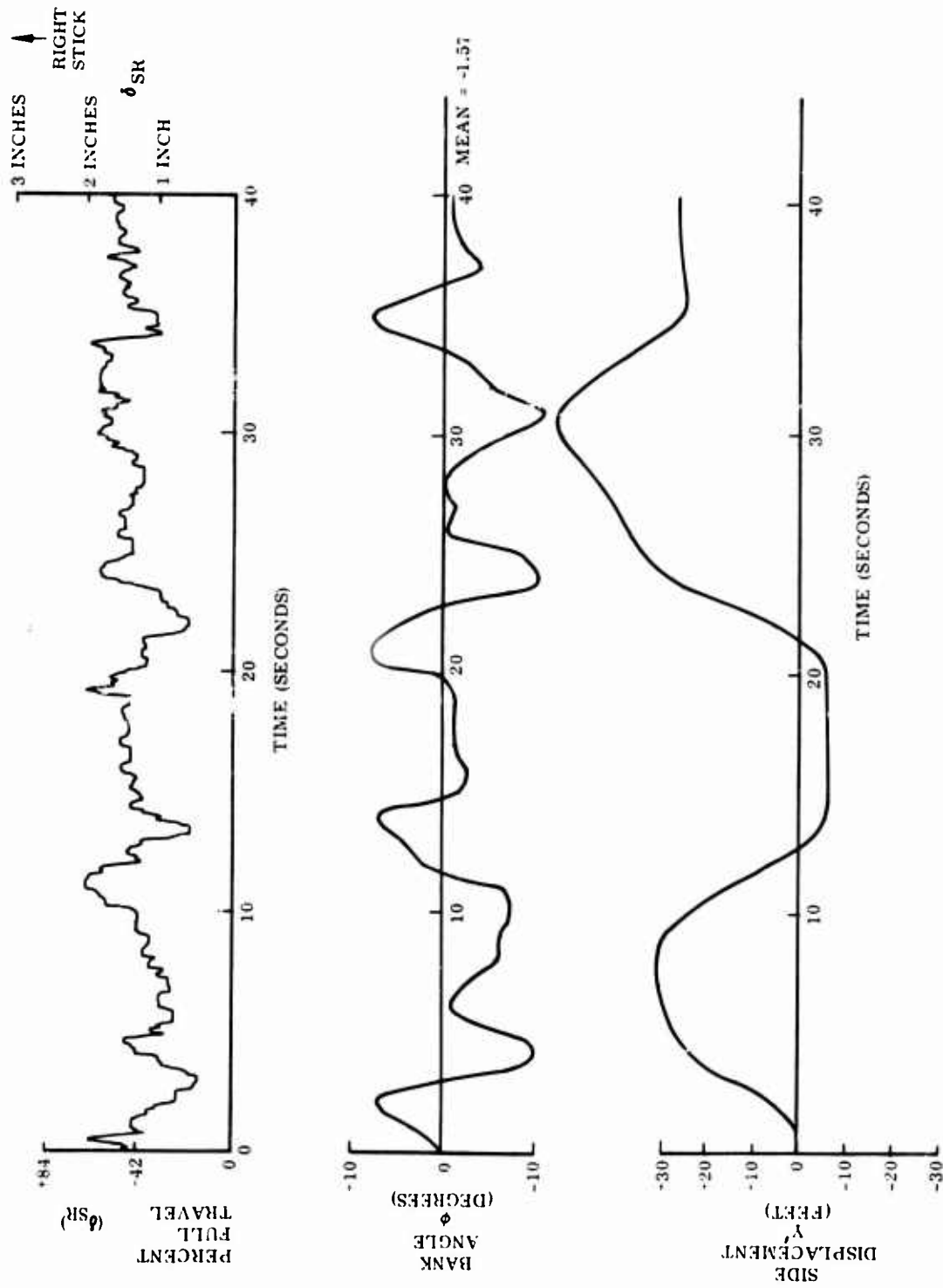


FIGURE 17. TIME HISTORY OF LATERAL QUICK-STOP MANEUVER, FLIGHT TEST

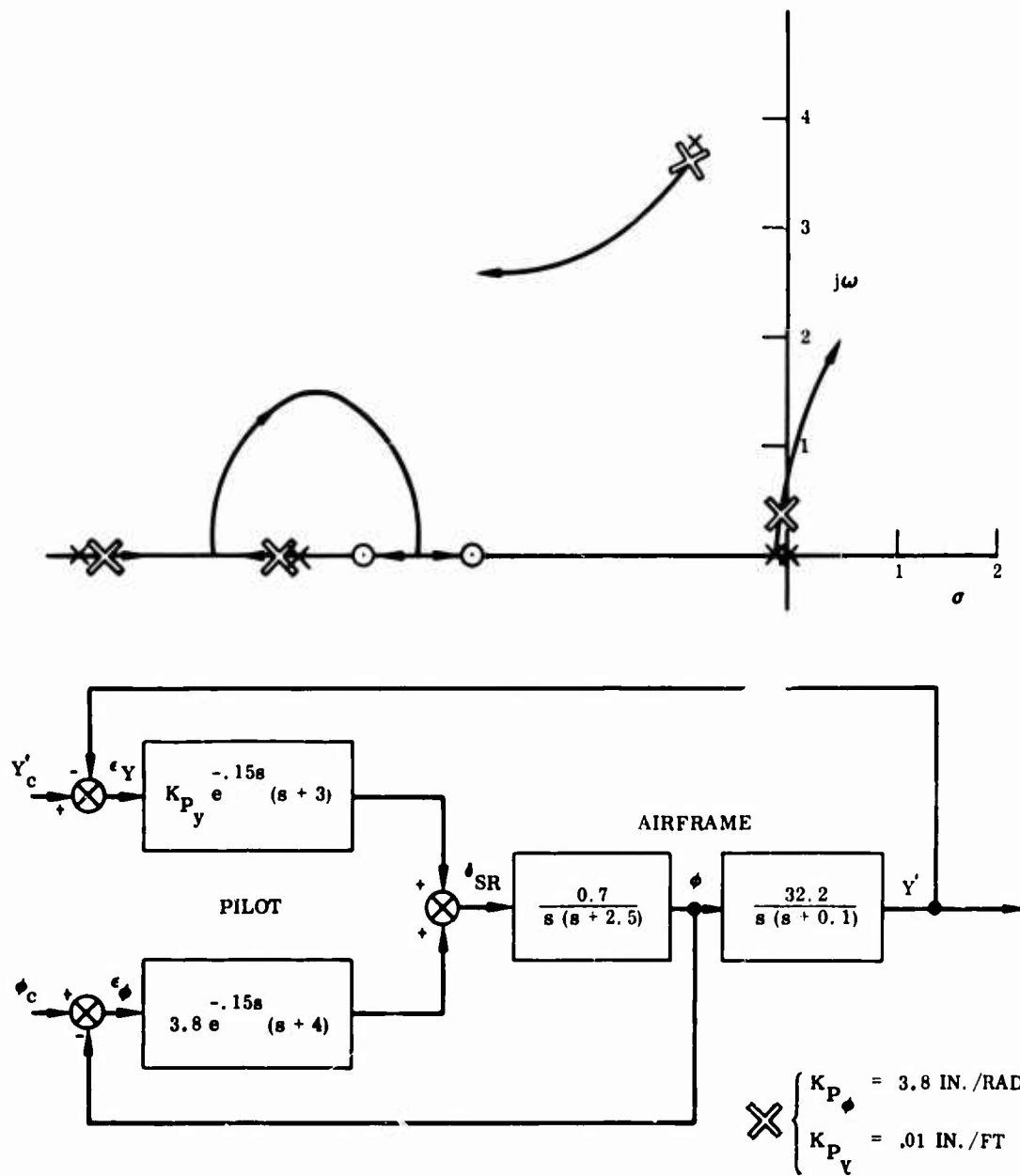


FIGURE 18. ROOT LOCUS OF PILOT'S POSITION AND ATTITUDE CLOSURE

It may be seen that the pilot's linear closure is severely gain-limited, which means that the addition of a position closure only serves to modify the attitude closure slightly while introducing two lightly damped complex roots near the origin.

Closed loop roots are shown for a particular pilot linear gain. Note that the position closure is lightly damped and of low frequency. This root location may be improved if the attitude closure roots were more heavily damped.

An examination of a power spectral density distribution for the lateral stick (Figures 3, 4, 6, 7, 9, 10, 13, and 14) shows dominant resonances at frequencies of 0.1 to 0.3 Hz and 0.5 to 1.0 Hz which correspond to the root locus just described. A comparison of power spectral density from flight or a moving-base simulator with those from a fixed-based simulator shows that a more dominant peak occurs at frequencies of 0.5 Hz for the fixed-base simulators, verifying that the attitude closure is lightly damped. It is probable also that cues working on the involuntary aspects of the perceptive/reactive system can be used by a highly skilled VTOL pilot. The latency time for the detection of linear accelerations is below the period of the position loop roots. This suggests that a highly skilled pilot could use linear acceleration cues supplied by his vestibular system. For the VTOL aircraft near hover, a linear acceleration is very nearly equal to attitude change times the acceleration of gravity. Therefore, this cue may be used as a sensitive attitude cue.

#### Effect of Display

It has been shown how the display can cause position holding performance to decrease. An examination of the power spectral density distribution of a simulator with a poor display reveals that the levels are generally lower than in flight. This points to the hypothesis that a correct attitude closure is not possible unless sufficient position cues exist. This is because, without correct position information, it is not necessary to control attitude accurately and the "drifting" kind of performance is observed. The position cues, therefore, are important both in content and in dynamics. They not only must provide the pilot with excellent information regarding his position and attitude in space, but also must provide him with the correct derivatives of his spatial coordinates. This means that the thresholds must be considerably less than the expected R.M.S. levels of these coordinates and below the pilot's visual threshold.

Nearby vertical towers with markings enhance a pilot's ability to perceive vertical motion. Familiar objects and known grid lines also help. The three-dimensional aspect of the point light type of visual display not only serves to give the pilot more information due to the wide field, but also allows him to scan for the most rapidly changing coordinate. Pilot scan rate was found to be high for the visual hovering task. Target fixation during precision hovering attempts often led to degraded performance which could be restored by briefly scanning once more.

Improper horizon detail was expected to be a problem with a point light display, but it was not. Apparently, attitude cues are obtained from distant objects while translational cues are obtained from near objects, thus making the limited transparency type of display suitable for attitude holding tasks. This is further proven by examining the R.M.S. levels of bank angle during hover (Table I), which were nominally about one degree.

### Effect of Task

This is an important point for the VTOL aircraft simulator. An examination of power spectral density of lateral stick inputs (Figures 3, 6, 9, and 13) reveals that the character of the spectral density varies drastically with task. For a hover task, the peak levels of the two dominant resonances are nearly the same. For a lateral maneuver, however, the low frequency resonance has a higher level. When these resonances are nearly together as in the case of Simulation B (Figure 6), the suggestion is that the pilot does not discern between attitude and position control. Interpreted differently, the poor visual position cues cause the pilot not to close the position loop and lower his gain on attitude, thus placing a single complex root between the frequencies at which he would normally place them.

The effect of task, therefore, is to cause the pilot to perceive more acutely the primary coordinate to be controlled during the performance of that task and possibly to pay less attention to the other loops. Simulator C was rated at 3-1/2 for hover, demonstrating that the visual position and attitude cues were sufficient for that task. For the lateral maneuver, however, the same control was unacceptable for reasons outlined before, namely, the lack of pilot lead preventing a good attitude closure. It was outlined previously that a poor attitude closure can only result in a poor and consequently downgraded position closure.

It may be stated here that the task dictates the characteristics of a primary loop closure relating to that task and that the simulator must be able to supply the pilot with the cues to close it well. Consequently, an inner loop must also be closed well in order to achieve a good outer loop closure. Stated differently by example, if a simulator is to represent a situation where the task is attitude changing only, then only attitude cues need be included and a position display is not necessary. If the task is now changed to one which requires an outer loop to be closed more tightly, the simulator requirements in attitude and the attitude performance change completely.

### Effect of Control System

During the discussion of the effects of motion, it was pointed out that if the pilot does not receive information which enables him to provide the required lead, poor performance with downgraded opinion will result. It follows that if this lead were not required, the performance would not deteriorate. The primary effect of a good control system is to negate the need for pilot lead and to allow him to perform well with low gain values. The inference, therefore, is that a simulation with a good control system does not require a high fidelity of representation. This point was not investigated during this study sufficiently to allow a discussion beyond this point.

### Effect of Simulator Approximations

The analysis of flight data revealed characteristics of high-order systems so typical of aircraft. The roll rate to lateral stick frequency response calculated from flight data revealed a series of poles and zeros which were not accounted for during the curve-fitting process used to calculate the effective transfer function. A periodic error dependent on frequency existed between the effective and the actual gain and phase curves, whose maximum values were approximately  $\pm 4$  db in gain and  $\pm 15$  degrees in phase. These values are for frequencies up to 1 Hz. Therefore, the approximate transfer functions used in Simulations B, C, and D were slightly in error.

Pilot comment from the simulations, however, indicated that the control felt like the airplane's control in its gross aspects. Some nonlinear features of the aircraft control system are described in reference 1.

It is felt, however, that the high-order systems which are commonly found in current V/STOL aircraft such as helicopters may not enjoy the freedom from approximation error as does the relatively rigid X-14A vehicle. For this reasons, a careful look at the control dynamics is suggested.

A second point regarding approximation is that associated with altitude control and gravity representation. It was consistently brought out in Simulations B and C that altitude perturbations occurred during attitude changes. This is caused by the normal component of gravity varying with the cosine of bank and pitch angles. Under usual circumstances, small-angle assumptions suffice for most simulations, but they do not in the case of representing accurately the vertical degree of freedom during hover. For this reason, no assumptions were made in the mechanization of this degree of freedom.

## Effect of Pilot Experience

All of the previous observations apply exclusively to the one NASA test pilot who flew all the simulators and the airplane during flight test. To determine the effects of pilot experience, some complementary tests were made in which other pilots were employed as test subjects. The pilots' experiences ranged from extensive military jet and some light aircraft (Pilot B) to only light aircraft (Pilot C). Table III contains the results of the brief study conducted during Simulation C to establish the effects of pilot experience.

The results are presented for the hover task and the lateral quick-stop maneuver. No pilot rating evaluations were attempted. Total checkout time for each pilot was approximately three hours.

As can be seen from Table III, no large differences in performance exist. Pilot rating, however, could vary considerably because of the feeling by the pilots that the task was quite difficult.

**TABLE III**  
**COMPARISON OF PILOT PERFORMANCE IN SIMULATOR C AND FLIGHT**

Root-Mean-Square Values of Various Lateral Quantities for Three Different Pilots for the Hover Task					
Pilot	R. M. S.	$\delta_{SR}$ Percent Full Travel	$\dot{p}$ Rad/Sec <sup>2</sup>	$\phi$ Degrees	$Y'$ Feet
Pilot A, Simulator C		2.9	.042	1.0	~ 2.4
Pilot B, Simulator C		5.9	.064	2.1	~ 2.3
Pilot C, Simulator C		4.7	.064	1.1	~ 2.0
Pilot A, Flight		4.25	.220	1.0	~ 1

Root-Mean-Square Values of Various Lateral Quantities for Three Different Pilots for the 40-Foot Lateral Quick-Stop Maneuver					
Pilot	R. M. S.	$\delta_{SR}$ Percent Full Travel	$\dot{p}$ Rad/Sec <sup>2</sup>	$\phi$ Degrees	
Pilot A, Simulator C		9.6	.136	3.0	
Pilot B, Simulator C		10.8	.155	3.0	
Pilot C, Simulator C		11.5	.145	4.5	°
Pilot A, Flight		11.5	.330	3.6	

Overcontrol tendencies in roll and overshoot in lateral position during maneuvering were observed. Inadvertent head motions were also observed. The vertigo tendency was nearly suppressed by both pilots. This was accomplished by introducing several factors:

1. The wearing of eyeshades which prevented the direct light from the transparency from entering the pilot's eyes and which also shut out the extraneous surface reflections of the transparency.
2. The adoption of a procedure where large simulator visual motion such as that occurring during startup and shutdown was not observed by the pilot simply by instructing him to close his eyes during those times.
3. Frequent rests.
4. The frequent scanning by the pilots of the total display and the avoidance of staring at a particular point during a precision hover or maneuver.
5. Pilot motivation.

#### Control Utilization

Control moment utilization was studied to provide additional data on which to base conclusions. Also, this parameter is of fundamental importance for designers of V/STOL vehicles. It can reveal information regarding pilot control inputs, since it represents the final output of essentially a filter which receives the pilot control motions.

Since the X-14A vehicle is nearly neutral, it has nearly zero rotary damping on all axes, and the rolling moment of the reaction control system divided by the roll moment of inertia  $\left(\frac{L_{RC}}{I_X}\right)$  is nearly equal to the rolling acceleration  $\dot{p}$ . The error is small and therefore these quantities are used interchangeably throughout this section in units of acceleration, radians per second squared.

Table I contains the measured R. M. S. values of  $\dot{p}$  for all simulators and flight test. Note that the ratios of the R. M. S. values of  $\dot{p}$  to  $\delta_{SR}$  during hover are nearly constant. However, these ratios for Simulator D (all motion) and flight test are different from the ratios for all other simulations. The results clearly show that the measured ratio of

R.M.S. rolling accelerations to R.M.S. lateral stick deflections from the simulators consistently is half the ratio measured in flight. Examination of the probability density functions for the pilot's lateral stick reveals that they are more Gaussian in nature for Simulator D and flight test.

The inference is that more pilot noise is present for a more realistic situation. In the case of flight, the probability density functions of the rolling moment are nearly Gaussian for hover. This is almost the case for Simulator D but not for the other simulators.

The flight hardware acted effectively as a high-pass filter, therefore, allowing noise from sources other than the pilot to enter the picture. In Simulation D, no artificial noise is present except for that generated by the simulators' actuators, and the probability density functions correspondingly show a reduced similarity to the Gaussian distribution.

The conclusion that can be reached based on these limited data is that pilot noise levels are a function of realism and that control moment utilization cannot be realistically obtained from a simulator unless this realism is provided and the extraneous noise is included.

#### Pilot Opinion in Light of Statistical Analysis of His Output

It already has been inferred by means of a root locus description how a pilot closes the position and attitude loops during hover operations. It has also been demonstrated how the power spectral density verifies these closures and how the energy in each varies with task. The power spectral density of the pilot's lateral inputs (Figures 3, 4, 6, 7, 9, 10, 13, and 14) also reveal energy in the attitude loop closure root for the fixed-base simulators during maneuvering, but not for the moving-base simulators or flight test. The controllability was also downrated because of the overcontrol tendency or low damping ratio of this mode.

The inference is that spectral density in the region of closure frequencies can be related to subjective pilot opinion. The point is still not clearly defined and will be covered by later work.

#### Effect of Nonlinearities

A specific nonlinearity that affects simulator performance is simulator position limitation. Due to mechanization limitations or poor performance, it is sometimes not possible to prevent the pilot from striking stops and resetting the simulator. If this occurs during a familiarization run, it will affect his later performance. For example, in Simulation C, bank angle limitation was expressed by the pilot during lateral

quick-stop maneuvers where overcontrol was prevalent. He was afraid of striking the stop (set at  $\pm 18$  degrees) and consequently modified his inputs slightly. This is reflected in his general performance indicated by R. M. S. bank angle as shown in Table I for the lateral quick-stop maneuver. Note (Table I) that for Simulation C, R. M. S. bank angle is 3 degrees as compared to 4.6 degrees for Simulation D and 3.6 degrees for flight.

Simulation D performance reflects the effect of limited translational motion. Since only  $\pm 10$  feet sideways was available from the simulation, the R. M. S. bank angle is slightly greater than flight because of the reluctance to strike the linear stop and the probable increased confidence the pilot has in this simulator.

## CONCLUSIONS

1. Valid V/STOL simulation may be accomplished if a sufficient degree of realism is supplied to the pilot by the simulator.
2. Motion cues appear to be important for hover-type flight operations, particularly those produced by rotary cockpit motion. These results are for the pilot located near the center of gravity of the vehicle.
3. The absence of motion when using the point light source visual display produced serious pilot vertigo with attendant loss in performance.
4. Control moment utilization was found to be lower in all the simulations studied as compared to flight.
5. Pilot noise is more noticeable as simulator realism increases.
6. Power spectral density of pilot control movements is a sensitive indication of pilot performance when related to aircraft motions, and therefore offers the possibility of correlation with subjective opinion.

## RECOMMENDATIONS

1. A study of cockpit motion schemes should be undertaken to determine the necessary means of providing the additional cues required by the pilot for low-speed operations near the ground. This is required to prevent vertigo onset and loss of pilot performance.
2. Future studies of V/STOL simulation should include the effects of high-order control systems and airframe dynamics.
3. Future studies should investigate pilot noise levels compared to in-flight levels as a function of realism and task.
4. Noise introduced by the pilot or from outside the system should be studied to learn its effects on control systems and overall performance.

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## APPENDIX I

### DESCRIPTION OF SIMULATIONS B AND C

#### EQUATIONS OF MOTION FOR AIRFRAME AND PERTINENT CONSTANTS

The equations are referenced to principal body axes fixed in the aircraft. No conventional aerodynamic terms are included, and the engine thrust vector is fixed to the aircraft. No thrust vectoring was included. The equations of angular motion are linearized. The gravitational force terms are from a transformation using the same order of rotation as the display transforms. Logic was included, not shown here, which facilitated landings and takeoffs and taxiing. No landing gear dynamics or ground effects were included. Refer to the List of Symbols for an explanation of the terminology.

#### Pertinent Constants

$$\frac{X_u}{m} = -0.1 \text{ sec}^{-1}$$

$$\frac{M_q}{I_y} = -2.5 \text{ sec}^{-1}$$

$$\frac{Y_v}{m} = -0.1 \text{ sec}^{-1}$$

$$\frac{L_{\delta_{SR}}}{I_x} = 0.7 \text{ rad/sec}^2\text{-in.}$$

$$\frac{Z_w}{m} = -0.1 \text{ sec}^{-1}$$

$$\frac{L_p}{I_x} = -2.5 \text{ sec}^{-1}$$

$$g = 32.2 \text{ ft/sec}^2$$

$$\frac{Z_{\delta_{TP}}}{m} = -6.44 \text{ ft/sec}^2\text{-in.}$$

$$\frac{N_{\delta_{RP}}}{I_z} = 0.25 \text{ rad/sec}^2\text{-in.}$$

$$\frac{Z_{\dot{T}}}{m} = -5 \text{ sec}^{-1}$$

$$\frac{N_r}{I_z} = -1.0 \text{ sec}^{-1}$$

$$\frac{M_{\delta_{SP}}}{I_y} = 0.7 \text{ rad/sec}^2\text{-in.}$$

Longitudinal Force,  $\dot{u} = -qw + rv + \frac{X_u}{m}u - g \sin \theta \cos \phi$

Lateral Force,  $\dot{v} = -ru + pw + \frac{Y_v}{m}v + g \sin \phi$

Normal Force,  $\dot{w} = qu + \frac{Z_w}{m}w + \frac{Z}{m}\delta_{TP} \delta_{TP} + \frac{Z}{m}\dot{T} + g \cos \theta \cos \phi$

Pitching Moment,  $\dot{q} = \frac{M}{I_y} \delta_{SP} \delta_{SP} + \frac{M}{I_y} q$

Rolling Moment,  $\dot{p} = \frac{L}{I_x} \delta_{SR} \delta_{SR} + \frac{L}{I_x} p$

Yawing Moment,  $\dot{r} = \frac{N}{I_z} \delta_{RP} \delta_{RP} + \frac{N}{I_z} r$

where

$$\left. \begin{aligned} M \delta_{SP} \delta_{SP} + M_q q &= M_{RC} \\ L \delta_{SR} \delta_{SR} + L_p p &= L_{RC} \\ N \delta_{RP} \delta_{RP} + N_r r &= N_{RC} \end{aligned} \right\} \text{Reaction Control Components}$$

The aircraft is considered to have no natural rotary damping compared to the artificial damping provided by the stability augmentation system.

### CONTROL SYSTEMS AND HANDLING QUALITIES

The control transfer functions are:

$$\frac{\theta(s)}{\delta_{SP}(s)} = \frac{0.7}{s(s + 2.5)} \dots \text{rad/in.}$$

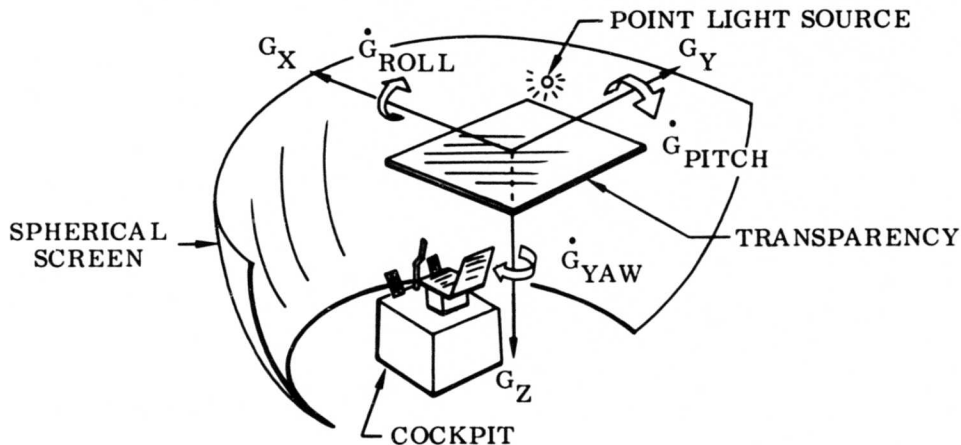
$$\frac{\phi(s)}{\delta_{SR}(s)} = \frac{0.7}{s(s + 2.5)} \dots \text{rad/in.}$$

$$\frac{\psi(s)}{\delta_{RP}(s)} = \frac{0.25}{s(s + 1.0)} \dots \text{rad/in.}$$

The handling qualities of such a control system have been reported by many investigators. Several studies conducted by NASA-Ames using the X-14A vehicle have indicated the above control system to be acceptable with a Cooper Rating of 3-1/2 or better.

### DISPLAY TRANSFORMATIONS

A general Euler axis transformation is used which utilizes the order of rotation of the simulator display system. The order of rotation is yaw → roll → pitch. The final quantities are referenced to an earth fixed-axis system. The neutral (center) position of the transparency is the origin. A further explanation of the signs is contained in the following sketch:



Second-order terms in the angular transformations are neglected and in the linear transforms for  $G_x$  and  $G_y$ ,  $\cos \theta = \cos \phi = 1$ . No assumptions are made in the  $G_z$  transformation. These are considered to be

compatible with the VTOL tasks investigated. The yaw angle  $\psi$  is generated by a resolving potentiometer mounted to the yaw gimbal and is measured clockwise from North.  $S$  is the transparency scale.

The transformations of the Euler rates are:

$$\dot{G}_{\text{pitch}} = -q + r\phi$$

$$\dot{G}_{\text{roll}} = -p - r\theta$$

$$\dot{G}_{\text{yaw}} = -r + p\theta$$

The transformations of the linear rates are:

$$\dot{G}_x = \frac{1}{S} \left[ -u \cos \psi + v \sin \psi - w (\sin \theta \cos \psi + \sin \phi \sin \psi) \right]$$

$$\dot{G}_y = \frac{1}{S} \left[ -u \sin \psi - v \cos \psi - w (\sin \theta \sin \psi - \sin \phi \cos \psi) \right]$$

$$\dot{G}_z = \frac{1}{S} \left[ +u \sin \theta \cos \phi - v \sin \phi - w \cos \phi \cos \theta \right]$$

Simulator B employed a 750-to-1 ( $S = 750$ ) transparency representing an airport scene with a 200-foot-square helicopter pad.

Simulator C employed an 80-to-1 transparency ( $S = 80$ ) which was a blowup of the helicopter pad of the 750-to-1 transparency. Two 30-foot towers were included in the Simulator C display. Photographs of Simulators B and C displays may be seen in Figures 5 and 8 respectively.

#### DISPLAY FREQUENCY RESPONSE AND LIMITS

Measured Bode plots of the performance of each hydraulic actuator listed according to the degree of freedom it represented are presented in Figures 19 through 24. Maximum limits are listed, and measured thresholds in terms of maximum travel are also given.

1. Bode Plots of Normalized Frequency Response (see Figures 19 through 24)

2. Maximum Limits

$G_{pitch}$	$G_{roll}$	$G_{yaw}$	$G_x$	$G_y$	$G_z$
$\pm 20^\circ$	$\pm 20^\circ$	No Limit	$\pm 2$ ft	$\pm 2$ ft	$\pm 0.42$ ft
$\dot{G}_{pitch}$	$\dot{G}_{roll}$	$\dot{G}_{yaw}$	$\dot{G}_x$	$\dot{G}_y$	$\dot{G}_z$
$\pm 28$ deg/ sec	$\pm 23$ deg/ sec	$\pm 39$ deg/ sec	$\pm 0.8$ ft/ sec	$\pm 0.8$ ft/ sec	$\pm 0.07$ ft/ sec

3. Thresholds (in terms of percent maximum travel)

$G_{pitch}$	$G_{roll}$	$\dot{G}_{yaw}$	$G_x$	$G_y$	$G_z$
0.15%	0.10%	1.8%	0.30%	0.20%	1.20%

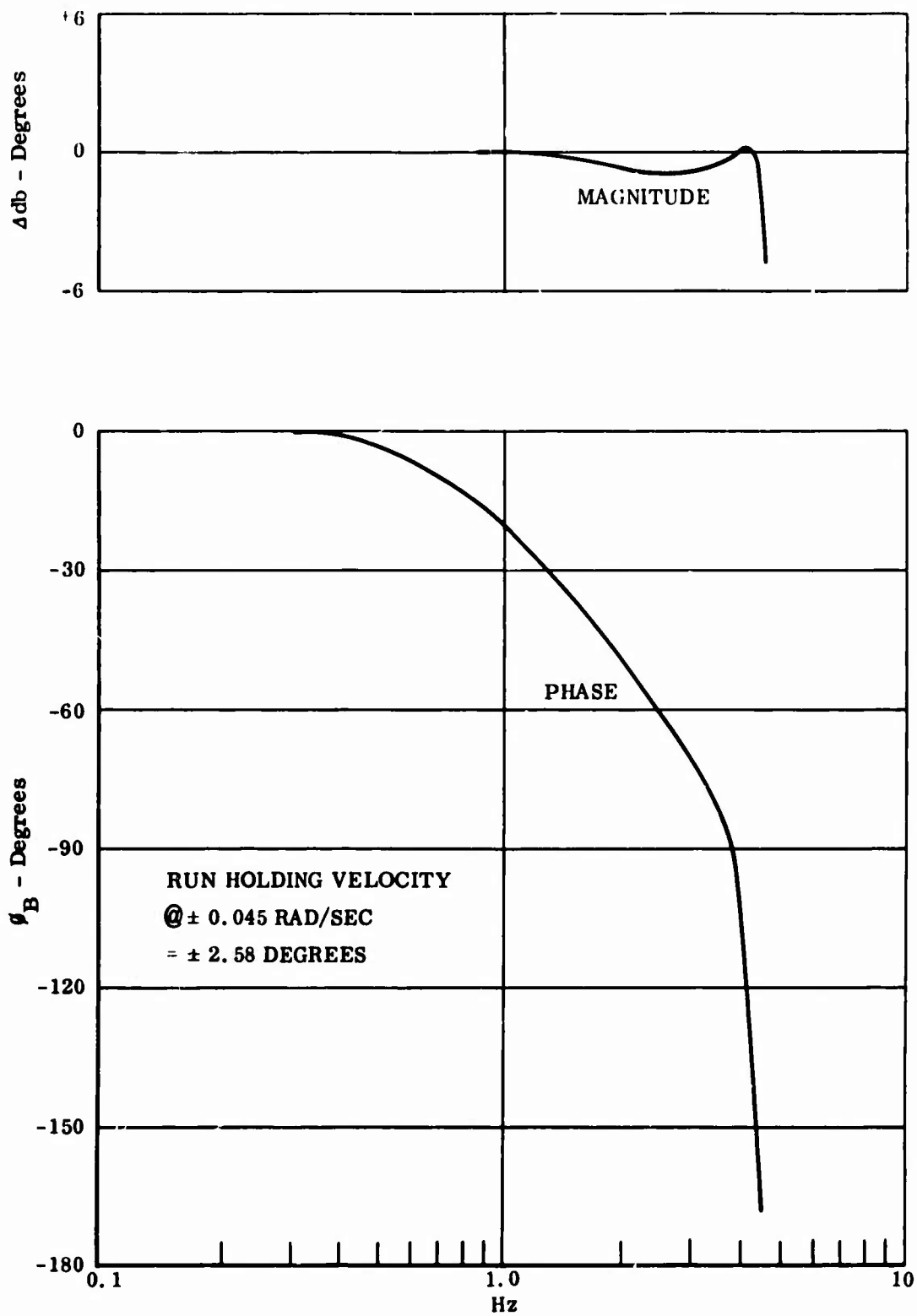


FIGURE 19.  $G_{\text{PITCH}}$  MEASURED FREQUENCY RESPONSE WITH INPUT COMPENSATION AT 0.67 RAD/SEC

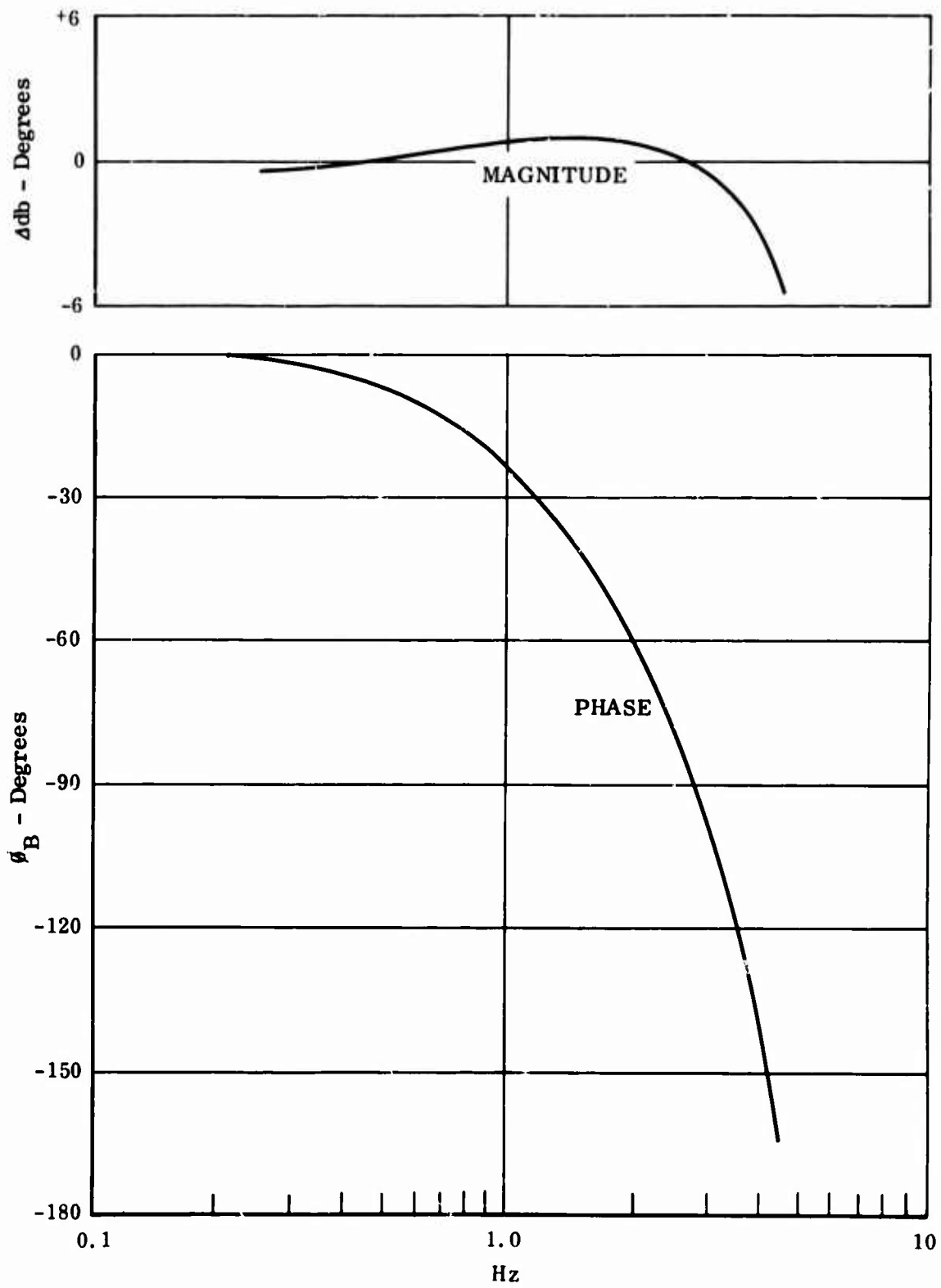


FIGURE 20.  $G_{ROLL}$  MEASURED FREQUENCY RESPONSE WITH INPUT COMPENSATION

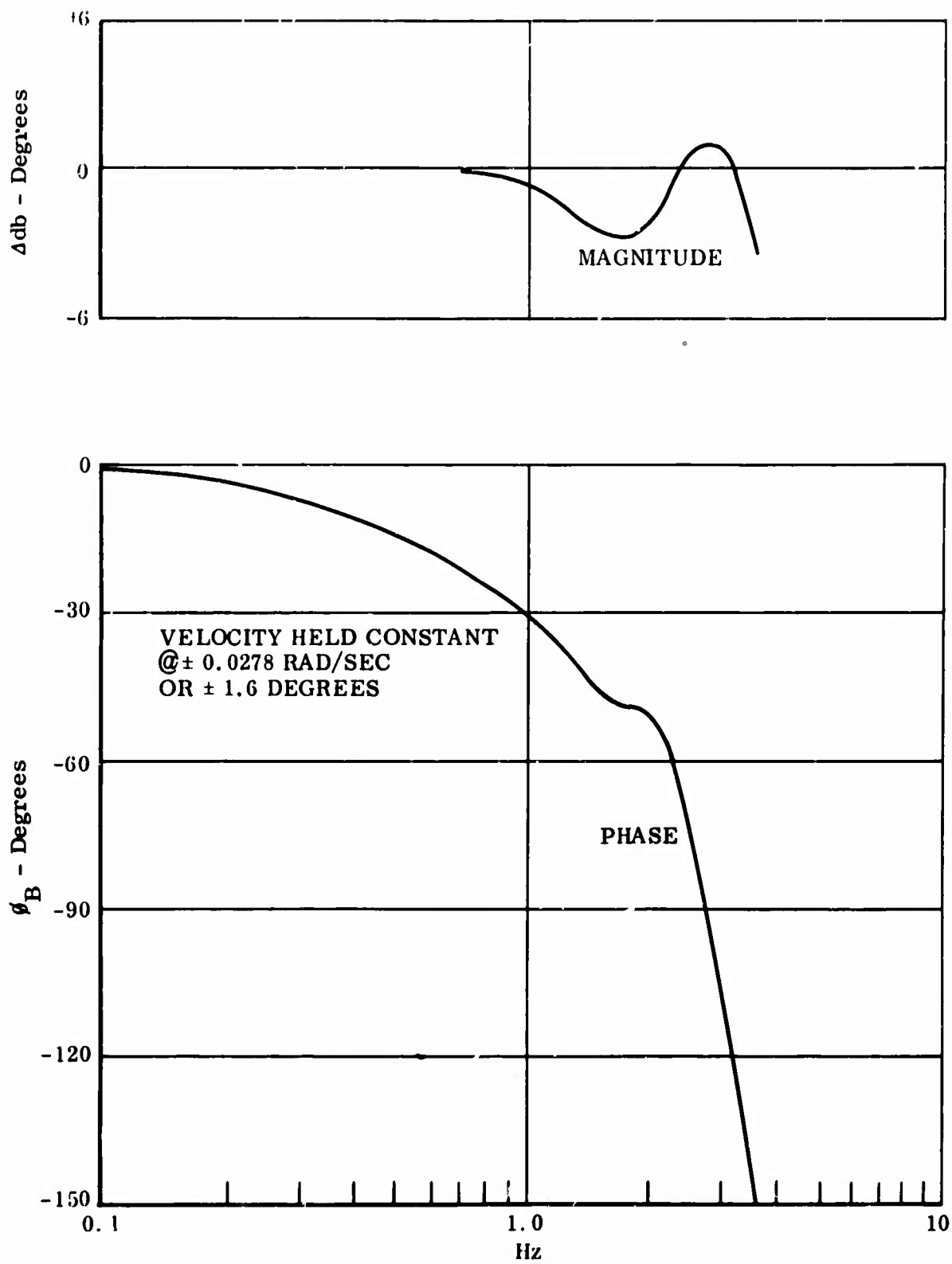


FIGURE 21.  $G_{\text{YAW}}$  MEASURED FREQUENCY RESPONSE WITH INPUT COMPENSATION

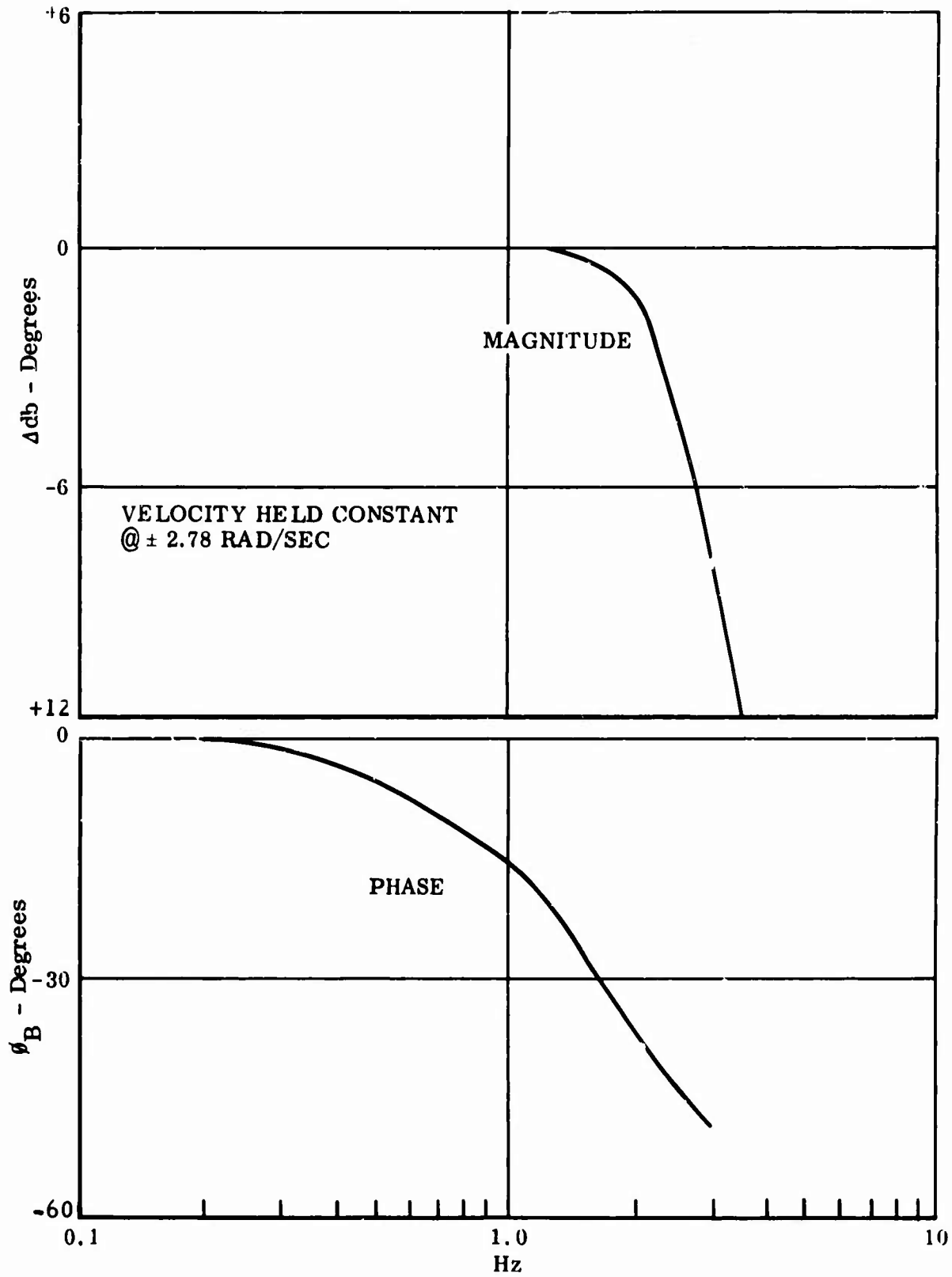


FIGURE 22.  $G_X$  MEASURED FREQUENCY RESPONSE WITH INPUT COMPENSATION

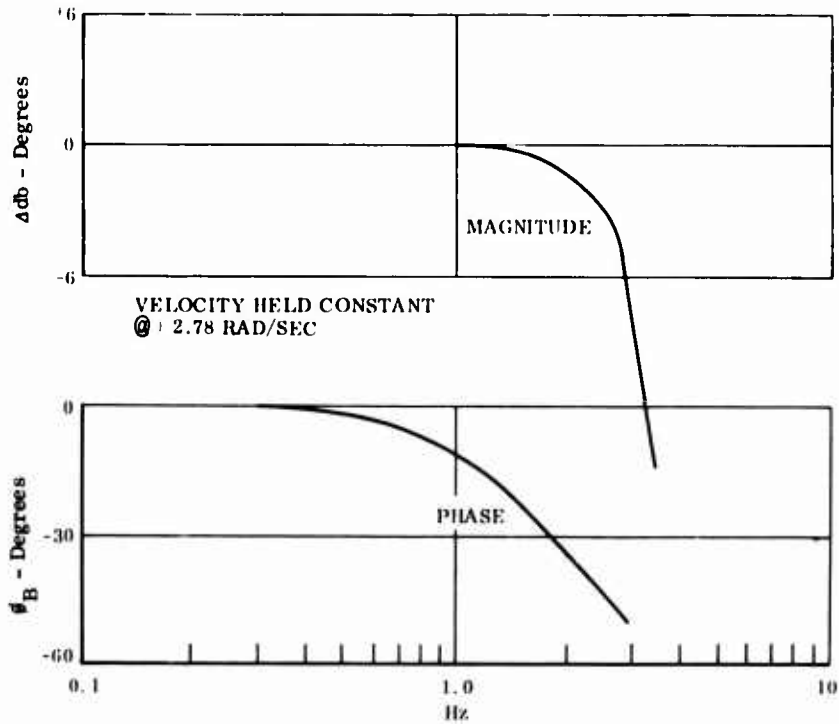


FIGURE 23.  $G_Y$  MEASURED FREQUENCY RESPONSE WITH INPUT COMPENSATION

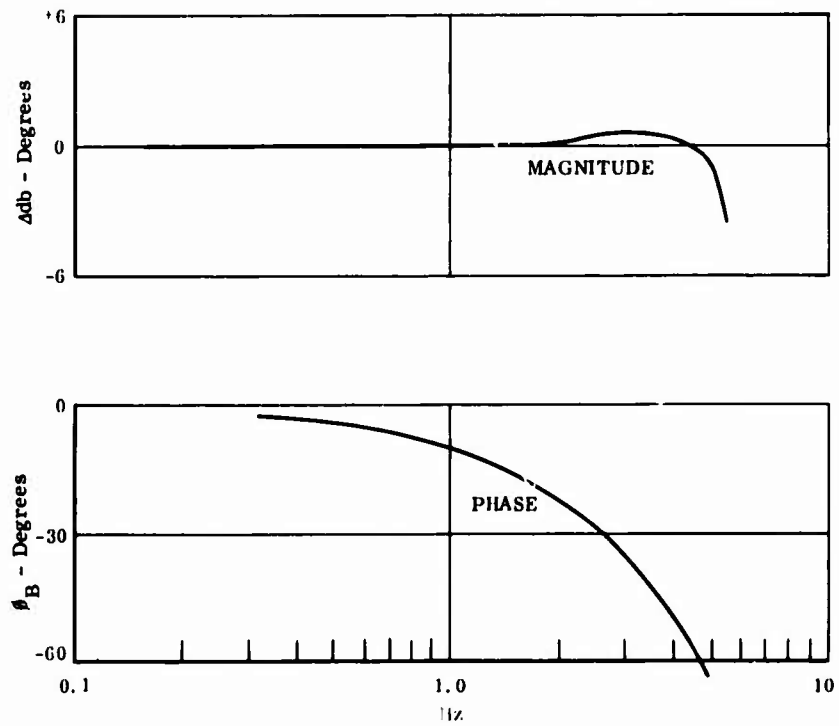


FIGURE 24.  $G_Z$  MEASURED FREQUENCY RESPONSE WITH INPUT COMPENSATION

## APPENDIX II

### DATA INDEX

Table IV, on the following page, summarizes the data analyzed for this study. The length of each record varies from 30 seconds to approximately 90 seconds. The mode of storage of the raw data (time histories) is noted for each item, and the kind of analysis performed also is given. A quantity with the asterisk (\*) indicates that it may be found in this report. The number following the asterisk indicates the figure number which contains that analysis.

Notation: In each box, the following applies:

The first group of letters starting from the top signifies storage mode:

M	-	Magnetic tape
P	-	Paper tape
O	-	Oscillograph film

The second group of letters denotes the analysis made:

R. M. S.	-	Root-mean-square
PSD	-	Power spectral density
PD	-	Probability density

The same nomenclature is used as in the List of Symbols except for  $\sigma$ , which is used in the figures of this Appendix to represent R. M. S. values. The lateral quick-stop maneuver is denoted by m and the hover task by h.

**TABLE IV  
DATA ANALYSIS SUMMARY**

TEST	TASK	QUANTITY			
		$\delta_{SR}$	$\bar{p}$ or $\frac{LRC}{I_x}$	$\phi$	$Y'$
Simulator A	h	MP R. M. S. * PSD*(1a) PD*(1b)	MP R. M. S. * PSD (3a) PD (3b)	P R. M. S. *	P R. M. S. *
	Pilot A m	MP R. M. S. * PSD*(2a) PD*(2b)	MP R. M. S. * PSD (4a) PD (4b)	P R. M. S. *	P
Simulator B	h	MP R. M. S. * PSD*(5a) PD*(5b)	MP R. M. S. * PSD (7a) PD (7b)	MP R. M. S. *	MP R. M. S. *
	Pilot A m	MP R. M. S. * PSD (6a) PD (6b)	MP R. M. S. * PSD (8a) PD (8b)	MP R. M. S. *	MP R. M. S.
Simulator C	h	MP R. M. S. * PSD*(9a) PD*(9b)	MP R. M. S. * PSD (12a) PD (12b)	MP R. M. S. *	MP R. M. S. *
	Pilot A m	MP R. M. S. * PSD*(10a) (11a) PD*(10b) (11b)	MP R. M. S. * PSD (13a) (14a) PD (13b) (14b)	MP R. M. S. *	MP R. M. S.
Simulator C	h	MP R. M. S. * PSD (15a) PD (15b)	MP R. M. S. * PSD (17a) PD (17b)	MP R. M. S. *	MP R. M. S. *
	Pilot B m	MP R. M. S. * PSD (16a) PD (16b)	MP R. M. S. * PSD (18a) PD (18b)	MP R. M. S. *	MP
Simulator C	h	MP R. M. S. * PSD (19a) PD (19b)	MP R. M. S. * PSD (21a) PD (21b)	MP R. M. S. *	MP R. M. S. *
	Pilot C m	MP R. M. S. * PSD (20a) PD (20b)	MP R. M. S. * PSD (22a) PD (22b)	MP R. M. S. *	MP
Simulator D	h	MP R. M. S. * PSD*(23a) PD*(23b)	MP R. M. S. * PSD (25a) PD (25b)	P R. M. S. *	P R. M. S. *
	Pilot A m	MP R. M. S. * PSD*(24a) PD*(24b)	MP R. M. S. * PSD (26a) PD (26b)	P R. M. S. *	P
Flight	h	MPO R. M. S. * PSD*(27a) PD*(27b)	MPO R. M. S. * (29a) PSD (30a) (29b) PD (30b)	PO R. M. S. *	P R. M. S. *
	Pilot A m	MPO R. M. S. * PSD*(28a) PD*(28b)	MPO R. M. S. * PSD (31a) (32a) PSD (31b) PD (32b)	PO R. M. S. *	P

NOTE: Magnetic tapes of complete simulator "flights" for Simulations B and C were taken which allow the playback of a "flight" through the appropriate DeFlorez display system. Sound tapes of the pilot's voice were also taken and can be synchronized with the visual tapes for complete sight and sound playback which can be viewed and heard from the cockpit.

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13. ABSTRACT <p>A study of various kinds of simulators has been made to determine their capability to produce data representative of visual flight. Four simulations of a jet-lift V/STOL aircraft were conducted using the same pilot. Control characteristics and airframe parameters were maintained constant (as closely as possible), and the same tasks were used by the pilot in each evaluation. The resulting data were compared with flight results from the same aircraft. The simulators used different displays, motion modes, and instrumentation, and the results are discussed in the light of the characteristics of each simulator.</p> <p>The results show clearly that in order to produce quantitative data representative of flight results, the display must have a quality level compatible with the task being performed. Specifically, a precision hovering task requires a high resolution display, while a translation (or transition task) can be performed with a display of much less resolution. The display content is important, particularly for the precision hovering task where height holding is required. For flight simulation of large translational movements, cockpit motion did not appear to affect the results; however, for precision hover and small, quick position changes, cockpit motion appears to be important in that it assists the pilot in detecting small drift and improves his ability to control vehicle attitude. The absence of cockpit motion when using a point source visual display for the presentation of visual information can cause vertigo and loss of performance.</p> <p>The study shows that valid V/STOL flight simulation can be accomplished and that quantitative and subjective data which closely compares with flight results can be obtained.</p>		

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
SIMULATION, V/STOL AIRPLANE TECHNIQUES, V/STOL AIR PLANE SIMULATION AIRPLANE, V/STOL SIMULATION						

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