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VERTICAL MOTION REQUIREMENTS FOR LANDING SIMULATION

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Abstract

Tests were conducted to determine the significance of vertical acceleration cues in the simulation of the visual approach and landing maneuver. Landing performance measures were obtained for four subject pilots operating a visual landing simulation mechanized in the Ames Height Control Test Apparatus, a device which provides up to ± 40 feet of vertical motion. Test results indicate that vertical motion cues are utilized in the landing task, and that they are particularly important in the simulation of aircraft with marginal longitudinal handling qualities. To assure vertical motion cues of the desired fidelity in the landing taks, it appears that a simulator must have excursion capabilities of at least ± 20 feet.

Introduction

Effective simulation of the pilot's task in the flare and landing maneuver continues to be an elusive objective nearly ten years after the introduction of the "visual attachment", the visual simulation of the pilots' view of the runway. Improvements in computer modeling of aircraft dynamics and in visual simulation technology, and the introduction of more extensive cockpit motion have increased over-all acceptance of simulators in visual-flight tasks; however, the task of flight path control near touchdown still appears unrealistically difficult. Deficiencies in visual and motion cue reproduction have been suggested as the probable sources, but quantitative definition of their respective effects has not been achieved. This paper reports the results of an exploratory investigation aimed at identifying the role of cockpit vertical acceleration cues in the landing task. The Ames Research Center Height Control Test Apparatus, a very large amplitude vertical motion device, was utilized in landing simulation tests in which the fidelity of the vertical acceleration reproduction was varied over a wide range.

Simulation

Simulation equipment - The Ames Height Control Test Apparatus (HCTA) is shown in figure 1. This device incorporates a simulated pilot station on a platform that can be moved vertically through a

total travel of 80 feet. No other motions are provided. The motion system is capable of producing acceleration to ± 0.6 and velocities to ±20 ft/sec. Dynamic tests of the motion system disclose no significant phase lag at frequencies below 1 Hz.

The simulation of the landing scene was generated with a GPS TV-terrain model visual simulation system, and was displayed in the cockpit on a 16 inch black and white TV monitor. Due to space and weight constraints, no collimation of the TV display was provided.

At touchdown cockpit height, the optical system provided sufficient depth of a field so that resultant picture resolution was determined primarily by the 525-line video system. The field of view was approximately 50 degrees horizontally by 36 degrees vertically.

Transport-type flight controls and flight instruments were provided. The aircraft simulation and the motion drive logic was programmed on two analog computers, an EAI 231R, and a Comcor 175.

Aircraft simulation - The basic airplane simulation used in these tests utilized aerodynamic coefficients typical for a 35 degree swept-wing jet transport airplane. Weight and pitching moment-of-inertia were chosen to represent a large business-jet aircraft of about 40,000 lbs landing weight. Six-degree-of-freedom flight dynamics were programmed. These included the aerodynamic effects of ground proximity, and landing gear reactions.

For part of the tests, the longitudinal dynamics of the simulated airplane were degraded by changing the static stability, C_{m_α}, and

the pitching moment-of-inertia, I_y. The characteristics of the

basic configuration (Configuration 1) and the variations are listed

in Table 1.

Cockpit motion - The simulator cockpit vertical motion system was

driven in response to the computed cockpit vertical acceleration

modified by high-pass filtering, or "wash-out", to constrain the

cockpit within the machine's excursion limits. The relationship of

simulator acceleration, $\ddot{Z}_{sim}$, to airplane cockpit acceleration,

$\ddot{Z}_{airplane}$ is given as:

$$\frac{\ddot{Z}_{sim}}{\ddot{Z}_{airplane}} = \frac{s^2}{s^2 + 2\,\zeta\omega_m s + \omega_m^{\,2}}$$

were s is the LaPlace operator, and ζ and ω_m are respectively

the damping ratio and natural frequency of the washout filter.

The mechanization and dynamic response of this washout system are

described in figure 2. For these tests a ζ of .7 was used. It

can be seen that at frequencies higher than about three times

ω_m high fidelity simulator motion is obtained, i.e., full-amplitude

motion, and phase error less than 30 degrees. The excursion

amplitude of the simulator is related to airplane acceleration by

the expression

$$\frac{Z_{sim}}{\ddot{Z}_{airplane}} = \frac{1}{s^2 + 2\,\zeta\,\omega_m\,s + \omega_m^{\,2}}$$

Thus it can be seen that in the limiting case of steady-state airplane acceleration (s=0)

$$Z_{sim} = \frac{\ddot{Z}_{airplane}}{\omega_m^2}$$

Therefore, the minimum value of ω_m that can be used in a given simulation depends upon the excursion range of the motion system and the amplitudes of airplane acceleration, particularly those at lower frequencies.

Tests

Task – The piloting task performed in these tests was a visual approach

and landing, from an altitude of 500 feet. The simulated aircraft was

initially trimmed on a four-degrees flight path intersecting the

runway 1000 feet beyond the threshold. The initial trim power setting

was maintained to touchdown. For most of the landings, the initial

conditions included a lateral offset of 400 feet, right or left, which

introduced a significant lateral maneuvering task. No flight-path

guidance information was provided in the cockpit instrumentation.

The pilot was asked to perform his approach with reference to the

simulated outside-the-cockpit scene, minimizing his references to

cockpit instruments, and to land within the first 2000 feet of the

runway while attempting to minimize his rate-of-descent at touchdown.

No winds or atmospheric turbulence were simulated.

Test plan – It has been observed in the simulator experience at Ames

Research Center that pilots having the opportunity to work with a

simulation for many hours can eventually demonstrate landing

performances approximating those of flight. This improved performance

is usually accompanied by a more favorable subjective assessment of

simulator fidelity. It has also been observed that the time required

for this learning process is a strong function of the longitudinal

handling qualities of the simulated airplane. Unfortunately, the

lack of simulation fidelity, and the obvious requirement for

"simulator adaptation" by the pilot has placed serious constraints on

the utilization of simulators for research on landing-related

problems, and for training in critical landing maneuvers. For the

objective of the subject tests, it was deemed necessary to document

the performance of pilots who were not "adapted" to landing

simulation. In order to most effectively isolate the effects of

vertical motion from those of other simulation artifacts (lack

of other motions, visual simulation deficiencies, etc.), each pilot

was provided with a familiarization period in which he could become

accustomed to the simulation in the presence of vertical motion cues

of maximum fidelity. Thus, each subject performed 30 landings with

airplane Conf. 1, with ω_m set at either 0.2 or 0.3. The subject was

then introduced to the degraded longitudinal handling qualities of

Conf. 2. After a brief familiarization (4 to 5 landings), varying

amounts of vertical motion constraint were introduced by increasing

the value of ω_m. In the subsequent 25 landings, ω_m and airplane

configuration were varied. Variations were scheduled in a random

manner in an attempt to avoid the possibility that continued

learning would distort the results.

Recorded data included time histories of altitude, altitude-rate,

pitch attitude, elevator deflection, and vertical acceleration of

the cockpit of the simulated airplane. Also recorded were the

vertical accelerations and excursions of the simulator cab. The only

quantitative measure of performance extracted from these records for

this report is the rate-of-descent at touchdown, a parameter that

has been shown to be sensitive to simulation fidelity and the

simulator experience of the pilot.

Subjects: Four professional pilots participated in the tests. Pilots
A and B were active Navy pilots, currently flying P3-C Orion 4-engine
turboprop patrol aircraft. Pilots C and D were airline pilots
current in 707 and 737 aircraft respectively. Both were military
trained, and had jet-fighter aircraft experience. All four of these
pilots had experience with training simulators, but none had extensive
experience with visual simulation of the landing maneuver.

Results and Discussion

The following discussions deal primarily with the single measure of
performance, the rate-of-descent at touchdown. This measurement is
listed for each simulated landing in Table II. The initial per-
formances of the subject pilots, before they were exposed to variations
in aircraft dynamics or simulator motion characteristics, are shown in
figure 3. The primary results of the tests, variations in performance
with changes in ω_m and airplane characteristics, are summarized in
figure 4. Example time histories of simulated landings, including
comparisons of computed and simulated vertical accelerations, are
shown in figure 5.

Simulator familiarization -   The first phase of the tests, a
familiarization exercise consisting of 30 landings with the basic
airplane simulation, was conducted in order to minimize the effects
of learning during the subsequent variations in motion fidelity. The

relatively crude visual display and the lack of motions other than vertical motion were factors obviously requiring pilot adaptation. The landing task of the subject tests was by design very simple; therefore, it was not suprising to see the obvious early performance plateau shown in figure 3. In this figure are plotted averages of touchdown sink rate for the first ten, second ten, and third ten landings of each pilot. These data are shown with the addition of one standard deviation (1σ) to indicate consistency of performance. Learning apparently did continue, however, as indicated by the collective performances of the same task later in the tests. An effect of vertical motion cues may be indicated by the comparison data from previous experiments on a fixed-cockpit simulator. The aircraft simulated in the earlier tests differed in detail from that of the subject tests, but the longitudinal handling qualities were not dissimilar. The task, and the pilot subject background were essentially the same. The same visual scene generator was used, but the pilots were provided with a collimated, full color picture. It is estimated that with a real airplane having characteristics of those simulated in either test, a pilot could be expected to produce average sink-rate values of 1 to 1.5 ft/sec after his first few familiarization landings.

The results of the second phase of the tests are summarized in figure 4 in which are shown the performance variations resulting from changes in airplane characteristics and motion cues. All of the data of figure 4

are from landings performed after the initial familiarization
period discussed above. The data shown in this figure for each
combination of ω_m and airplane confituration reflect performances
recorded at various stages of this test period; thus the data are
considered to be not seriously contaminated by learning effects.

Examination of the data of Table II discloses only minor evidence
of learning with a given airplane and motion configuration in the
course of the second phase of the tests.

Effects of degraded handling qualities - (ω_m = 0.2, 0.3) - With
the motion constraint used during the familiarization period
(ω_m = 0.2 and 0.3), reductions in longitudinal stability significantly
increased the difficulty of the landing task, according to subjective
observations by the pilot, but degradations in touchdown performance,
as seen in figure 4, were modest. As indicated in the figure,
performances with Conf. 2 and Conf. 3 were combined to provide a
larger data sample. This was justified by the absence of significant
differences in performances obtained with Configurations 2 and 3.

A comparison of landing time histories, figure 5 (a) and 5(b),
indicates the more oscillatory nature of the task with reduced
airplane stability. It can be noted in figure 5 (b) that at
ω_m = 0.2, the computed variations in cockpit vertical acceleration
are faithfully reproduced in the simulator during these oscillations.

Variations of ω_m (ω_m = 0.2 - 1.4) - Referring again to figure 4,

it is indicated that constraining cockpit motion in the simulation

of Configurations 2 and 3 resulted in a marked degradation in

landing performance; at values of ω_m of 1 and above (or with no

cockpit motion) divergent flight path oscillations were common, and

touchdown was essentially uncontrolled in many landings. This

oscillatory behavior is indicated in figure 5 (b). In some cases,

the pilots discontinued their approach rather than make an uncontrolled

touchdown. For performance averaging, these runs were credited with

a sink-rate at touchdown of 10 ft/sec. At intermediate values of

ω_m, though data samples are small, there is a consistent variation

of performance with ω_m. These data indicate that the motion

distortions introduced by ω_m larger than about 0.4 can be expected

to degrade pilot performance in the presence of marginal longitudinal

handling qualities. In marked contrast is the small change in

performance as motion is constrained in the simulation of

configuration 1, an airplane possessing very good longitudinal

handling qualities. The time history of Figure 5 (a), however,

does demonstrate an oscillatory tendency with the absence of cockpit

motion.

A comparison of the time histories in Figure 5 (b) for ω_m = 0.2 and

1.0 discloses the motion-cue distortion introduced by higher values

of ω_m. At ω_m = 0.2, cues sensed by the simulator pilot are closely

in phase with accelerations computed for the airplane. At ω_m = 1.0,

motion-cue fidelity is obviously poor.

Simulator Vertical Motion Requirement

The results of this very limited experiment are interpreted as indicating that pilots utilize even very low-level vertical acceleration cues in the performance of demanding longitudinal control tasks. It follows that high-fidelity motion cues are important to assure definitive evaluations of handling qualities on pilot-aircraft performance in critical longitudinal maneuvers. Even for the low-amplitude maneuvering accelerations typical of low-speed flight, as in approach or takeoff, extensive vertical motion of the simulator cockpit is required to provide these high-fidelity cues. As indicated in an earlier section, simulator excursion amplitudes increase markedly as ω_m is decreased. Of course, simulator excursions also depend on the amplitude of the maneuvering accelerations of the simulated airplane. For the low-speed flight tasks of research interest, the relationship between simulator travel requirements and ω_m is illustrated in Figure 6. Experience with two motion simulators has been used to define this relationship. In extensive use of the Ames Simulator for Advanced Aircraft (FSAA), which has 8 ft of vertical movement, it was determined that values of ω_m less than 1.4 resulted in an intolerable number of encounters with the excursion limits of the machine. General experience with the HCTA (80 ft of travel) showed encounters with travel limits for ω_m less than 0.2. The interpolation between these points is based on the computed variation of simulator excursion with ω_m for an airplane acceleration pulse of 3 to 5 seconds duration. The

results of the current study were interpreted from Figure 3 as indicating that the value of ω_m must be less than 0.4 to provide the desired motion-cue fidelity. As shown in Figure 6, at least 40 to 50 ft of vertical travel is required to permit use of these low values of ω_m in the simulation of maneuvers typical of low-speed flight.

TABLE 1

Characteristics of Simulated Airplane

Wing area, ft^2--625

Mean Chord, ft--10

Weight, lb--43,750

Pitch moment of inertia, slugs-ft^2:

    Configuration 1--2.19×10^5

    Configurations 2 and 3---------------------------------4.38×10^5

Distance from cockpit to airplane center of gravity, ft---------25

Lift-curve slope, C_{L_α}, 1/rad--5.1

Variation of lift coefficient with elevator deflection,

    $C_{L_{\delta_e}}$, 1/rad--0.25

Pitching-moment coefficient due to elevator deflection,

    $C_{m_{\delta_e}}$, 1/rad-- -0.70

Pitching-moment coefficient due to pitch-rate,

    $Cm_{\frac{qc}{2V}}$, 1/rad/sec--- -14.0

Pitching moment coefficient due to rate-of-change of

    angle of attack, $Cm_{\frac{\dot{\alpha}c}{2V}}$, 1/rad/sec-------------------------- -5.0

Pitching-moment coefficient due to angle of attack, Cm_α,

    1/rad:

    Configuration 1-- -0.75

    Configuration 2-- 0

    Configuration 3-- +0.25

Approach speed---120 knots

TABLE II

Pilot / Run	A		B		C		D	
	Conf-ω_m	$\dot{h}_{TD}$	Conf-ω_m	$\dot{h}_{TD}$	Conf-ω_m	$\dot{h}_{TD}$	Conf-ω_m	$\dot{h}_{TD}$
1	1-NM*	5.2	1-NM	10.5	1-NM	9.8	1-NM	6.6
2	1-.3	6.5	"	8.2	"	10.7	"	4.7
3		1.4	1-.3	10.0	1-.2	5.2	1-.2	4.2
4		.6		6.2		5.0		2.5
5		9.3		5.8		4.6		4.6
6		3.2		2.1		2.1		4.9
7		5.5		2.2		3.4		6.5
8		4.0		4.2		3.2		2.6
9		2.8		4.8		4.2		4.0
10		2.0		5.3		5.1		.9
11		5.4		2.7		.8		2.5
12		6.5		3.7		3.7		2.3
13		2.6		2.8		1.7		3.4
14		1.6		3.1		.5		2.1
15		1.5		2.9		3.8		2.1
16		4.6		2.8		3.5		1.7
17		4.3		2.1		*		1.6
18		3.4		2.7		3.4		1.6
19		4.8		2.9		2.6		4.3
20		4.0		2.4		1.7		2.4
21		2.0		1.7		3.7		3.0
22		3.0		1.0		3.6		6.5
23		1.8		3.6		3.3		4.1
24		4.8		2.2		3.1		1.7
25		1.8		1.5		2.3		.5
26		2.3		2.5		.5		3.3
27		1.8		4.5				3.7
28		3.3		3.6		2.5		1.4
29		2.3		2.0		4.5		5.3
30		1.1		2.8				2.6
31		5.0		1.6		2.3		2.6

32	2-.3	W/O*	↓	1.8	↓	4.0	↓	.9
33	"	7.8	2-.3	W/O		1.5	1-NM	3.6
34	"	3.2	"	4.2	↓	4.3	"	1.2
35	"	2.3	"	1.4	2-.2	5.3	"	3.1
36	2-1.4	7.5	"	4.5	"	3.1	2-.2	2.4
37	"	20.5	"	5.8	"	3.5	"	3.3
38	2-.3	6.6	2-1.4	W/O	"	3.2	"	4.0
39	"	1.0	"	W/O	"	3.8	"	1.8
40	2-1.4	10.0	"	6.0	2-.7	1.2	2-NM	18.8
41	"	25.0	"	4.0	"	10.5	"	6.2
42	1-1.4	2.4	"	7.0	"	9.8	"	12.8
43	"	3.6	2-.3	2.0	"	9.5	2-1.0	8.0
44	1-.3	1.7	"	5.0	2-.2	3.1	"	5.7
45	"	2.3	2-1.4	6.7	"	3.5	"	8.3
46	2-.3	2.3	"	5.8	2-1.4	10.5	2-.3	3.3
47	"	1.3	1-1.4	2.7	"	13.0	"	3.4
48	3-.3	2.7	"	2.3	2-.5	5.2	"	3.6
49	3-1.4	6.0	"	2.6	"	5.3	"	1.6
50	"	30.0	1-.3	2.0	"	2.0	2-1.4	6.0
51	3-.3	3.7	"	1.3	"	6.5	"	3.0
52	"	4.2	3-.3	3.2	2-.2	4.9	1-.2	3.8
53	1-.3	1.3	"	5.8	"	5.2	"	1.9
54	↓	.4	3-.5	.8	"	4.2	"	.8
55		1.9	"	3.9	2-1.4	8.0	"	4.0
56		1.9	"	6.2	"	5.8	"	1.7
57		1.0	3-1.0	W/O	1-.1.4	2.4	3-.2	2.9
58		2.3	"	W/O	"	2.5	3-1.4	15.0
59		2.3	3-.3	5.2	1-.3	1.8	3-.7	1.7
60		2.8	"	5.0	3-.3	5.2	1-.2	2.8
61		2.0	"	4.0	"	2.4		
62	↓		"	2.0	3-.7	2.3		
63			"		"	11.5		

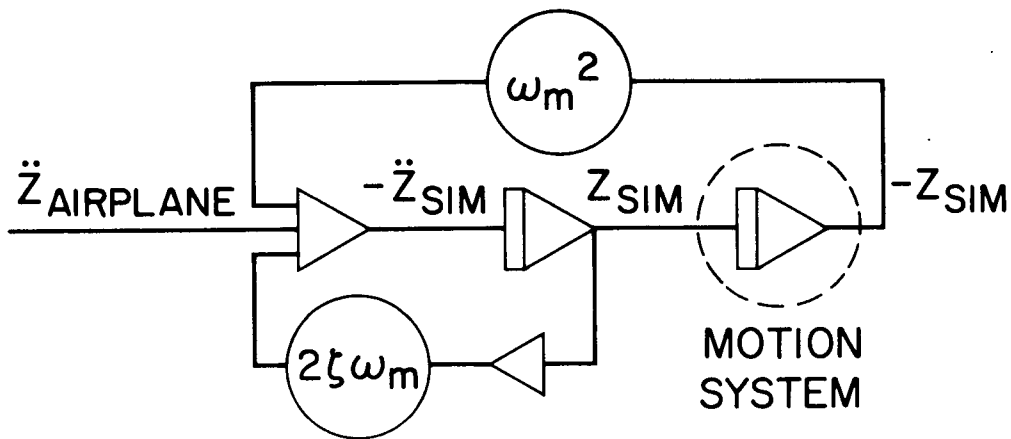* NM: No motion

W/O: Discontinued approach

——:   Data void, malfunction

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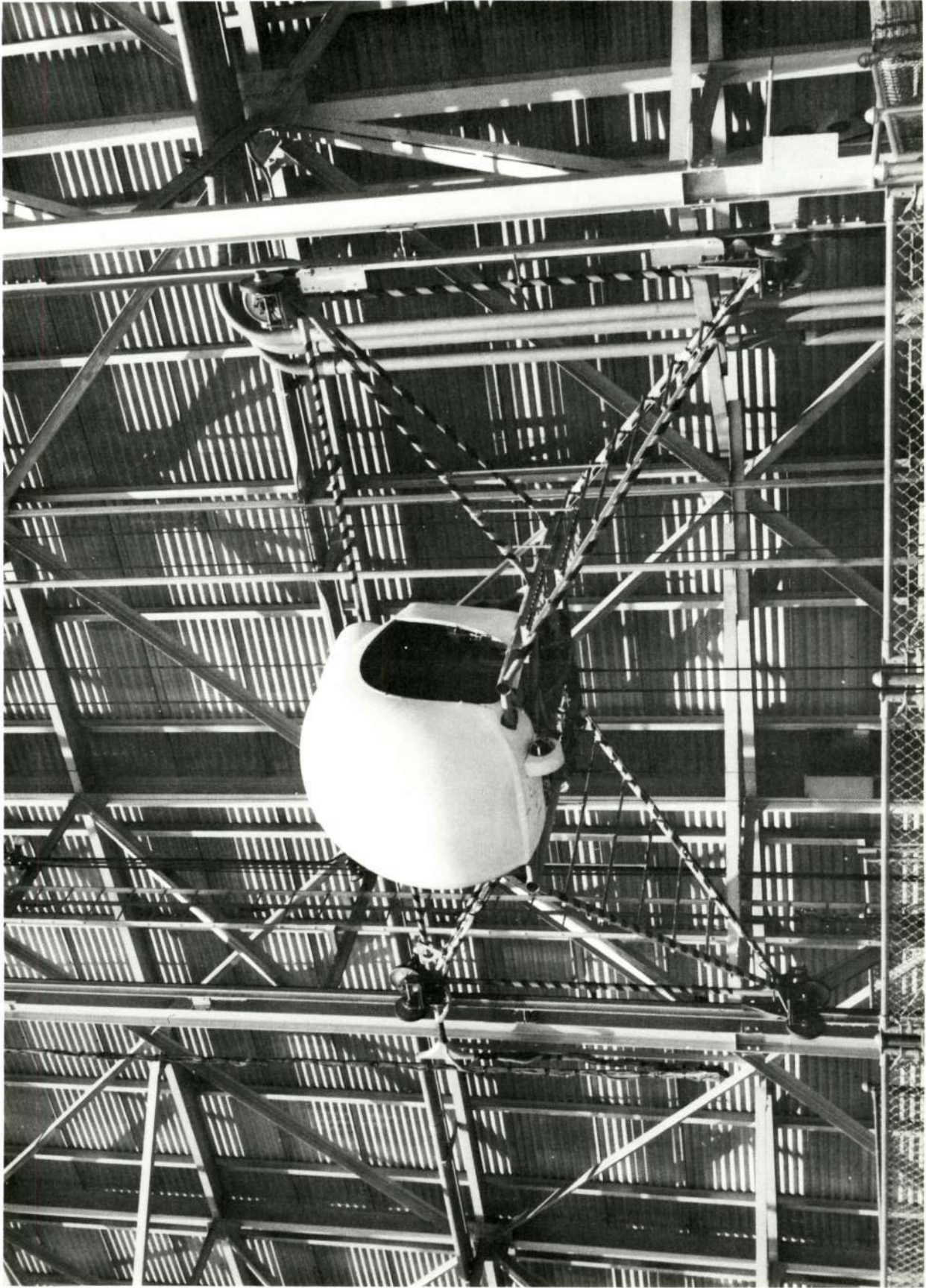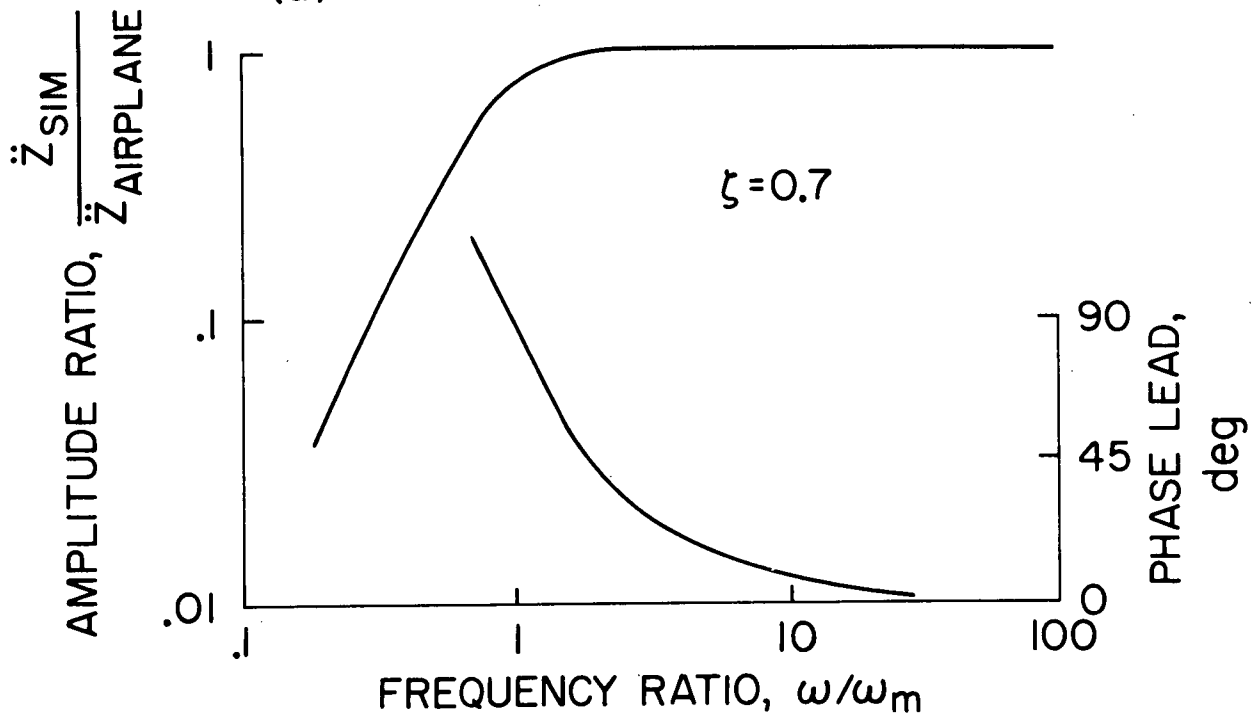
FIGURE 1 - THE AMES HEIGHT CONTROL
TEST APPARATUS

(a) WASHOUT SYSTEM SCHEMATIC

(b) DYNAMIC RESPONSE OF WASHOUT SYSTEM

FIGURE 2. BASIC SECOND-ORDER HIGH-PASS-FILTER MOTION
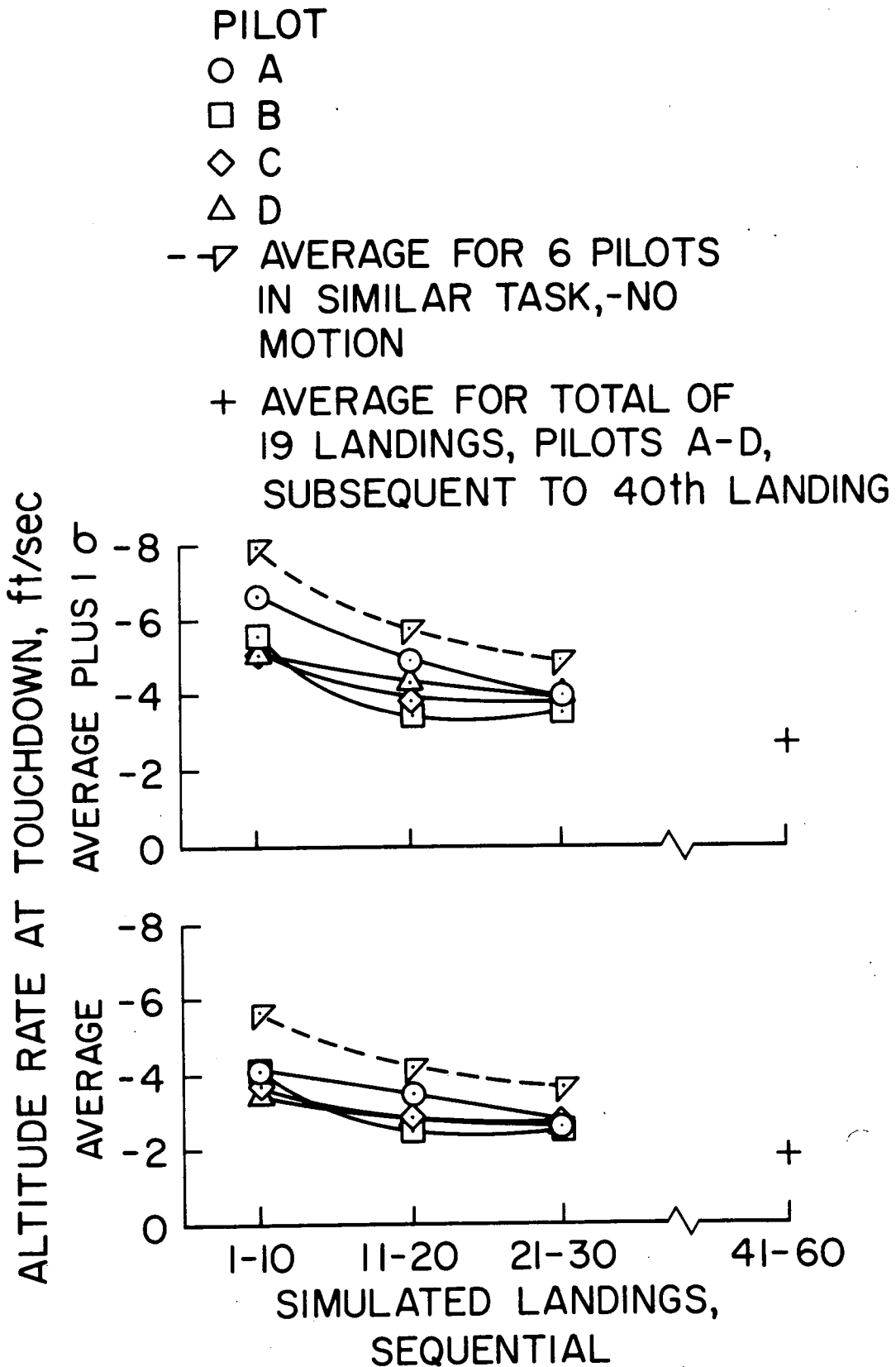
CONSTRAINT SYSTEM.

FIGURE 3. EFFECT OF LEARNING ON THE PERFORMANCE OF THE
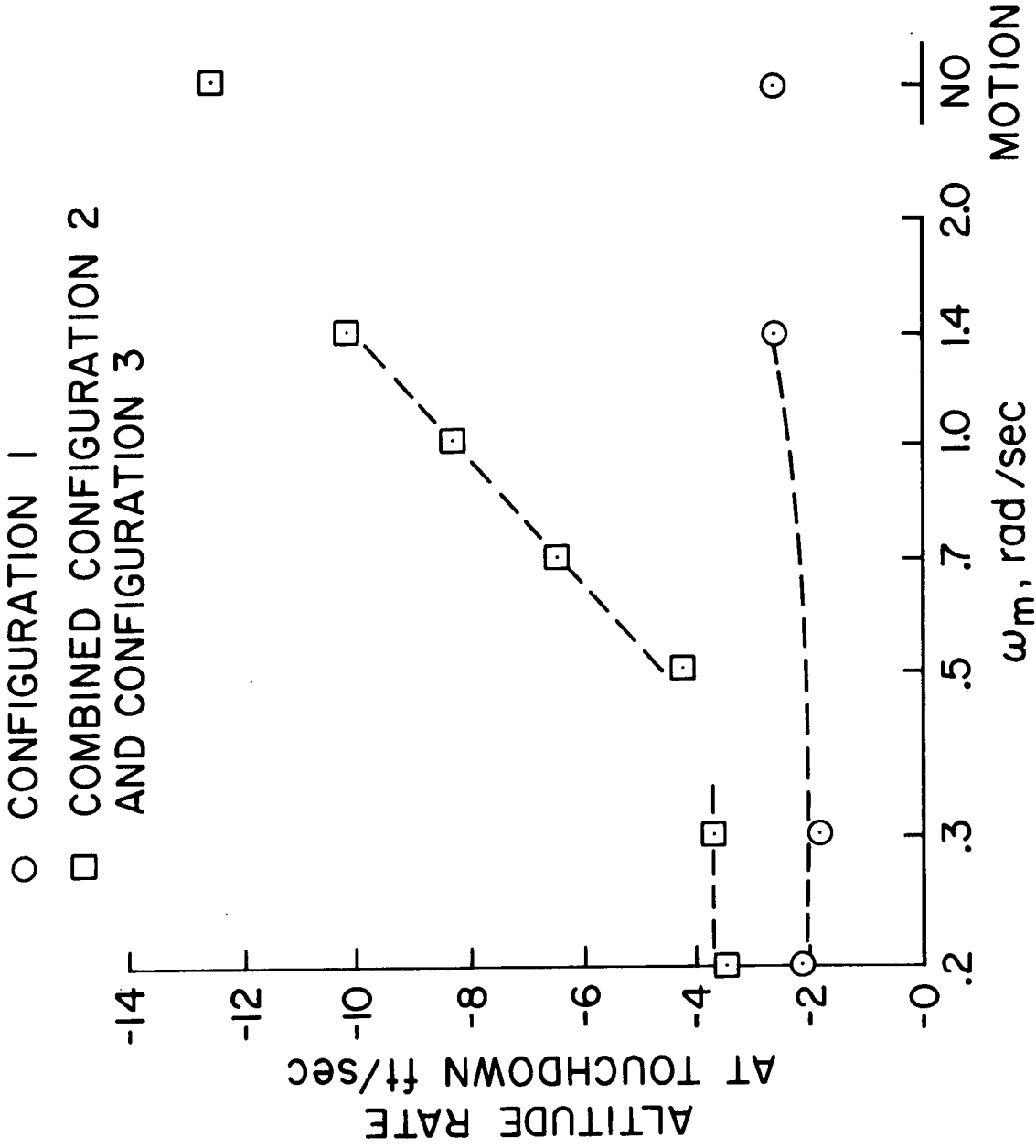
SIMULATED LANDING TASK, CONFIGURATION 1.

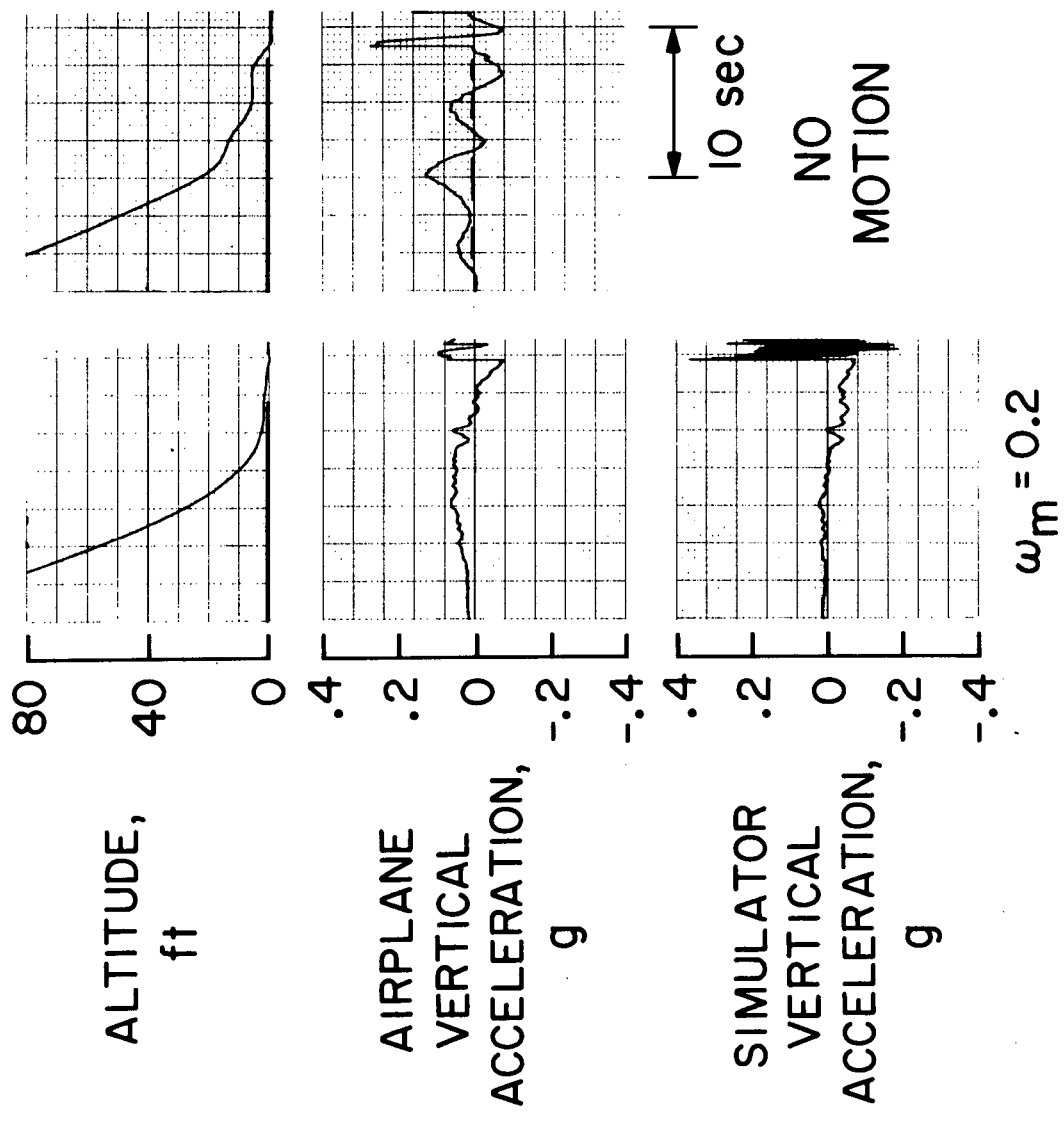FIGURE 4. EFFECTS OF WASHOUT FILTER NATURAL FREQUENCY, ω_m, ON LANDING PERFORMANCE.

FIGURE 5(a). TIME HISTORIES OF SIMULATED LANDINGS, PILOT D.,
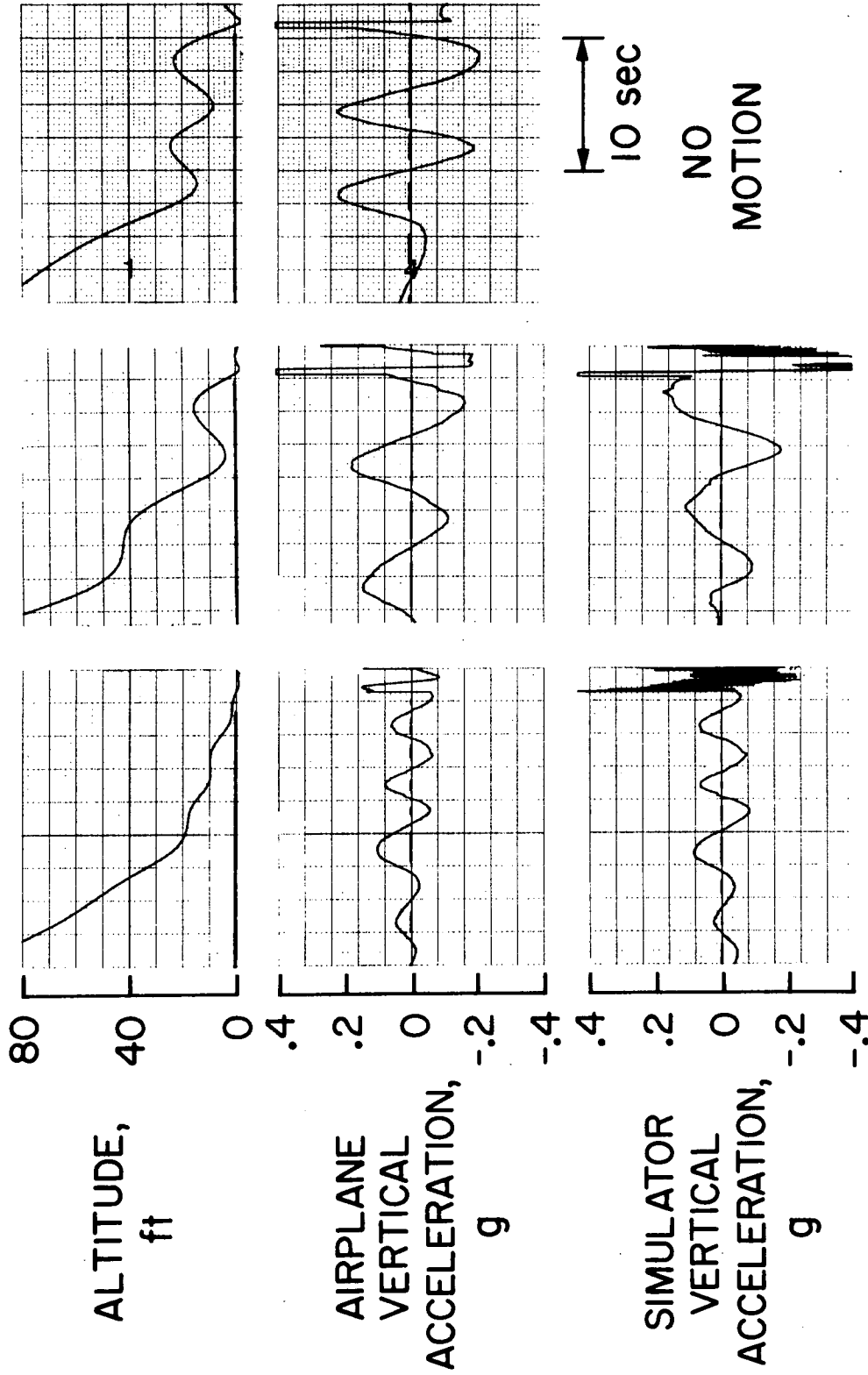CONFIGURATION 1.

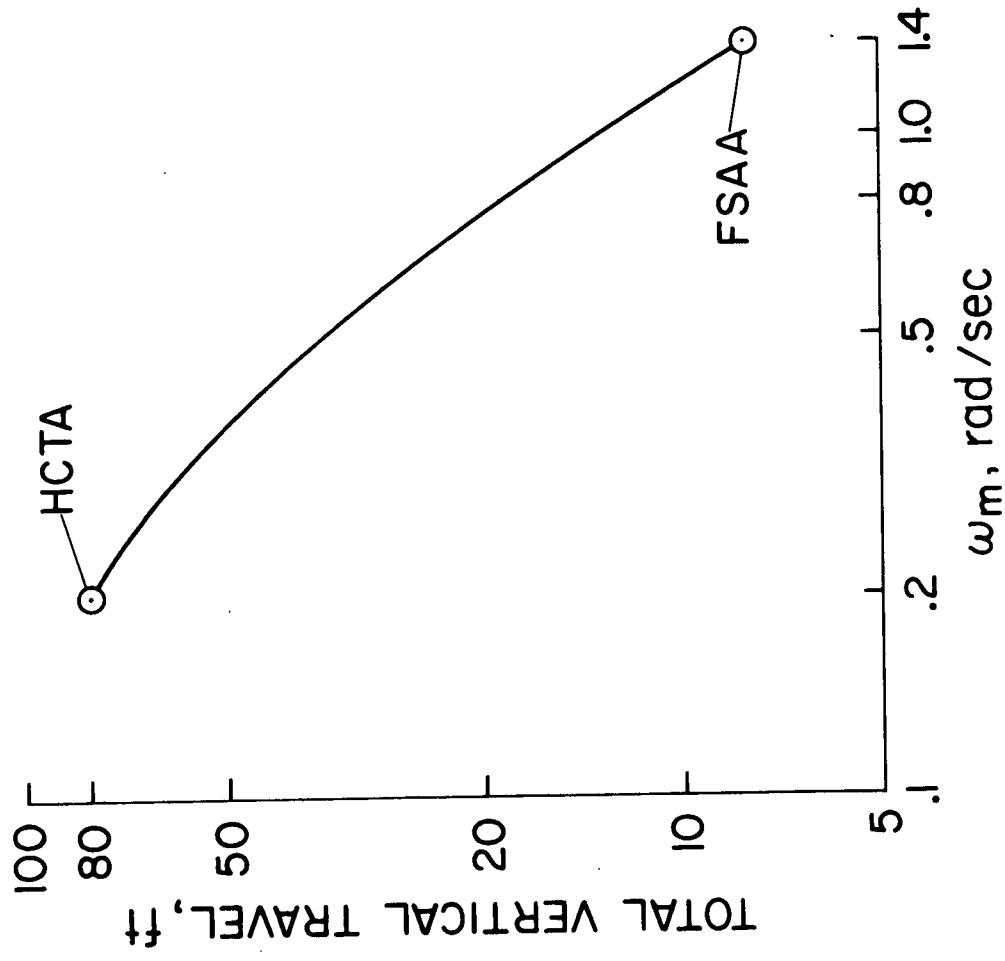FIGURE 5(b). TIME HISTORIES OF SIMULATED LANDINGS, PILOT D.,

CONFIGURATION 2.

FIGURE 6.   RELATIONSHIP OF VERTICAL TRAVEL REQUIREMENT TO ω_m FOR SIMULATION OF LOW-SPEED FLIGHT MANEUVERS.