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A PILOTED MOTION SIMULATOR INVESTIGATION OF VTOL HEIGHT-CONTROL REQUIREMENTS

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SUMMARY

A moving-cockpit piloted simulator was used to investigate VTOL aircraft height control requirements during hover. Pilot opinion ratings were used to determine the relationships of control power, damping, and time constant in realistic VTOL hovering tasks. The minimum upward acceleration for "normal operation" was found to be 1.06g while minimum acceptable safe operation was determined to be between 1.02g and 1.03g. Minimum damping levels for normal operation were dependent on control system time constant when operating with high thrust-to-weight ratios. Acceptable control of altitude could be maintained in the event of artificial vertical damper failure as long as the control system time constant remained below 0.37 second. Minimum acceptable control power was found to depend on the vertical velocity response during lift-off and touchdown maneuvers. Hovering steadiness tests with zero velocity damping indicated a tendency to overcontrol at time constants above 0.6 second while the pilot's full attention was required at 1.2 seconds. The relative importance of cockpit motion and visual display in correlating simulator and flight data was briefly investigated.

INTRODUCTION

Precise altitude control near the ground is essential to the success of any VTOL airplane mission, be it commercial or military. Height-control boundaries established with a piloted fixed-cockpit simulator are reported in reference 1 and those with a limited travel motion simulator in references 2 and 3. Reference 2 emphasizes the importance of motion in height-control simulation studies and points out that fixed-cockpit simulator results are apt to be unduly conservative, particularly if the pilot must rely entirely on an instrument for height reference.

The present study was undertaken to define more clearly satisfactory height-control boundaries through use of a moving-cockpit simulator which allowed an investigation of the important height-control parameters with true motion cues. The maneuvers for evaluating height control were not restricted by the equipment since the large vertical travel and acceleration available substantially exceeded the test requirements.

Results of this study are compared with previous studies to indicate the effects of motion in an "outside-world" environment. Control power and damping relationships are discussed with particular emphasis on the effects of the response time of the control system. The effects of increasing levels of control response time constant on hovering steadiness are also presented.

NOTATION

C.P.   maximum upward control power, g

g   acceleration due to gravity, 32.2 ft/sec^2

PR   pilot-opinion rating

τ first-order time constant, sec

EQUIPMENT

The tests were conducted on the Ames Height Control Simulator shown in figure 1. The simulator includes a true, "outside-world" environment and a 100-foot altitude capability. The two-place helicopter-type cockpit (fig. 2) has one degree of freedom of movement (vertical) and is electrically driven through cables. Accelerations of ±2g and maximum velocities of ±20 ft/sec are possible. The pilot's instrument panel contains vertical position, rate, and acceleration indicators.

Altitude is controlled by means of a collective pitch controller. Controller sensitivity is linear and fixed at 0.1g per inch of travel as measured along an arc at the hand grip. Maximum upward control power is varied by adjustment of the top mechanical stop of the controller. The maximum downward acceleration provides a zero g (free fall) condition with the controller bottomed.

The function of the analog computer in the simulation is shown in the block diagram of figure 3. The pilot's controller displacement, acting through a linear gain, commands vertical acceleration. This signal is further modified by a first-order time-delay circuit to approximate engine response and control lag characteristics. Vehicle damping is furnished by feeding back a velocity term. The resultant vehicle acceleration signal is integrated twice to provide an altitude position signal. A lead network is incorporated to reduce the lag in the simulator drive system. Simulator cockpit response to a command step input is improved to an equivalent 0.07-second first-order time lag with the lead compensation operative.

TESTS

Four NASA research pilots participated in the tests. The Cooper Pilot Opinion Rating System, as reproduced in table I and described in reference 4, was used to rate the control characteristics.

Hovering operations, required of military VTOL aircraft during tactical operations in the field, were considered in defining the primary mission as follows: (1) Vertical takeoff from a confined area prior to transition to forward flight; (2) hovering gun platform from which to deliver tactical weapons; (3) vertical letdown and landing into a confined area. To simulate these operations the pilots were asked to (1) lift off and climb to an altitude of from 30 to 50 feet as smoothly and rapidly as possible with a minimum of "overshoot;" (2) hover at the selected altitude; (3) commence a vertical descent and touchdown at a specified time interval (20 to 30 sec) after initiation of the lift-off. Factors such as maximum vertical velocity, controller displacement, "overshoot," hovering steadiness, sink rate arrestment, and touchdown precision were to be considered. A wheel touchdown reaction force was included in the simulation to help determine landing capability. Gusty air conditions and ground proximity effects were not included.

Control sensitivity was fixed at 0.1g per inch, which is a representative design value. Control power was varied from 1.02g to 1.2g and velocity damping varied from 0 to -1 per second. A response time constant for the vehicle height control system, representative of typical engine thrust response characteristics and other control motion lags, was approximated by a first-order time delay (i.e., time to reach 63 percent of the steady-state value).

Maximum upward control power and velocity damping were first mapped at a very low value of control response time constant and was repeated using two higher values of time constant. Pilot-opinion ratings of hovering steadiness as a function of time constant were also determined with zero damping and constant control power. The pilot's task for these tests was simply to hover as smoothly as possible at a constant altitude.

RESULTS AND DISCUSSION

Control Power and Time Constant

The results of the maximum upward control power studies are presented in figure 4. Shown is the variation, with velocity damping, of the maximum upward control power at three levels of control response time constant. The approximate values of maximum upward control power and velocity damping for the X-14, X-14A, SC-1, and H-23C aircraft are plotted on figure 4 for comparison purposes.

A minimum damping level requirement is established as control power is increased. The $\tau = 0.07$ also defines a minimum satisfactory control power level of about 1.06 at a damping level of -0.5 per second. Increasing the damping at this control power causes sluggish or velocity-limited (less than 3 ft/sec) operation while decreased damping causes overcontrolling. Increasing the time constant to 0.37 second shifts the minimum control power requirement to the right (1.08g) and raises the minimum damping requirement to about -0.2 per second. This agrees quite well with the results obtained in reference 2 at a time constant of 0.2 second. Raising the time constant to 0.87 second drastically increases the minimum damping requirement, and makes damping insensitive to control power changes in the region tested. It is interesting to note the apparent convergence of two of the 3-1/2 boundary curves.

Results indicate that high levels of vertical damping are required when control system time constants are large. An increase in time constant resulted in an increase in pilot induced "overshoot" during operation within the region of low damping and high control power (lower right quadrant). The inherent low velocity-damping characteristics associated with nonrotary wing VTOL vehicles would thus require that height-control systems have low time constants. Flight data for the X-14, X-14A, SC-1, and H-23C aircraft agree well with data of the present study.

In general, upward maximum velocities used did not exceed 15 ft/sec, even with high control power. The pilots limited their downward velocities as the control power and/or damping were decreased in order to assure that sink rate could be checked prior to touchdown. Pilot comments indicated that 10 ft/sec was used as an average comfortable velocity when combinations of control power and damping permitted. Low control powers were rated unacceptable in terms of velocity requirements for climb out (high damping area) and to arrest rapid sink rate on landing (low damping area).

Pilots felt that all values of control power and damping examined at time constants of 0.07 and 0.37 second were within the operational region of table I; therefore only the 6-1/2 boundary for $\tau = 0.87$ is presented in figure 4. This would indicate that acceptable control of altitude can be maintained regardless of whether the artificial height-control augmentation device failed as long as the height-control system time constant remains less than 0.37 second. The minimum level of control power for acceptable safe operation lies between 1.02 and 1.03g.

Control system time constant effects were reported in references 1 and 2 by selecting representative control power and damping combinations and obtaining controllability pilot opinion data as the time constant was varied. Similar data from the present study have been plotted with the data from reference 1 for comparison (see fig. 5). In this figure, three combinations of control power and damping (A, B, C) were selected from each study as follows:

Combination	Control power		Velocity damping	
	Present study	Fixed cockpit (ref. 1)	Present study	Fixed cockpit (ref. 1)
A	1.2	1.2	-1.0	-1.0
B	1.2	1.2	0	-.125
C	1.02	1.06	-.50	-.50

Although all combinations selected were not identical, it is felt that they are similar enough for this discussion and for that which is to follow concerning simulator performance.

The results of this investigation are generally in agreement with previous studies (refs. 1 and 2). Comparison of the slopes of curves A and B indicates that hovering controllability deteriorates at a greater rate in the low damping case. Likewise, high damping is beneficial in enabling the pilot to cope with the time delay. High values of pilot rating for curve C are attributed to sluggish, velocity limited control response. The difference in absolute values for the three combinations is discussed later.

For discussion purposes the results of figure 4, in terms of the mission parameters previously described, can be divided into four general areas. The upper left-hand area (low control power and high damping) is characterized by sluggish response and very low velocities. Even though the vehicle can be lifted off and landed, the success of the mission is doubtful because of maneuvering response restrictions. Time constant effects are masked. Below this region, in the area of reduced damping, maneuvering response is improved yet limited by total thrust. Sink rates can be excessive for landing, but the primary mission can be accomplished if the time constant is less than 0.37 second. The upper right-hand region is most desirable for all aspects of the mission. Lift off and landing are easily controlled and the primary mission is assured. Damping levels are adequate for satisfactory control at moderate time constants. Hovering steadiness provides a good gun platform. Success of the primary mission in the lower right-hand region depends on the time constant. Response is rapid, but increased time constant causes the pilot to overcontrol in all hovering phases of the mission.

Reference 5 recommends minimum vertical thrust margins of 1.05g for take-off and 1.15g for landing with a maximum vertical thrust response time constant of 0.3 second. Comparison of these recommendations with figure 4 reveals that the landing condition would be satisfactory as long as the damping exceeded about -0.2 per second. However, the take-off value of 1.05g appears to be unsatisfactory even for low time constants and optimum damping.

Hovering Steadiness

Figure 6 depicts the results of the hovering steadiness test. The pilots were asked to maintain a constant altitude with control power, control

sensitivity, and damping fixed while the time constant was increased from 0.07 to 2.4 seconds. The pilot opinion ratings were based on the requirements of reference 6, which is to hold height ±1 foot with 1/2 inch or less of collective control motion. Sensitivity was 0.1g per inch, maximum upward control power was 1.15g, and zero velocity damping was used. A noticeable decrease in hovering steadiness was observed as the time constant was increased to 0.3 second. Overcontrolling was evident at 0.6 second and the pilot's full attention was required at 1.2 seconds. The referenced specifications were not met above 0.6 second and a time constant of 2.4 seconds was considered too dangerous for actual flight because of large excursions in altitude.

A comparison of figures 4 and 6 reveals the importance of considering the pilot control task when pilot opinion data are compared. Although control power (1.15g), damping (0), and time constant (0.07 sec) values for the two tasks were the same, the hovering steadiness task, easier of the two, received a more satisfactory pilot rating.

Comparison of Simulators and Flight

The relative importance of cockpit motion and visual display is of general interest when data obtained from piloted simulators are considered. Results from the present study have been correlated with previous investigations to determine motion and display variation effects. Three classes of simulators are considered in the discussion to follow: fixed cockpit, limited travel moving cockpit, and large travel moving cockpit. The first simulator (ref. 1) was a rudimentary fixed cockpit type with a two-dimensional visual display. The cockpit of reference 2 had a limited travel of 8 feet (see ref. 3) and a projected point visual display. The moving cockpit used in this study has unlimited travel in light of typical VTOL missions previously described and true outside-world vertical motion cues. If hovering controllability is assumed to be a direct function of the vehicle response stimuli fed back to the pilot, then one would expect the results of the present study to be in closer agreement with flight.

The 3-1/2 pilot opinion ratings for references 1 and 2 are plotted in figure 7 with similar data from the present study for direct comparison. It should be noted that the control sensitivity of the referenced studies was 0.3g per inch; however, sensitivity tests (refs. 1 and 2) indicated similar pilot ratings at 0.1 and 0.3g per inch.

Comparison of the three curves of figure 7 reveals that the introduction of cockpit motion reduces the minimum control power and damping requirements for satisfactory operation. These data indicate that unlimited motion tend to improve the correlation of simulator data with flight results.

The pilot opinion data of figure 5 indicate that the addition of motion usually enables the pilot to cope with increased values of time constant. For example, with high damping and control power (A), normal operation is possible

to about 0.9 second, while similar data from references 1 and 2 indicated this limit to be only 0.4 second. It is interesting to note how closely the two low control power curves agree (C). These data illustrate how vehicle response characteristics can modify simulator motion requirements. Combinations of control power and damping represented by curves A and B result in rapid response to control inputs while curve C operation is characterized by very slow and sluggish response. One possible reason for the proximity of curves C is that cockpit motion cues play a lesser roll in the determination of controllability when control response is low. A second possible reason could be the small difference in control power (1.02 and 1.06g).

It is, thus, evident from the above that pilot opinion data obtained from simulator studies can be strongly influenced by the degree of motion response fed back to the pilot. The use of unlimited motion and an ouside-world environment in the present study resulted in closer agreement between simulator and flight data.

CONCLUSIONS

Hovering height-control boundaries for control power and damping have been evaluated in a moving cockpit simulator using a realistic VTOL mission flying task. This investigation has resulted in the following conclusions:

1. The minimum upward acceleration for "normal operation" for typical hovering maneuvers should be about 1.06g. The minimum level for acceptable safe operation should be between 1.02 and 1.03g.

2. For normal operation, the minimum damping level is highly dependent on control system time constant, particularly during operation at high thrust to weight ratios.

3. As long as the control system time constant remains below 0.37 second, acceptable control of altitude can be maintained in the event of artificial vertical velocity damper failure.

4. Velocity response plays an important part in the determination of minimum acceptable control power. Operation is sluggish and velocity limited for takeoff in the high damping case, and there is inadequate arrest of high velocity sink rates for landing in the low damping case.

5. Tests of hovering steadiness at zero velocity damping indicate a pilot tends to overcontrol at time constants above 0.6 second, and requires his full attention at 1.2 seconds.

6. The use of unlimited motion and an outside-world environment tend to improve the correlation of simulator data with actual flight.

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    National Aeronautics and Space Administration
        Moffett Field, Calif., June 15, 1964

REFERENCES

1. Gerdes, Ronald M., and Weick, Richard F.: A Preliminary Piloted Simulator and Flight Study of Height Control Requirements for VTOL Aircraft. NASA TN D-1201, 1962.

2. Garren, John F., Jr., and Assadourian, Arthur: VTOL Height-Control Requirements in Hovering as Determined From Motion Simulator Study. NASA TN D-1488, 1962.

3. Brown, B. Porter, and Johnson, Harold I.: Moving-Cockpit Simulator Investigation of the Minimum Tolerable Longitudinal Maneuvering Stability. NASA TN D-26, 1959.

4. Cooper, George E.: Understanding and Interpreting Pilot Opinion. Aero. Eng. Rev., vol. 16, no. 3, March 1957, pp. 47-51, 56 (Also IAS Reprint 683).

5. Botrel, A.: Recommendations for V/STOL Handling Qualities. AGARD Rep. 408, Oct. 1962.

6. Anon.: Helicopter Flying and Ground Handling Qualities; General Requirements for Military Specification. MIL-H-8501A, Sept. 7, 1961.

TABLE I.- PILOT OPINION RATING SYSTEM

	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Limited operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[1]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[1]	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

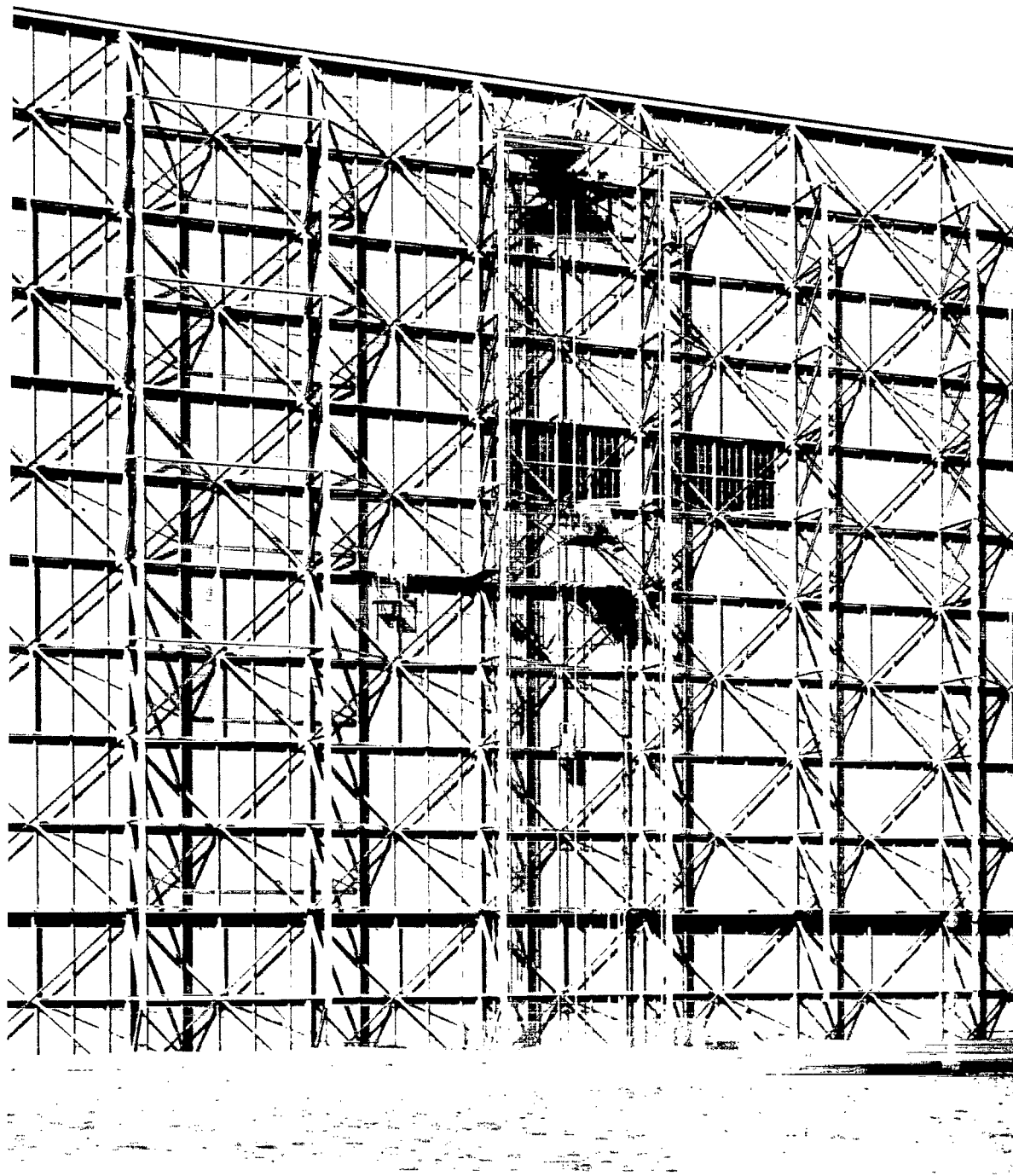[1]Failure of a stability augmenter

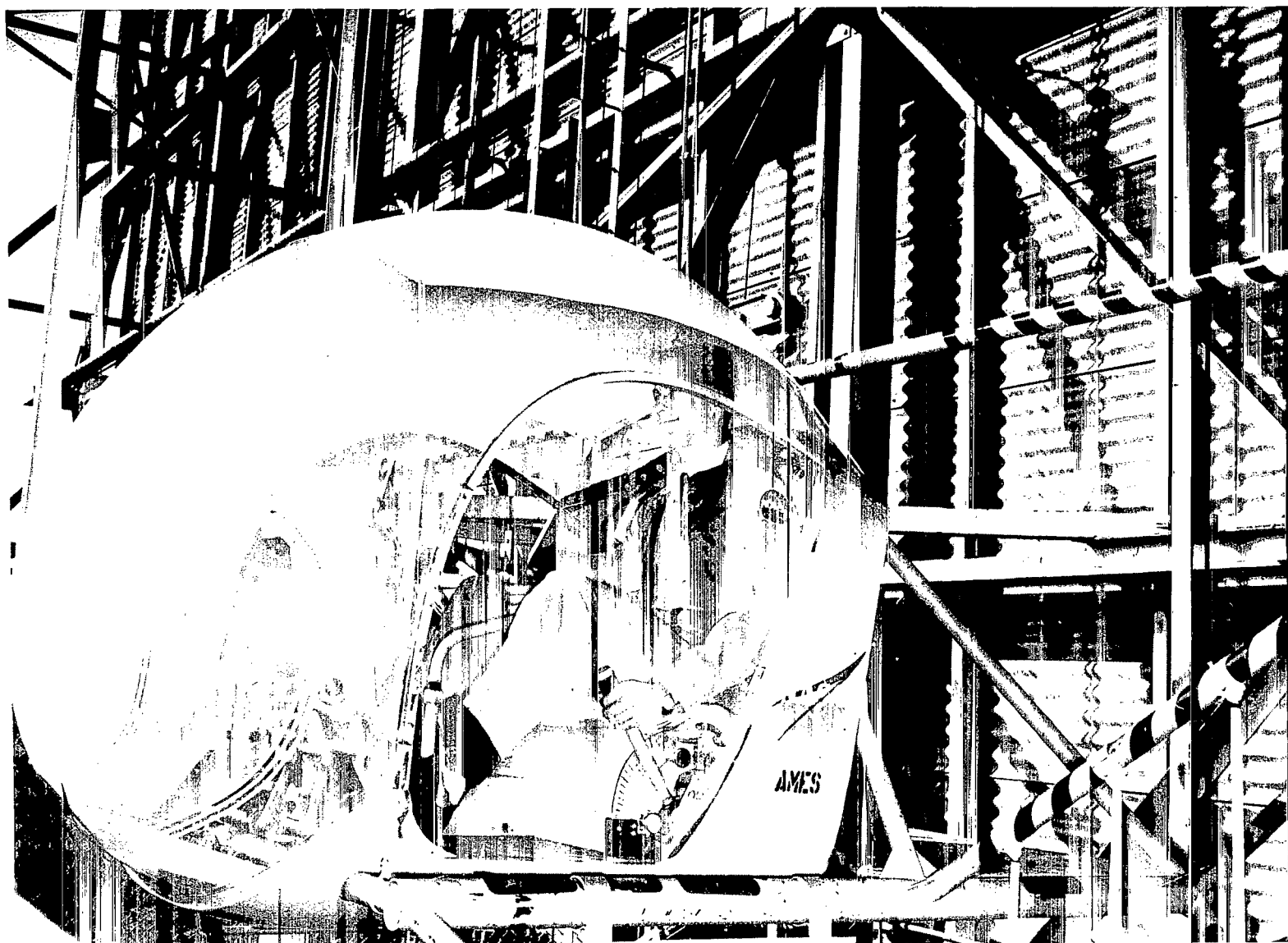Figure 1.- General view of simulator.

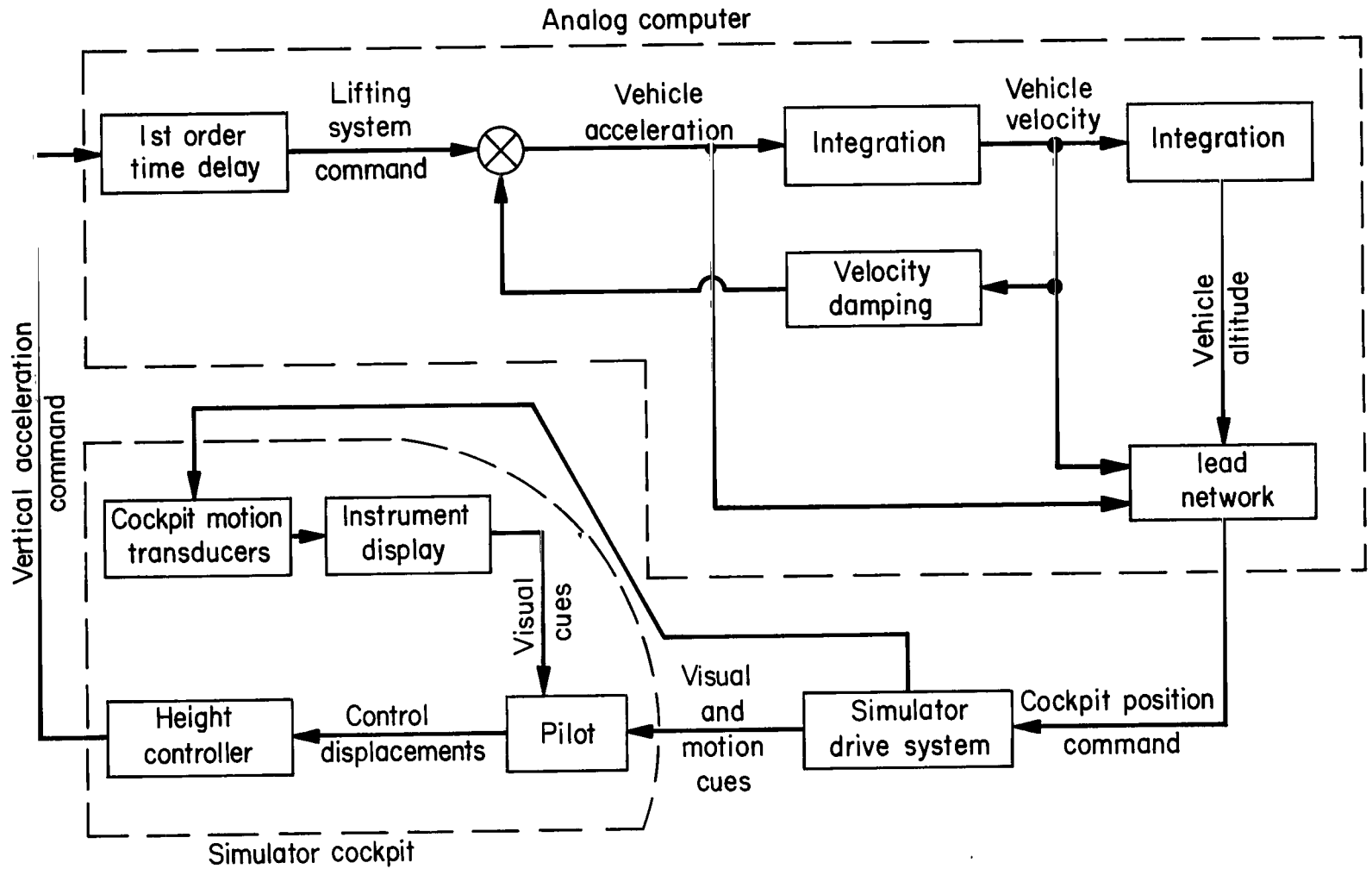A-30430

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Figure 2.- View of simulator cockpit.

A-30433

Figure 3.- Block diagram of simulator.

Maximum downward control power = Og
Control sensitivity = 0.1 g/inch(present study)
First order time constant (τ)
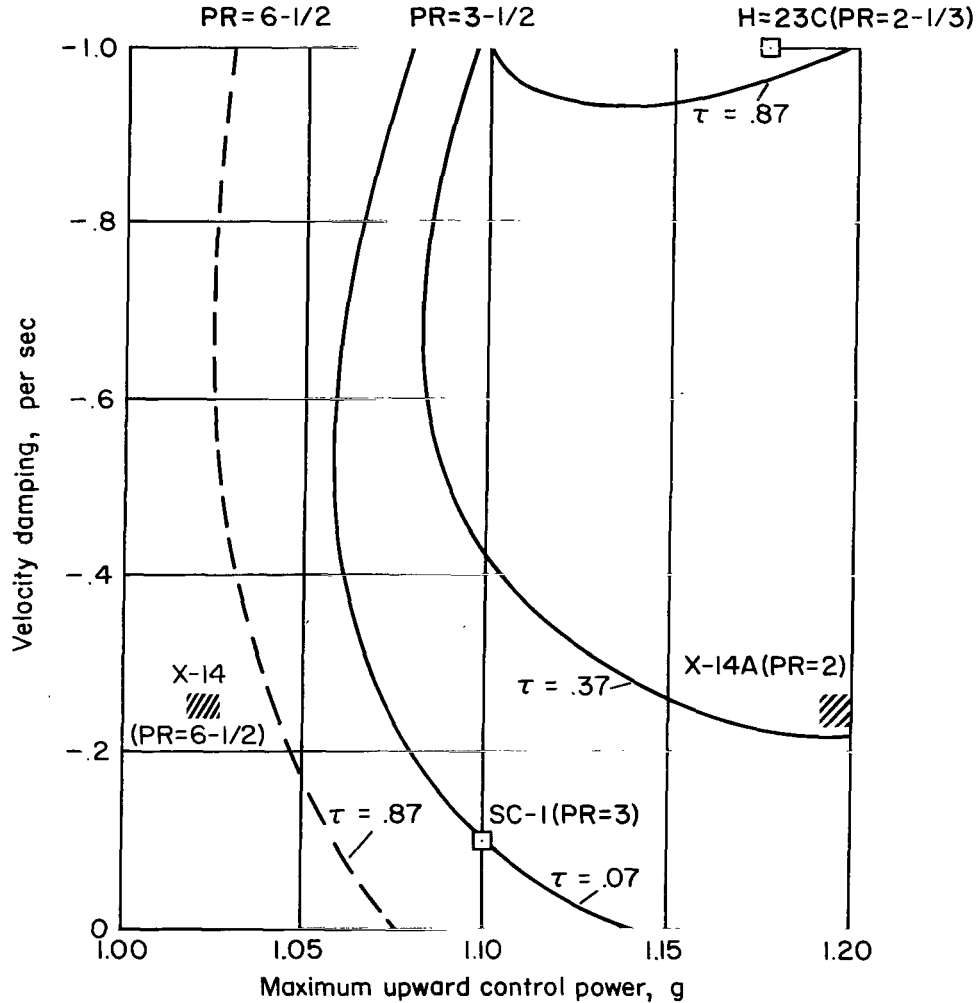
X-14 & X-14A = .28 sec
SC-1 = .10 sec
H-23C = .25 sec

PR=6-1/2   PR=3-1/2   H=23C(PR=2-1/3)

τ = .87

τ = .37

X-14
(PR=6-1/2)

X-14A(PR=2)

τ = .87

SC-1(PR=3)

τ = .07

Velocity damping, per sec

Maximum upward control power, g

Figure 4.- Maximum control power boundaries out of ground effect at various levels of time constant.

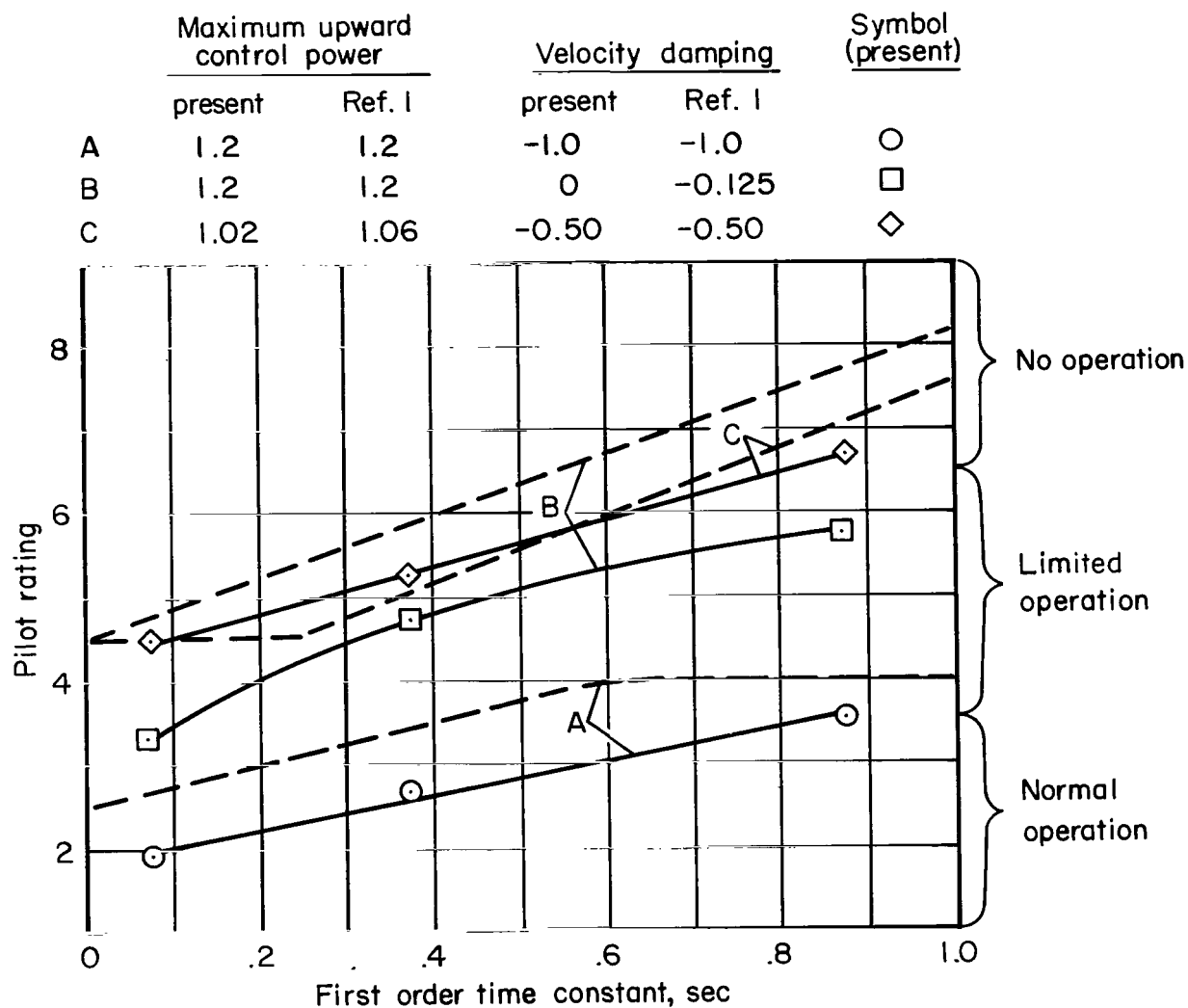Fixed cockpit simulator (Ref. I)
Moving cockpit simulator (present study)

	Maximum upward control power		Velocity damping		Symbol (present)
	present	Ref. I	present	Ref. I	
A	1.2	1.2	−1.0	−1.0	○
B	1.2	1.2	0	−0.125	□
C	1.02	1.06	−0.50	−0.50	◇

Figure 5.- A comparison of pilot rating shift due to control system time constant as determined on fixed and moving cockpit simulators.

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Maximum upward control power = 1.15 g
Control sensitivity = 0.1 g/inch
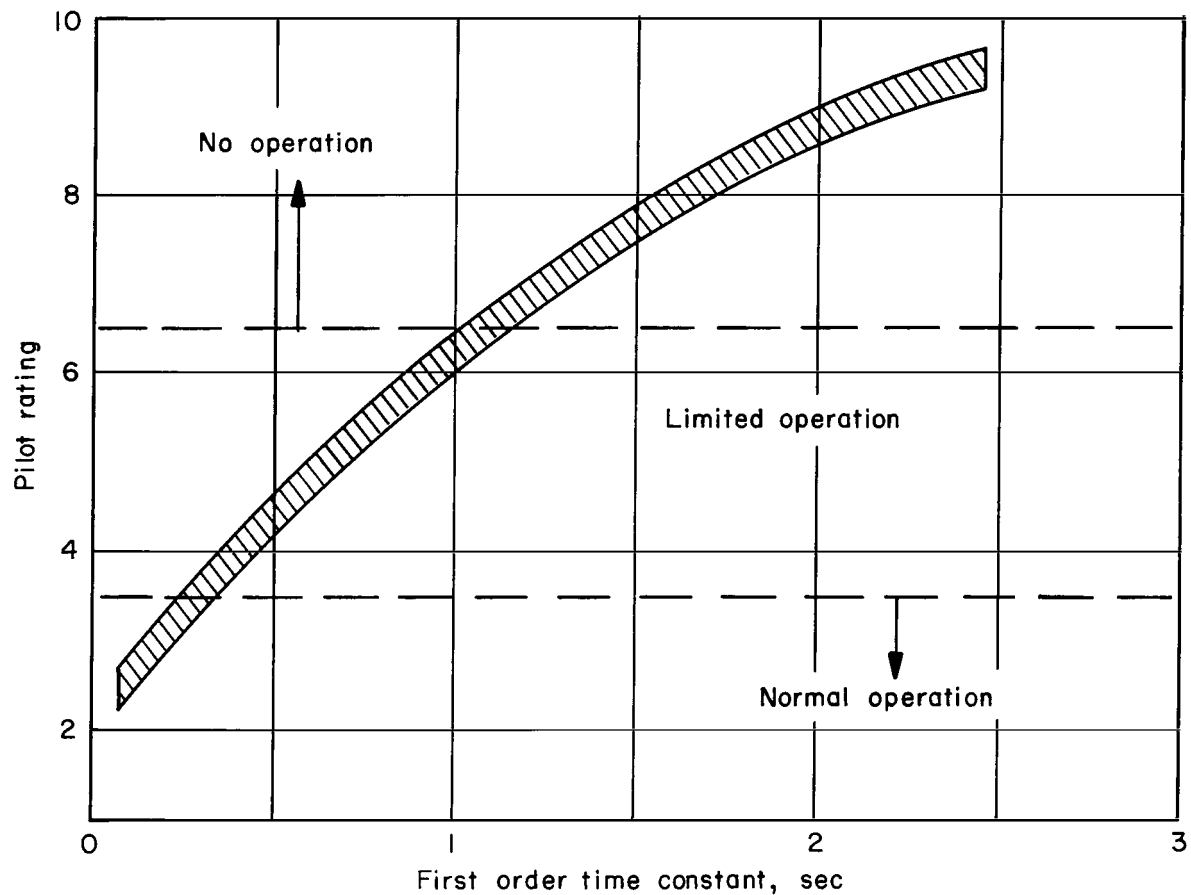No velocity damping

Figure 6.- Variation of pilot rating with first order time constant
for a constant altitude hovering task.

Control sensitivity (g/inch)   First order time constant (τ)
   Present study = .10   Simulators   = 0 → .2 sec
   Ref. 1 and 2 = .30   X-14 & X-14A = .28 sec
   H-23C   = .87   SC-1   = .10 sec
   SC-1   = .10   H-23C   = .25 sec
   (X-14 & X-14A not determined)

PR=3-1/2   H-23C(PR=2-1/3)

Fixed cockpit
simulator
(Ref. 1)

Limited travel
moving cockpit
simulator
(Ref. 2)

X-14A
(PR=2)

X-14
(PR=6-1/2)

SC-1
(PR=3)

Present
study

Velocity damping, per sec

Maximum upward control power, g

Figure 7.- A comparison of maximum control power boundaries as determined
on three types of simulators.

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