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PILOT-VEHICLE SYSTEM SIMULATION FOR LOW-ALTITUDE, HIGH-SPEED FLIGHT

by Melvin Sadoff and Thomas E. Wempe

Ames Research Center
Moffett Field, Calif.

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SUMMARY

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Based on a review of previous results pertinent to low-altitude, high-speed flight manual control problems, piloted simulator studies were formulated and carried out in certain areas where additional research appeared desirable. The vehicle simulated had variable wing sweep and was capable of supersonic speed at low altitude.

The utility of the piloted flight simulator for examining and evaluating anticipated problem areas for the low altitude, supersonic speed penetration mission is indicated. Information is presented on handling qualities and stability augmentation system requirements, display and control requirements, and on the effects of cockpit acceleration environment (including an oscillatory component, assumed to approximate a predominant structural mode) on terrain-following task performance.

Author

INTRODUCTION

One particularly demanding, tactical penetration mission that has been given considerable attention in recent years is that of low-altitude, high-speed flight. The use of aircraft with variable wing sweep would permit low-altitude supersonic-speed (LASS) flight without compromising the low-speed performance and handling qualities. However, the introduction of such aircraft in combination with the demanding mission requirements has posed a number of anticipated problems which, superficially at least, appear to require considerable research. These are:

Handling quality requirements.
Display and control considerations.
Acceleration stress effects.

Although considerable research effort has been devoted to handling quality requirements for a wide variety of aircraft (refs. 1 to 10), special requirements were anticipated for the LASS mission as a result of the combination of the aircraft configuration (relatively slender and flexible with the crew located well forward of the center of gravity) and the mission demands (precise terrain-avoidance task, all weather operation, and acceleration stress). Longitudinal handling qualities requirements for low-altitude, high-speed

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flight (ref. 11) display and control-feel requirements (refs. 12 and 11), and acceleration-stress effects on pilot tolerance, performance, and physiology (refs. 11 to 18) have been investigated. However, the direct applicability of these results to the LASS flight mission is not clear cut and additional research on the special problems of the low-altitude, supersonic-speed flight appeared desirable.

The utility of the piloted flight simulator for studying a wide range of pilot-vehicle integration and control problems is well documented (see, e.g., refs. 19 and 20). The approach to simulation has been described (ref. 20) as not unlike that used by the Wright Brothers in the design of their airplane. (See fig. 1.) This approach involved several systematic steps, including a review of available knowledge, design, flight test, and analysis. This process was then repeated until a successful airplane was developed. Today, a similar approach, utilizing extensive flight tests, is economically and temporally impractical; thus simulators have been resorted to.

The specific objective of the present paper is to apply a somewhat similar approach to investigating pilot-vehicle system problems for LASS flight using piloted flight simulators. This approach comprises:

1. A review of pertinent available information on some of the above problem areas which was of value in the formulation of the present studies.

2. A presentation of some results of NASA piloted-simulator research, specifically,

Handling qualities evaluations of a representative LASS flight vehicle.

Display research (suitability for long-duration LASS flight, performance capabilities relative to VFR and automatic terrain-following flight, and utility for monitoring automatic terrain-avoidance systems).

Comparative pilot controller evaluation.

Acceleration stress effects for extended periods of LASS flight.

Simulated bending-mode effect.

In the discussion of the results of several studies referred to in this paper, the details of the experiments and the associated facility used are omitted. The reference source and the type of equipment used in these studies are listed in table I. The notation used in this report is defined in the appendix.

REVIEW AND PRELIMINARY ANALYSIS

In this section, information relevant to the formulation of the simulator programs discussed in the following main section is reviewed. For the purposes of the present paper, this review is confined to a discussion of handling qualities requirements or guidelines and to the effects of acceleration stress on crew tolerance and performance. The estimated handling characteristics and gust-induced acceleration characteristics of a low-altitude supersonic-speed (LASS) vehicle are compared with available data to isolate potential problems. The primary results of this review and preliminary analysis are provided in figures 2 to 7.

Handling Qualities Review

In figure 2, handling qualities criteria, or guidelines, for U. S. military airplanes are provided for the longitudinal short-period (fig. 2(a)), lateral (fig. 2(b)), and Dutch roll (fig. 2(c)) modes of motion. The longitudinal criteria are based on two important short-period parameters, undamped frequency ω_n and damping ratio ζ, first evaluated by Cornell (ref. 21). Two curves defining ranges of satisfactory handling characteristics are shown - flight data (ref. 21) and the more recent data obtained by North American (ref. 11) in a moving cockpit simulator study. The latter results also incorporated a terrain-following task in turbulent air as one of the factors considered by the pilots in their evaluation,[1] whereas the former study did not. Also included in figure 2(a) are estimated basic vehicle short-period characteristics (present study) for the LASS condition, as well as for the landing approach condition (wings unswept) and for a high-altitude supersonic-speed condition. (Though primary attention in this paper is directed at LASS flight, estimates for the other two conditions are shown to illustrate the range of short-period characteristics and anticipated requirements for stability augmentation.) The two points obtained from reference 22 are not directly pertinent to the present discussion and will be referred to in a later section.

Three observations may be drawn from these results. First, there appears to be a discrepancy between the two sets of handling data generated in previous studies. Second, there is a definite need for pitch damping for the high altitude flight. Third, there may be a requirement for stability augmentation (both rate and attitude feedback) for the landing approach and LASS conditions. The possible stability augmentation system (SAS) requirement for the LASS case is considered very important in view of the possible consequences of SAS malfunction during operation at low altitudes and high speed. (This aspect is discussed in some detail in the following section.)

Lateral control guidelines, based on the reference 3 study, are presented in figure 2(b). The important control and response parameters here

[1]In reference 11, however, the pilots did not consider this factor too significant because of the masking of the short-period mode by the particular task and by the continuous jostling due to turbulence.

are the maximum effective lateral control power $L_{\delta_{H_a}} = \left(\delta_{H_a}\right)_{max}$ and the roll time constant T_R (roughly the negative inverse of the roll damping derivative L_p). The parameter $(\omega_\varphi/\omega_d)^2$ takes into account the roll response modification due to roll Dutch roll mode coupling. The estimated characteristics for the three flight conditions are again provided for comparison. This comparison indicates primarily that the roll control power (or sensitivity based on constant stick-to-aileron gearing) is too high for the LASS condition and that roll damping augmentation (and perhaps a reduction in roll control power) would be required for the high-altitude flight. The lateral control characteristics for the landing approach appear adequate, on the basis of the comparison.

In figure 2(c) the Dutch roll mode handling quality guidelines are presented in terms of relatively familiar parameters (the inverse of the number of cycles required to damp to one-half amplitude $1/C_{1/2}$ and the ratio of roll to yaw amplitude $|\varphi/\beta|$).[2] Comparison of the estimated Dutch roll characteristics for the vehicle considered in the present study with the guidelines in figure 2(c) indicates that augmentation (yaw damping) would probably not be required for the LASS mission

Effects of Stability Augmenter Malfunction

In considering the possible requirements for stability augmentation, based on evaluations such as those provided in the preceding section, serious consideration should be given to the potential consequences of a stability augmentation system failure. This is particularly important in flight situations which demand continuous, precise control of the vehicle by either the pilot or an autopilot. One prime example of such a situation is, of course, low-level, supersonic-speed flight. In the study of reference 24, attention is directed at this problem, and a brief review of the results is believed warranted here. The effects of a series of malfunctions comprising, simply, sudden degradation of the vehicle characteristics from the augmented to the unaugmented situation were evaluated. (The effects of servo hardover failures were not considered.) The pitch damper failures considered are compared in figure 3 (Dynamics "A," "B," "C") with pilot-opinion boundaries for short-period longitudinal handling qualities (ref. 1). Also shown in figure 3 (Dynamics "D") is an assumed stability augmenter malfunction evaluated during a terrain-following task (ref. 22). This latter SAS failure will be discussed in a later section. The control problem is illustrated in figure 4 which shows time histories of simulated damper failures (fig. 4(a)) and the

[2]In addition to these two factors, other important parameters relevant to Dutch roll handling qualities are the factor $(\omega_\varphi/\omega_d)^2$ noted in connection with the discussion in figure 2(b), the roll time constant T_R, and others. Discussion of the effects of these other factors which influence the degree of coupling between the roll and Dutch roll modes is beyond the scope of the present paper. (See, however, reference 23 for a complete discussion.)

associated control performance during a simulated tracking task (fig. 4(b)). The time histories show the damper failure by the rapid buildup of aircraft response and by the sudden increase in tracking error. These representative results indicate that the pilot-vehicle system tends to become unstable immediately following the simulated damper malfunction. This period of instability is shown in reference 24 to be related to the type of failure, the motion feedback to the pilot (simulator cockpit fixed versus moving), and to the type of controller used by the pilot. Motion feedback had a generally adverse effect on pilot adaptation to SAS failures. The use of a pencil type side-arm controller (see ref. 25 for descriptive details), rather than the conventional center-stick control, reduced the adverse effects of motion feedback, particularly at high short-period natural frequencies. This latter result is of particular interest in view of the high short-period frequencies associated with LASS flight. (See fig. 2.)

Acceleration Stress

Crew comfort and task performance are obviously related to the acceleration environment to which the crew will be exposed. For low-altitude, supersonic-speed flight in rough air, the acceleration stresses could be important. Unfortunately, very few systematic data are available which are directly applicable to the LASS flight mission. Figure 5 summarizes some of the available flight experience from reference 26. Two curves are presented showing pilot-tolerance and task-proficiency boundaries as functions of duration of exposure to varying levels of cockpit acceleration. These data were obtained with aircraft having peak power in the acceleration spectra in the neighborhood of 0.8 cycle per second, the longitudinal short-period frequency. In addition to being affected by the intensity of vibration, as measured by RMS acceleration, crew comfort has been shown in reference 14 to be related also to structural vibrations. Oscillatory frequencies (ref. 14) in the range of 4 to 6 cps may be particularly unpleasant because the upper-body motion is amplified relative to seat motion. A spring-mounted seat was quite effective (ref. 14) in isolating the crew from objectionable structural vibration at 4 cps.

In addition to the interesting work reported in reference 14, considerable research has been directed at determining the effects of oscillatory accelerations on human tolerance and physiology (e.g., appendix D of ref. 18). Results of some of this research are presented in figure 6. Human subjective impressions of oscillatory accelerations, taken from reference 16, and a 3-minute tolerance curve obtained from reference 17 are shown. The dip in the curves (fig. 6) is apparently related to upper-body and visceral resonance effects.

As noted earlier, the significance of the above acceleration-tolerance data to the LASS mission is not entirely clear. The gust-filtering characteristics of a rigid vehicle with variable wing sweep are undoubtedly better at supersonic speeds than those of most current aircraft flying at moderate subsonic speeds because of the combined low lift-curve slope, high wing loading, and pilot's location well forward of the center of gravity. One potential problem due to crew location near a fuselage antinode is that fuselage bending may introduce an objectionable oscillatory component into the cockpit vibration. Further research on this problem is needed.

Some information is available on the effects of vibratory acceleration stress on pilot performance of a terrain-following task. A simulated terrain-following task was performed both in flight and in a moving-cockpit simulator for varying levels of turbulence (ref. 11). The results of this study presented in figure 7 show that: (1) Pilot performance (RMS altitude error) is not appreciably affected by acceleration up to a level of about 0.3 g, RMS, based on the simulator data; and (2) the flight results have considerably more scatter and a two or threefold increase in error, relative to the simulator results. The differences between the simulator and flight performance measures were ascribed to differences in pilot workload (no lateral disturbances or navigation tasks were included in the ground-based simulation), indoctrination time (more training time was available in simulator), and in pilot psychology (no "flight" hazards in simulator). It should be noted that these data (both in-flight and ground-based simulator flights) were obtained from runs of about 20-minute duration. Since penetration missions could take 1-1/2 hours or more, additional information on piloted terrain-following performance for extended-duration flights appears desirable.

SOME RESULTS OF NASA PILOTED SIMULATOR RESEARCH

Handling Qualities Evaluations

The review of available information and the preliminary analysis of stability augmentation requirements for the longitudinal short-period mode (fig. 2(a)) indicated that for the LASS vehicle it might be necessary to increase pitch damping and reduce short-period frequency. In addition, the effect of the pilot's compartment being well forward of the center of gravity in this type vehicle must be considered. The lift effectiveness of the horizontal tail is large for this flight condition, so relatively rapid onset of normal acceleration is experienced at the pilot station for abrupt nose-up control input.

The study of these problems obviously required a piloted simulator which provides normal acceleration feedback to the pilot. Accordingly, the Ames Height Control Apparatus (fig. 8) was selected and instrumented. A view of the simplified instrument panel and a block diagram of the simulator setup for this study and for terrain-following performance studies (discussed in subsequent sections) are shown in figures 9 and 10. The simulator has a usable travel of about 80 feet and a response bandwidth of about 2 cps, which was considered adequate to evaluate realistically the potential longitudinal control problems described above.

The initial reactions of the two Ames test pilots who participated in this study were somewhat unexpected. They indicated there was no appreciable longitudinal control problem due to the short-period characteristics alone.

Variations in pitch damping from $\zeta = 0.3$ to $\zeta = 0.7$ (base level $\zeta = 0.46$) had very little effect on pilot opinion. When vibratory accelerations due to turbulence were added ($\sigma_{wg} = 10$ ft/sec), the pilots indicated that the pitch control was too sensitive. Increasing the stick force from the initial level of 3 lb/g to 6 lb/g and adding a breakout force of 2 pounds corrected this deficiency (since inadvertent control inputs with the center stick were reduced). A summary of the results is provided in figure 11. The pilot rating schedule used is shown in table II.

It is possible that the lack of complete fidelity in representing the actual aircraft motion (normal acceleration) on the simulator may have influenced the above results. In figure 12, computed aircraft responses are compared with the simulator cockpit responses for a 1 g step control input. Although there are differences in response due both to the limited bandwidth of the simulator response and to the use of a washout[3] circuit, these are not considered sufficiently large to compromise the results obtained.

In addition to the longitudinal handling evaluation, results of over-all handling qualities evaluations and augmentation requirements for the low-altitude, supersonic-speed condition are provided in table III and for the high-altitude, supersonic-speed condition in table IV.

In general, the results confirm the requirements for pitch, roll, and yaw damping, indicated in figure 2.

Effects of Simulated Stability Augmenter Malfunction

Results of reference 24 demonstrated that the malfunction of a stability augmenter while the pilot is performing a precise control task could be serious. Thus the failure of a stability augmented system (similar to that in ref. 24) was investigated. The type of failure considered (ref. 22) is shown in figure 3 as Case "D." The short-period dynamics for the augmented vehicle are well within the satisfactory boundary defined in reference 11; those for the basic (unaugmented) vehicle are just outside this boundary. The augmenter failures were simulated simply by suddenly changing the vehicle dynamics from the augmented to the basic levels. The pilot's control task was terrain-following during a 90-minute flight at low levels (nominal clearance altitude, 500 ft) at supersonic speeds. The average gust intensity for this flight was 10 ft/sec RMS (cockpit acceleration about 0.3 g, RMS). Four augmenter "failures" were programmed during this flight.

The results of this study showed that the type of failure considered caused no significant control problem. There was no evidence of transient pilot-vehicle instability while the pilot was adapting to the failures (as observed in ref. 24 and in fig. 4). The augmenter failures were apparent to the pilot by increased oscillatory response in his display and, to a lesser degree, by slight changes in cockpit accelerations.

[3]Washout is required for any simulator with limited track travel to return the cab to the middle of the track when sustained steady-state accelerations are commanded.

Despite these results, it is felt serious consideration should be given to minimizing, or eliminating, stability augmentation for the low-altitude, high-speed flight. The possibility of control system failures with potentially more serious consequences than those demonstrated in the present study should be weighed against the improvement in riding and handling qualities for the stability-augmented vehicle. The vehicles considered in the present piloted simulator studies do not appear to require stability augmentation of the vehicle pitch mode for satisfactory performance of the terrain-following task in low-altitude, supersonic flight.

Display Research

In the review of available information on terrain-avoidance pilot displays (e.g., ref. 12), data appeared to be lacking in three areas: (a) utility of display for extended periods (1-1/2 hours or more) of manual terrain-avoidance flight, (b) comparative performance for manual IFR, VFR, and automatic terrain-following systems, and (c) utility of situational displays for monitoring an automatic system.

Some information in these areas was provided by studies conducted, initially in a rudimentary fixed-base simulator (ref. 27) and, subsequently, in a moving-cockpit simulator which provided normal acceleration feedback to the pilots (ref. 28 and figs. 8 to 10). Results of these studies are briefly reviewed here.

Display evaluation.- Several situational displays were evaluated (ref. 27) to provide an acceptable display for general research on the terrain-following task. Four of the six display configurations, considered in the reference study, are shown in figure 13(a). The primary display variables were scaling changes on the terrain information and on aircraft pitch attitude. In addition, the terrain information displayed to the pilot was varied from angular measures to relative heights (display C to display D) and a height "memory" dot was added in display E. Pilot terrain-following performance with these various display modes is summarized in figure 13(b) and in table V. The performance improvement as the display was evolved from mode "C" to mode "F" is quite apparent.

Display D was used in a sustained 90-minute terrain-following task to study human capability of performing this task for relatively long time periods. The results presented in figure 14 and table VI show pilot performance, averaged over 10-minute intervals, for the entire run. The normalized performance measure used (fig. 14) is the ratio of the standard deviation of the clearance height to that of the terrain S_H/S_T.[4] These results indicate very little effect of fatigue on performance in this fixed-cockpit simulator. Although the practical significance of these results is questionable because

[4]Additional performance measures (ref. 27) correlate airplane flight path to terrain profile in terms of two variables r, a correlation coefficient related to flight-path terrain phasing and S_A/S_T (ratio of flight path to terrain standard deviations), indicating the amount of overcontrol or filtering of aircraft path relative to terrain profile.

of the lack of motion feedback and other factors, results provided in references 22 and 29 indicate no significant effect on pilot terrain-following performance of RMS g levels of 0.3 and 0.4 for sustained "flights" up to 3 hours in duration.

Comparative performance.- Some information on the effectiveness of situational displays, such as those described in figure 13, is given in figure 15. Results for display "G"[5] were taken from the moving cockpit study (ref. 28) for low-altitude, supersonic-speed flight. The VFR results (ref. 14) and the automatic system results are representative of those observed in flight tests. These results are for terrain characteristics roughly similar when portrayed on the same time scale.

In general, the results in figure 15 indicate that performance with the situational display (display "G") compares favorably with that observed in terrain avoidance flight tests for either manual (VFR) or automatic control.

Utility for monitoring.- The utility of a situational display alone for monitoring an automatic system is illustrated in figures 16 and 17. Figure 16 is a block diagram of the simplified automatic system considered, and the results observed during simulated system failures are shown in figure 17. As indicated, the automatic system was made to fail several times during this particular run. The results suggest that the terrain-following display used was of little value to the pilot in determining that the automatic system had failed. Even though the pilot was anticipating a failure of the automatic system, he was unable to prevent collisions twice when the system failed as the aircraft was approaching a hill. The pilot commented that if this type of failure were possible, he would prefer to fly the aircraft manually at all times. It is recognized that current concepts of automatic terrain-following systems provide for warning the pilot of system failure, and they also incorporate fail safe features, such as automatic pitch-up command if the system malfunctions. The results of this brief study confirm the need for such devices.

Comparative Pilot Controller Evaluation

The use of a pencil-type side-arm controller was investigated as a possible means of improving pilot performance[6] and reducing pilot fatigue.

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[5]This display is essentially the same as display "F" (fig. 13(a)), except for an increase in pitch-angle scaling from 2.2°/cm to 4°/cm which was found desirable in the moving-cockpit simulator study.

[6]The effectiveness of pencil-type side-arm controller during high sustained accelerations, typical of atmospheric entry missions, was demonstrated in a centrifuge study (ref. 25). Also, its effectiveness in reducing inadvertent control inputs for vehicles with poor longitudinal dynamics (high short-period frequencies, low damping) and in minimizing pilot-induced oscillations during simulated pitch damper failures was demonstrated (refs. 1 and 24).

The tests were made with a moving-cockpit piloted simulator (ref. 22). A center-stick control was used in part of the tests for comparison (fig. 18).

In figure 18(a) average pilot performance is compared for several conditions during extended periods of simulated low-altitude, supersonic flight. Figure 18(b) shows comparative results for average RMS cockpit accelerations. It is clear from these comparisons that the use of a side-arm controller improved pilot performance appreciably and reduced the cockpit acceleration during these tests. The pilot also commented that the side-arm controller made the task easier to perform and permitted them to relax more than was possible with the center stick.

Acceleration Stress Effects (Long-Duration Flights)

A review of available data on acceleration stress effects on pilot tolerance, performance, and physiology indicated a need for additional information, particularly for extended duration penetration missions. Some of this information was provided by a series of tests conducted in a moving-cockpit simulator. These tests consisted of 1-1/2-hour "flights" in a LASS vehicle under varying, turbulence levels. Because of the excellent gust-filtering characteristics of the LASS configuration, gust levels up to 20 ft/sec RMS were simulated. This was done, both to acquire basic tolerance data for these long-duration flights and to increase pilot workload so that potential problems could be more readily isolated. The results of this study are provided in reference 22. A brief review of pertinent results of this investigation is presented here.

Pilot tolerance.- At the highest gust velocities considered (σ_{wg} = 20 ft/sec), the average cockpit acceleration, due to both gust-induced and control-induced effects, was about 0.3 g RMS. The results in figure 5 show that this level of acceleration stress is slightly higher than the tolerance boundary previously established (ref. 26). The pilot indicated this level was tolerable and not excessively tiring. Further results (ref. 29), also shown in figure 5, indicate that average RMS acceleration levels of 0.4 g were tolerated for periods of 1-1/2 to 3 hours. However, the pilots observed these missions were fatiguing. The pilot involved in the 3-hour endurance run experienced extreme fatigue and some vertigo for a day or two following his run, although no symptoms were evident during the run.

It is possible that the apparent discrepancies between the flight results and simulator results (fig. 5) may be partly due to the increased mental fatigue associated with actual flight at low altitudes and high speeds. This factor is difficult to account for in ground-based simulator tests and constitutes one of the more serious limitations of piloted simulator studies of hazardous and demanding flight control tasks.

Pilot performance.- Fatigue effects on pilot terrain-following performance (ref. 22) were examined by comparing standard deviations of the altitude clearance at the beginning and end of the 90-minute run. The results obtained, normalized with respect to the standard deviation of the terrain, are given in figure 19. No significant change in performance is observed in these results which are shown for an acceleration stress level of 0.3 g RMS. Also shown in this figure are results for the 3-hour endurance run described above. In this case, pilot performance generally improved during the course of the flight.

Physiological aspects.- Some preliminary data on the effects of vibratory acceleration stress on pilot physiology was measured with a NASA physiological instrumentation package (ref. 30) in the reference 22 study. This instrumentation monitored the pilots cardiovascular response (EKG) and respiration rate. In addition, biochemical measures including blood enzyme and urine analysis were obtained. The results from the simulated 1-1/2-hour flights, for the maximum acceleration stress environment were generally negative, indicating the pilots can physiologically tolerate this environment. Some evidence of an increase in respiratory rate was observed with increase in acceleration stress. However, no evidence of hyperventilation was present. The biochemical measures did not reveal any organ damage, and heart rates were considered within the normal range with no significant changes due to acceleration stress.

Simulated Bending Mode Effect

In current designs of vehicles capable of extended periods of low-altitude, supersonic-speed flight, the crew compartment is located some distance ahead of the airplane center of gravity. If this location is also well forward of the fuselage low-frequency vertical bending mode, an oscillatory vibration will be introduced into the cockpit acceleration environment with possible adverse effects on crew comfort and performance.

A brief study of the possible effects of this vibratory component on pilot tolerance and performance was conducted on the Ames Height Control Apparatus (fig. 8). It was assumed that the fuselage of the representative LASS vehicle considered in this study would have a first bending mode frequency of about 6 cps, and that this bending mode would be excited somewhat by turbulence. For the purpose of this study, the simulator servo drive system (see fig. 10) was given an additional 6 cps signal, and adjusted to provide an oscillatory acceleration component of 0.4 g peak to peak. Previous results (fig. 6), rate this component alone subjectively as "mildly annoying." Previous studies (e.g., refs. 14 and 18) indicated the frequency selected is near viceral and upper-body resonance frequencies.

Initial 90-second exposures to this environment resulted in the following observations: One pilot stated he could orient the aircraft fairly well by the panel instruments (fig. 9), but could not follow the terrain with the display provided (CRT display, fig. 13). He further indicated that should this acceleration environment be actually encountered, he would increase altitude until that patch of turbulence was behind the aircraft and then resume the terrain-following task. Two other pilots made roughly the same comments after brief exposure to the same environment. Subsequently, one of the pilots attempted the terrain-following task again in this environment and performed as well over a 5-minute period as he previously had without the simulated bending mode. Figure 20(a) is a sample of this pilot's terrain-following performance during the 5-minute run. Figure 20(b) is a reproduction of his performance over the same portion of terrain, extracted from a previous test session with the bending mode removed. The cockpit acceleration environment, including the simulated bending mode, is presented in figure 21. The pilot's comments made during the simulation were: "It's not so bad after you learn to relax." "It seems to be about the same frequency as the vibration you get in a helicopter, but with much more amplitude."

Apparently, this simulated bending mode vibration initially startled the pilot and made the motion seem worse than it was, particularly when he attempted to perform a precise terrain-following task in turbulence. Subsequent exposures reduced this effect, and the pilots were able to perform as well as before, at least for a short period of 5 minutes.

CONCLUSIONS

A review of available information and preliminary analysis of pilot-vehicle system problems in LASS flight led to several piloted-flight simulator studies of problems anticipated for LASS aircraft configurations. Results of these studies indicated:

1. The basic (unaugmented) longitudinal handling qualities of the vehicle studied were acceptable for LASS flight. For conventional center-stick control, stick force gradients of about 6 pounds per g, and a 2-pound breakout force were considered desirable control-feel characteristics for flight in turbulent air.

2. Simulated longitudinal stability augmenter failures (sudden changes in vehicle dynamics from the augmented case to those for the basic LASS vehicle) during a terrain-following task did not pose a significant control problem.

3. Terrain-following performance with a simplified terrain-avoidance display was comparable to that during manual and automatic terrain-avoidance tests in flight; however, this display alone was not suitable for pilot monitoring the malfunction of an automatic terrain-avoidance system.

4. Comparison between test results for conventional center-stick control and those for a pencil-type side-arm controller indicated that the side-arm controller significantly improved terrain-following performance and reduced cockpit accelerations appreciably by reducing inadvertent control input and by increasing control precision.

5. Results of piloted simulator tests during LASS flights of up to 1-1/2 hours showed terrain-following performance remained relatively constant and there were no significant physiological aberrations (respiratory, cardiovascular, blood enzyme deviations from norms).

6. The introduction of a simulated constant bending-mode vibration into the cockpit acceleration environment for a 5-minute period caused no appreciable effect on pilot tolerance and performance (after the initial startling effect of this oscillatory component was reduced by several exposures).

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Sept. 11, 1964

APPENDIX

NOTATION

A	airplane altitude, ft
A_N	normal acceleration, g
$C_{1/2}$	cycles for oscillation to damp to one-half amplitude
F_s	pilot applied stick force, lb
g	acceleration of gravity, 1 g = 32.2 ft/sec^2
H	airplane clearance altitude (A - T), ft
$\overline{H}$	mean clearance altitude, ft
H_o	offset, or desired, clearance altitude, ft
L_p	roll damping parameter, 1/sec
$L_{\delta_{H_a}}(\delta_{H_a})_{max}$	maximum lateral control power, 1/sec^2
M_{δ_e}	longitudinal control effectiveness, 1/sec^2
N	sample size
r	correlation coefficient
S_A	standard deviation of aircraft altitude, ft
S_H	standard deviation of aircraft height above terrain, ft
S_T	standard deviation of terrain altitude, ft
T	terrain altitude, ft
T_R	roll-subsidance time constant $\left(\approx -\frac{1}{L_p}\right)$, sec
T_{θ_2}	time constant in pitch transfer function $\left(\approx -\frac{1}{Z_w}\right)$, sec
t	time, sec
w	perturbed velocity along airplane Z axis
Z_w	airplane lift sensitivity parameter, 1/sec

δ_s	stabilizer deflection, deg
β	sideslip angle, deg
ϵ	tracking error, deg
θ	pitch angle, deg
θ_i	forcing function for tracking task, deg
φ	bank angle, deg
ω_n	undamped longitudinal short-period frequency, 1/sec
ω_d	undamped Dutch roll natural frequency, 1/sec
$(\omega_\varphi/\omega_d)^2$	Dutch roll and roll subsidance coupling parameter
σ_{w_g}	root-mean-square vertical gust velocity, ft/sec
ζ	longitudinal short-period damping ratio
ζ_d	Dutch roll damping ratio
$(\dot{\ })$, $(\ddot{\ })$	single and double differentiation with respect to time

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TABLE I.- SOURCE AND FACILITY FOR RESULTS PRESENTED

Result	Reference	Facility
Fig. 2(a)	11	North American "G" seat
	21	Variable stability airplane
2(b)	3	Ames pitch-roll chair, various airplanes, flight test
2(c)	AGARD Rep. 336	Variable stability airplane
3, 4	24	NADC Johnsville centrifuge
5	26	Various aircraft, flight test
6	16, 17	Vibrating platforms
7	11	North American "G" seat, aircraft, flight test
11	Unpublished	Ames Height Control Apparatus
12	Unpublished	Ames Height Control Apparatus
13	27	Rudimentary fixed-cockpit simulator
14	27	Rudimentary fixed-cockpit simulator
15	14, 28, Unpublished	Ames Height Control Apparatus, various aircraft, flight test
17	28	Ames Height Control Apparatus
18	22	North American "G" seat
19	22, 29	North American "G" seat
20, 21	28	Ames Height Control Apparatus

TABLE II.- PILOT OPINION RATING SCHEDULE

	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
Emergency 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

[1]Failure of a stability augmenter

TABLE III.- BASIC AND AUGMENTED HANDLING QUALITY PARAMETERS (LASS CONDITION)

Over-all evaluation

Parameter	Basic configuration		Augmented configuration	
	Value	Pilot rating	Value	Pilot rating
ω_n, rad/sec	7.9	6.0	7.9	2.5
ζ	.46		.7	
$1/T_{\theta_2}$, 1/sec	1.18		1.18	
F_s/g, lb/g	[a]3		[a]6	
ω_d, rad/sec	4.8		4.8	
ζ_d	.12		.41	
T_R, sec	.43		.23	
$L_{\delta_{H_a}}(\delta_{H_a})_{max}$, rad/sec^2	30.5		15.3	
$\lvert\varphi/\beta\rvert$	3.8		3.8	
$(\omega_\varphi/\omega_d)^2$	1.07		1.00	

[a]Based on stick-force, stick-deflection ratio of 10 lb/in. (control effectiveness M_{δ_e} halved for augmented configuration).

TABLE IV.- BASIC AND AUGMENTED HANDLING QUALITY PARAMETERS (HASS CONDITION)

Longitudinal evaluation

Parameter	Basic configuration		Augmented configuration	
	Value	Pilot rating	Value	Pilot rating
ω_n, rad/sec	3.9	6	3.9	2.5
ζ	.076		.54	
$1/T_{\theta_2} \approx -Z_w$, 1/sec	.15		.15	
F_s/g, lb/g	[a]9		[a]9	

[a]Based on optimum stick-force, stick-deflection ratio of 5 lb/in.

Lateral-directional evaluation

Parameter	Basic configuration		Augmented configuration	
	Value	Pilot rating	Value	Pilot rating
ω_d, rad/sec	2.8	6	2.8	3
ζ_d	.073		.40	
T_R, sec	3.03		.59	
$L_{\delta_{H_a}}(\delta_{H_a})_{max}$, rad/sec^2	5.6		2.8	
$\lvert\varphi/\beta\rvert$	7.3		7.3	
$(\omega_\varphi/\omega_d)^2$	.57		.57	

TABLE V.- SUMMARY OF TERRAIN-FOLLOWING PERFORMANCE

Display	Description	N	Sampling interval, sec	r	S_A/S_T	$\bar{H}$, ft	S_H, ft	S_H/S_T
C	Terrain ahead displayed as angular measures, 6°/cm on CRT	80	10	0.71	$\frac{411\text{ ft}}{304\text{ ft}} = 1.35$	505	292	0.96
D	Terrain ahead displayed as relative height, 333 ft/cm, with altimeter	484	10	.90	$\frac{421\text{ ft}}{276\text{ ft}} = 1.52$	560	207	.75
E	Terrain displayed as relative height, 333 ft/cm, maximum of T_{10} added	36	10	.94	$\frac{500\text{ ft}}{386\text{ ft}} = 1.30$	384	193	.50
F	Lower frequency terrain. Display same as E except pitch angle scaled 2.2°/cm and heights scaled 250 ft/cm	30	30	.94	$\frac{384\text{ ft}}{351\text{ ft}} = 1.09$	296	131	.37

TABLE VI.- TERRAIN-FOLLOWING PERFORMANCE DURING 90-MINUTE RUN

10-min time period	N	r	s_A/s_T	$\bar{H}$, ft	s_H, ft	s_H/s_T
1	61	0.93	$\frac{428 \text{ ft}}{268 \text{ ft}} = 1.60$	527	205	0.77
2	61	.81	$\frac{323 \text{ ft}}{189 \text{ ft}} = 1.71$	589	202	1.07
3	61	.90	$\frac{458 \text{ ft}}{311 \text{ ft}} = 1.47$	589	222	.71
4	[a]57	.94	$\frac{526 \text{ ft}}{338 \text{ ft}} = 1.56$	601	241	.71
5	61	.92	$\frac{373 \text{ ft}}{264 \text{ ft}} = 1.41$	526	166	.63
6	61	.95	$\frac{333 \text{ ft}}{228 \text{ ft}} = 1.46$	508	134	.59
7	61	.88	$\frac{438 \text{ ft}}{301 \text{ ft}} = 1.46$	613	222	.74
8	61	.89	$\frac{419 \text{ ft}}{269 \text{ ft}} = 1.56$	530	217	.81
Total	484	.90	$\frac{421 \text{ ft}}{276 \text{ ft}} = 1.52$	560	207	.75

[a]Four samples occurred during a reset to correct for computer drift and were removed.

TABLE VII.- TERRAIN-FOLLOWING PERFORMANCE COMPARISON

Task	Description	N	Sampling interval, sec	r	S_A/S_T	$\bar{H}$, ft	S_H/S_T, ft
I	Simulated low-altitude, supersonic speed with situational display G. Gust effects slight to marked.	20	30	0.974	$\frac{542\text{ ft}}{549\text{ ft}} = 0.99$	369 (H_o = 250)	$\frac{126\text{ ft}}{549\text{ ft}} = 0.229$
II	Visual in a Hunter 6 over hilly desert at Mach 0.90. Gust effects marked to unpleasant. Maximum effort used to attempt to maintain a low height above the ground. Very tiring after 10 minutes. Maximum accelerations: -0.6 to +2.8 g.	36	10	.945	$\frac{522\text{ ft}}{503\text{ ft}} = 1.04$	493	$\frac{171\text{ ft}}{503\text{ ft}} = 0.340$
III	Same as Task II, except: minimum effort used to maintain low clearance height. Maximum accelerations: 0 to 1.7 g.	36	10	.83	$\frac{362\text{ ft}}{468\text{ ft}} = 0.77$	608	$\frac{261\text{ ft}}{468\text{ ft}} = 0.560$
IV	Automatic terrain-following flight at Mach 0.44. Terrain (when displayed on same time base about the same as that for Tasks I, II, and III.	a	a	a	a	799 (H_o = 750)	$\frac{62\text{ ft}}{360\text{ ft}} = 0.172$
V	Automatic terrain-following at Mach 0.59. Terrain (when displayed on same time base) has larger band width than that for Tasks I to IV.	a	a	a	a	610 (H_o = 500)	$\frac{135\text{ ft}}{347\text{ ft}} = 0.388$

[a]Not available.

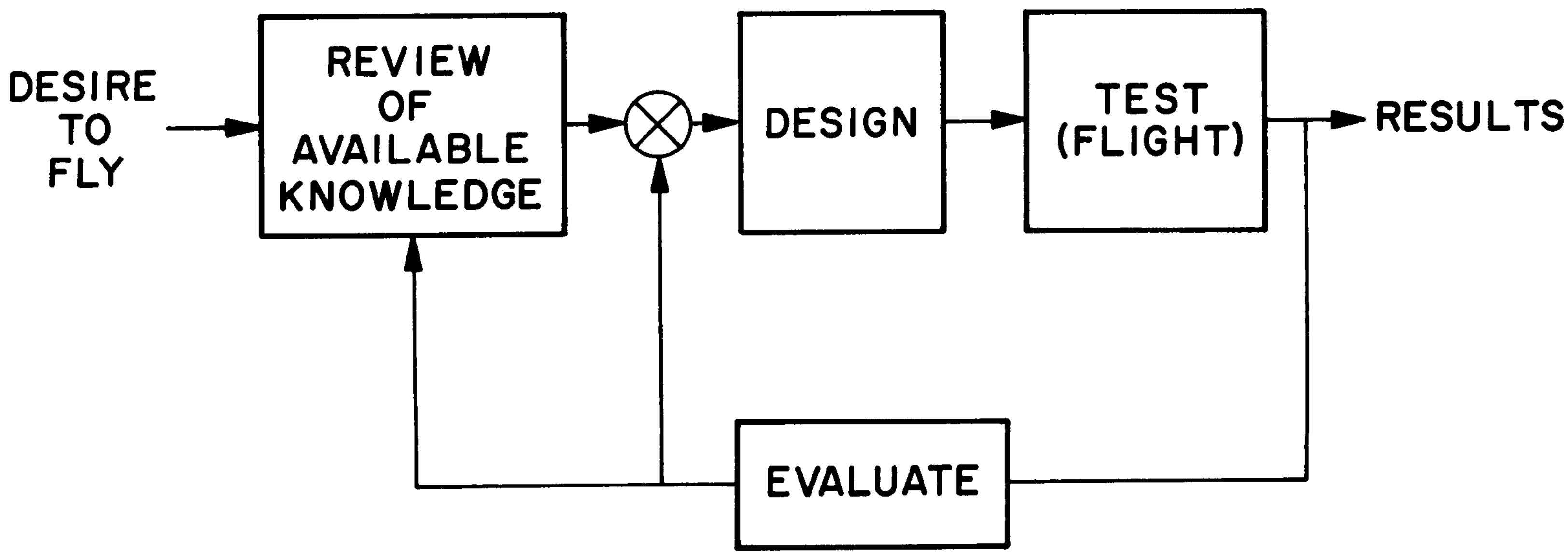
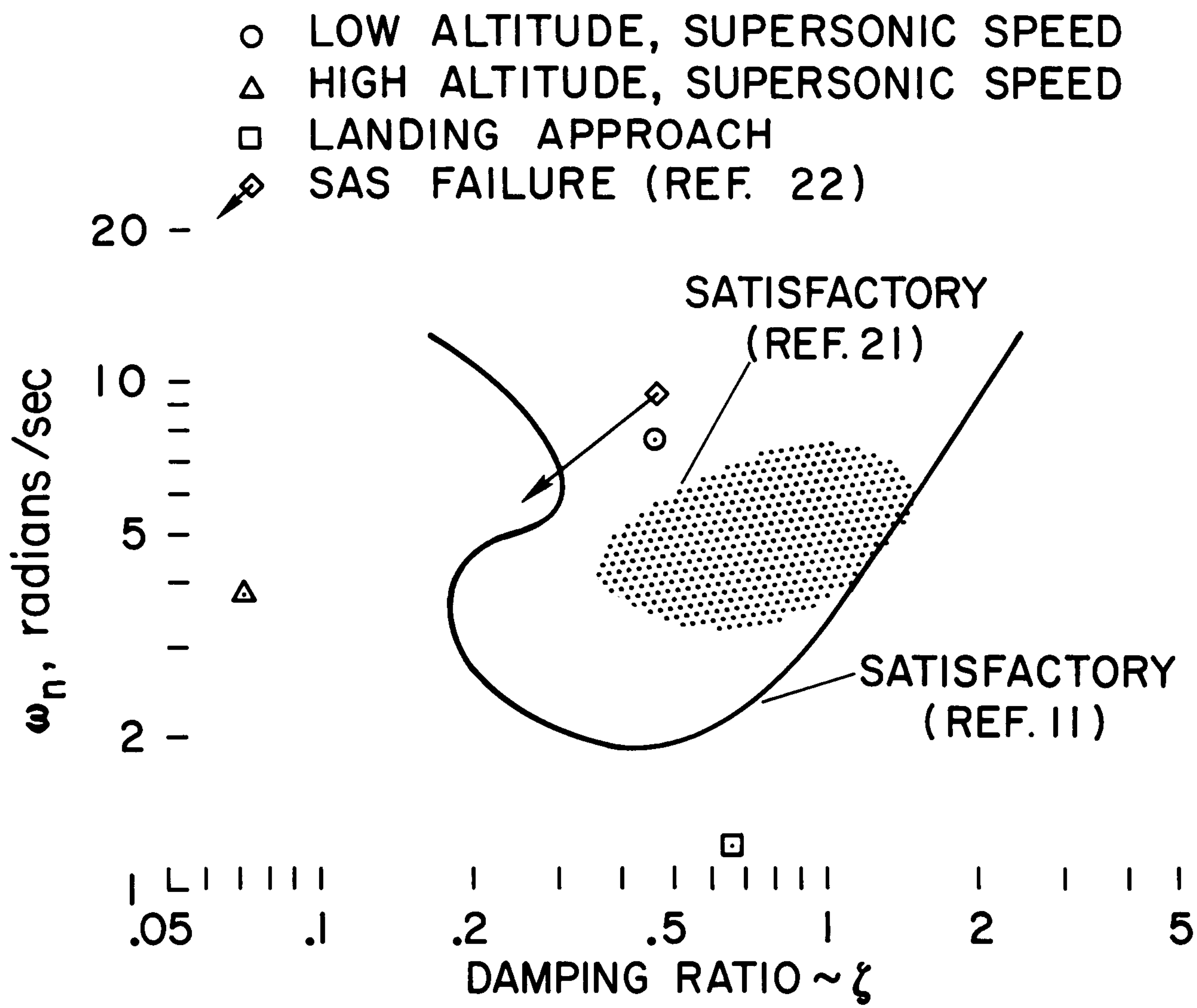
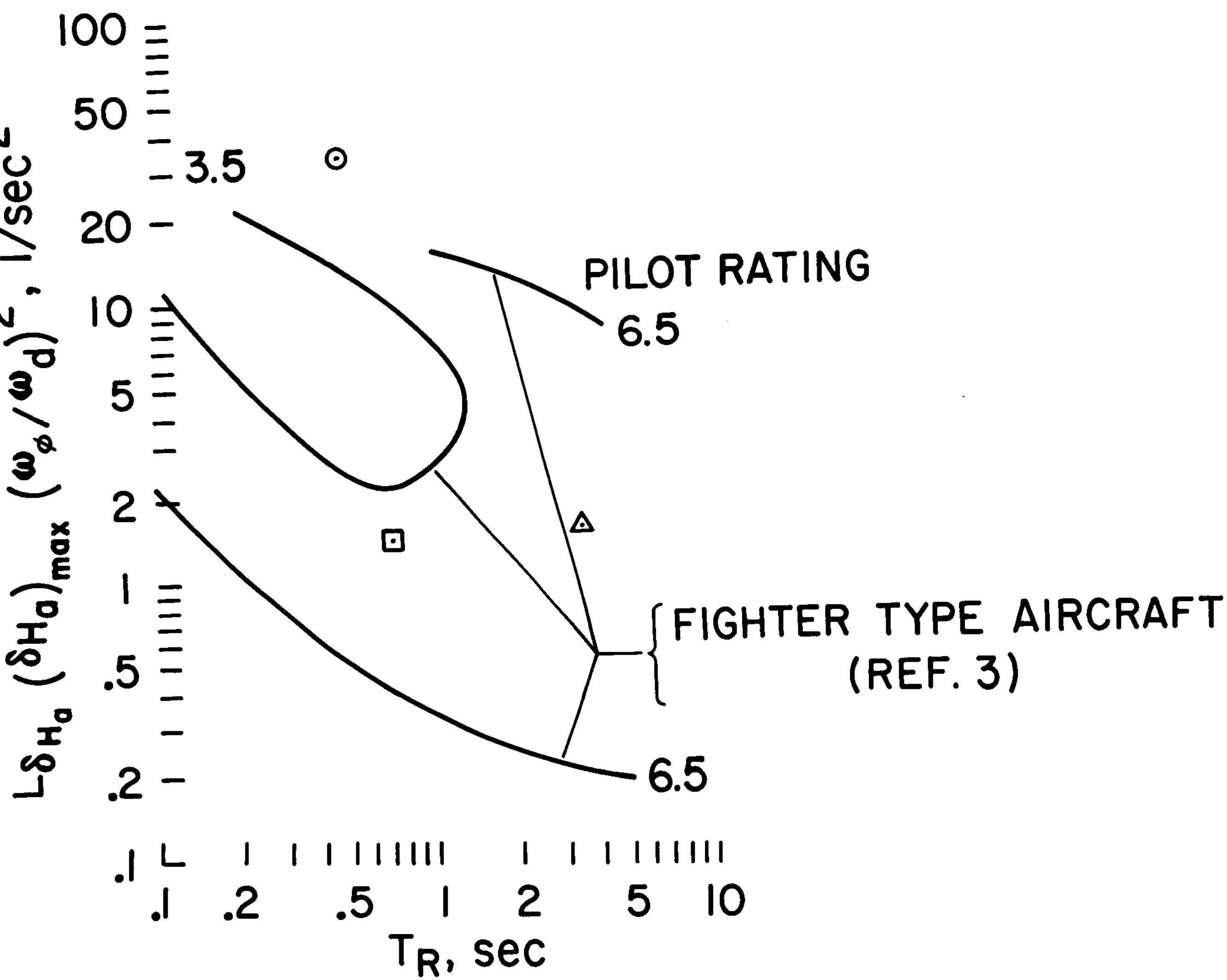


Fig. 1.- Block diagram of Wright Brothers' approach to vehicle design.



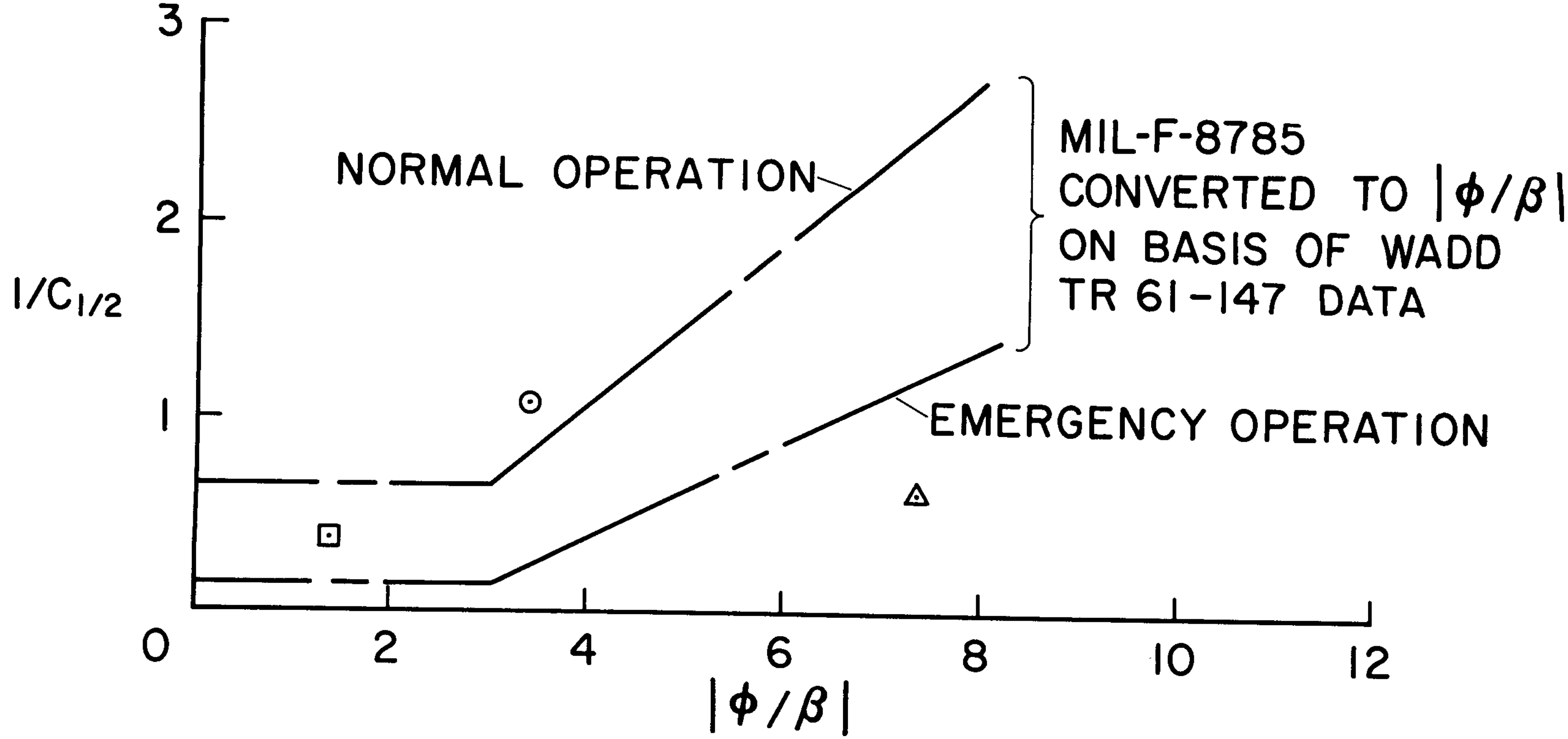
(a) Longitudinal short period.

Fig. 2.- Handling qualities guidelines.



(b) Lateral control.

Fig. 2.- Continued.



(c) Dutch roll.

Fig. 2.- Concluded.

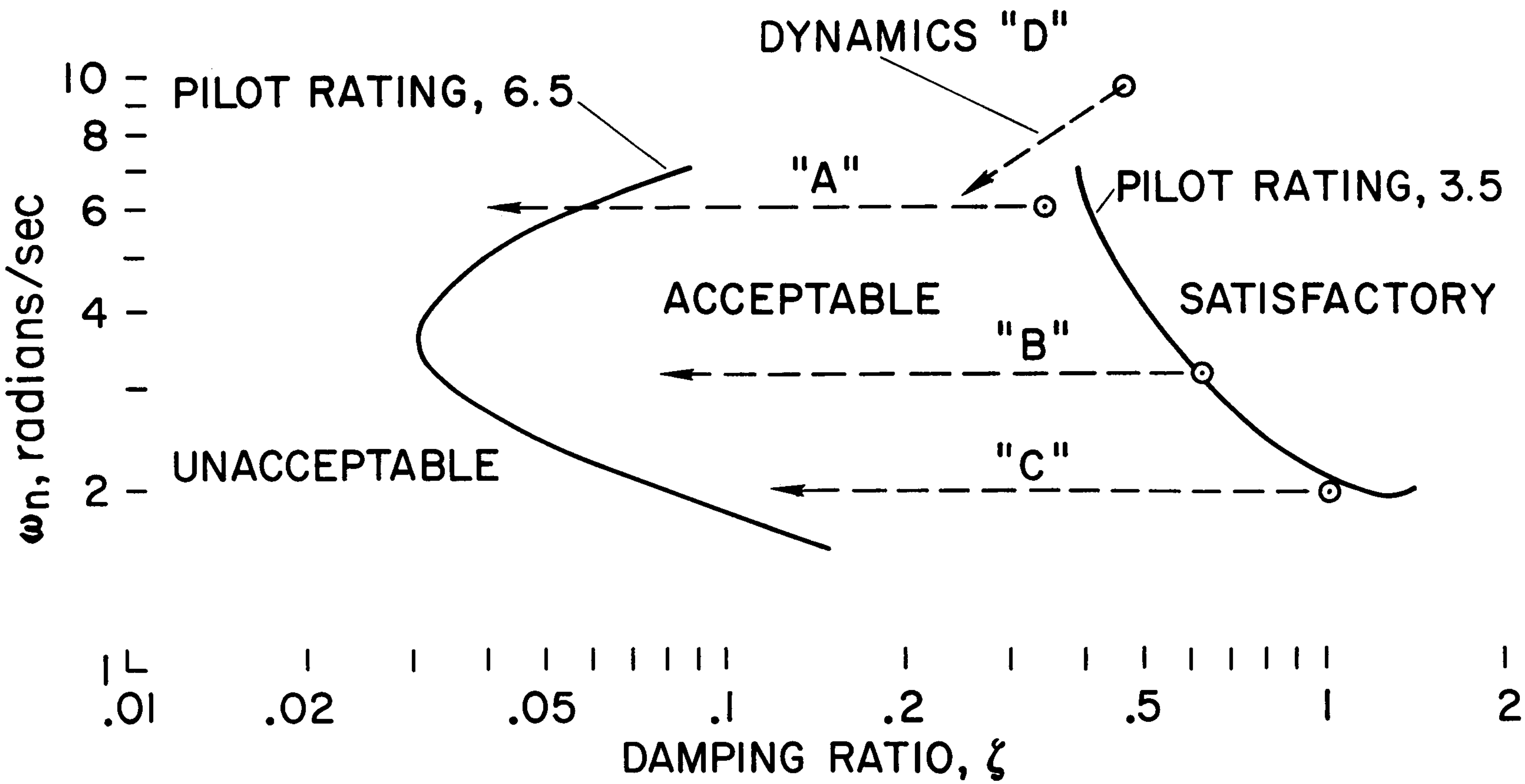
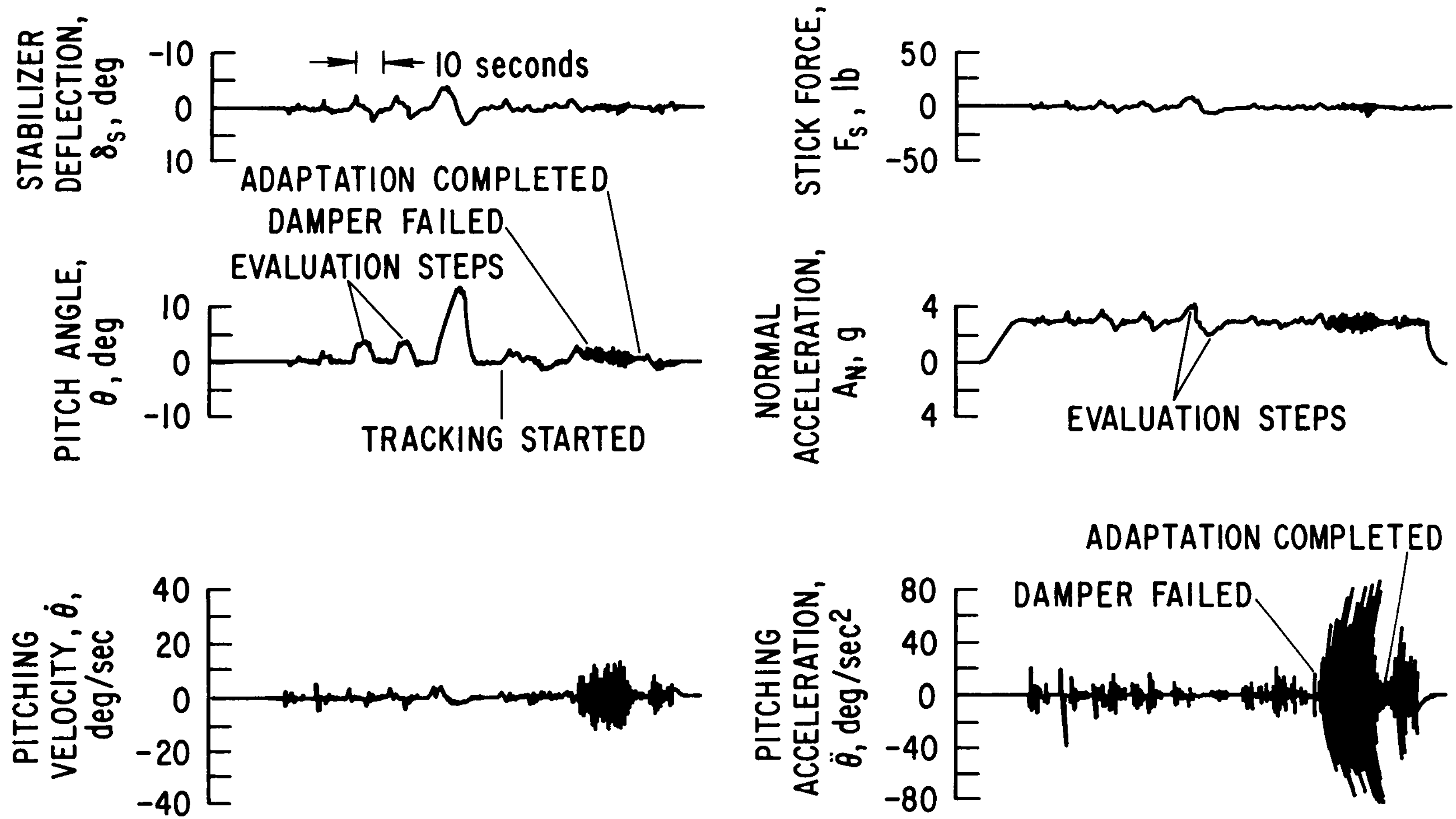
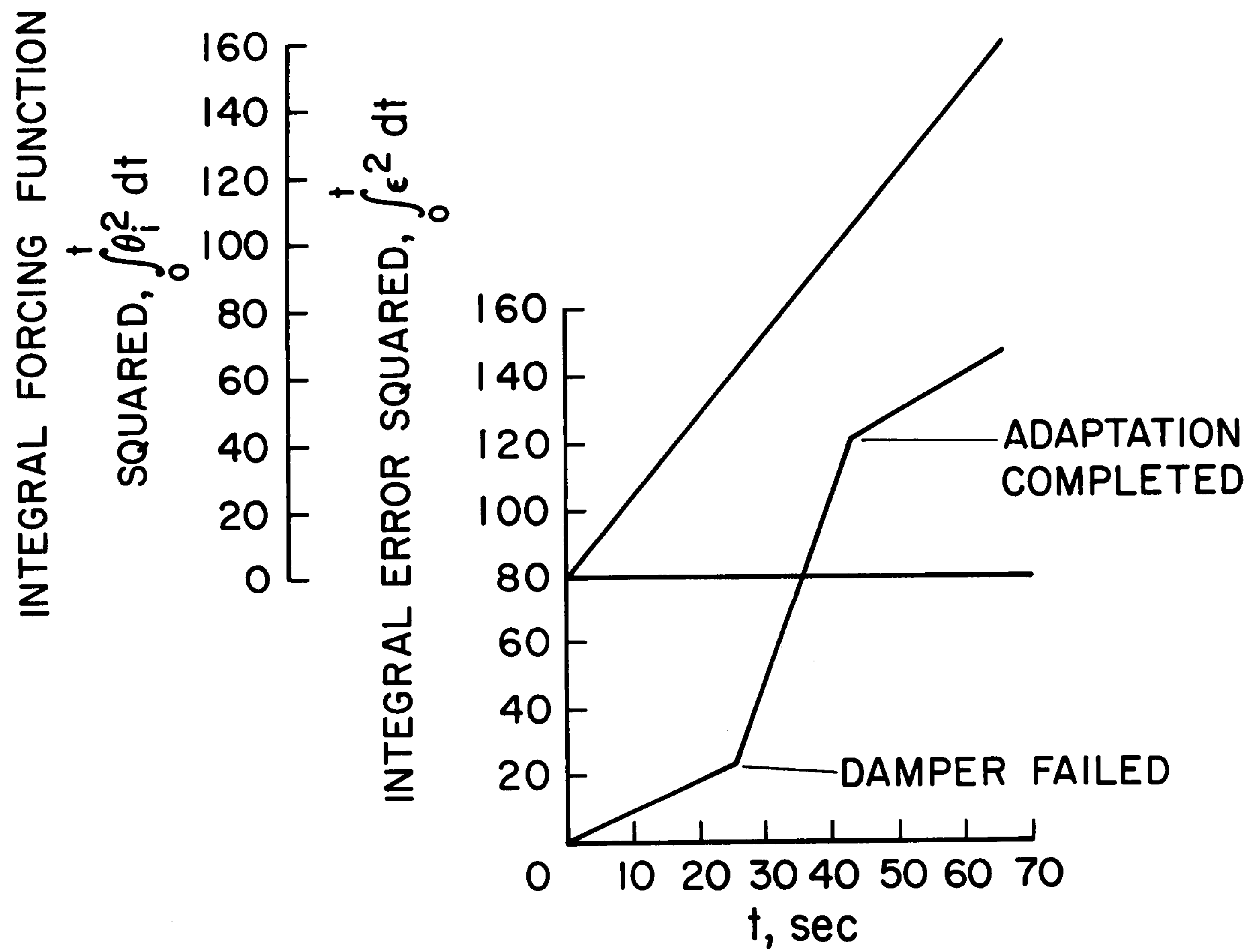


Fig. 3.- Stability augmentation failures considered.



(a) Time history.

Fig. 4.- Typical pitch-damper failure.



(b) Pilot performance.

Fig. 4.- Concluded.

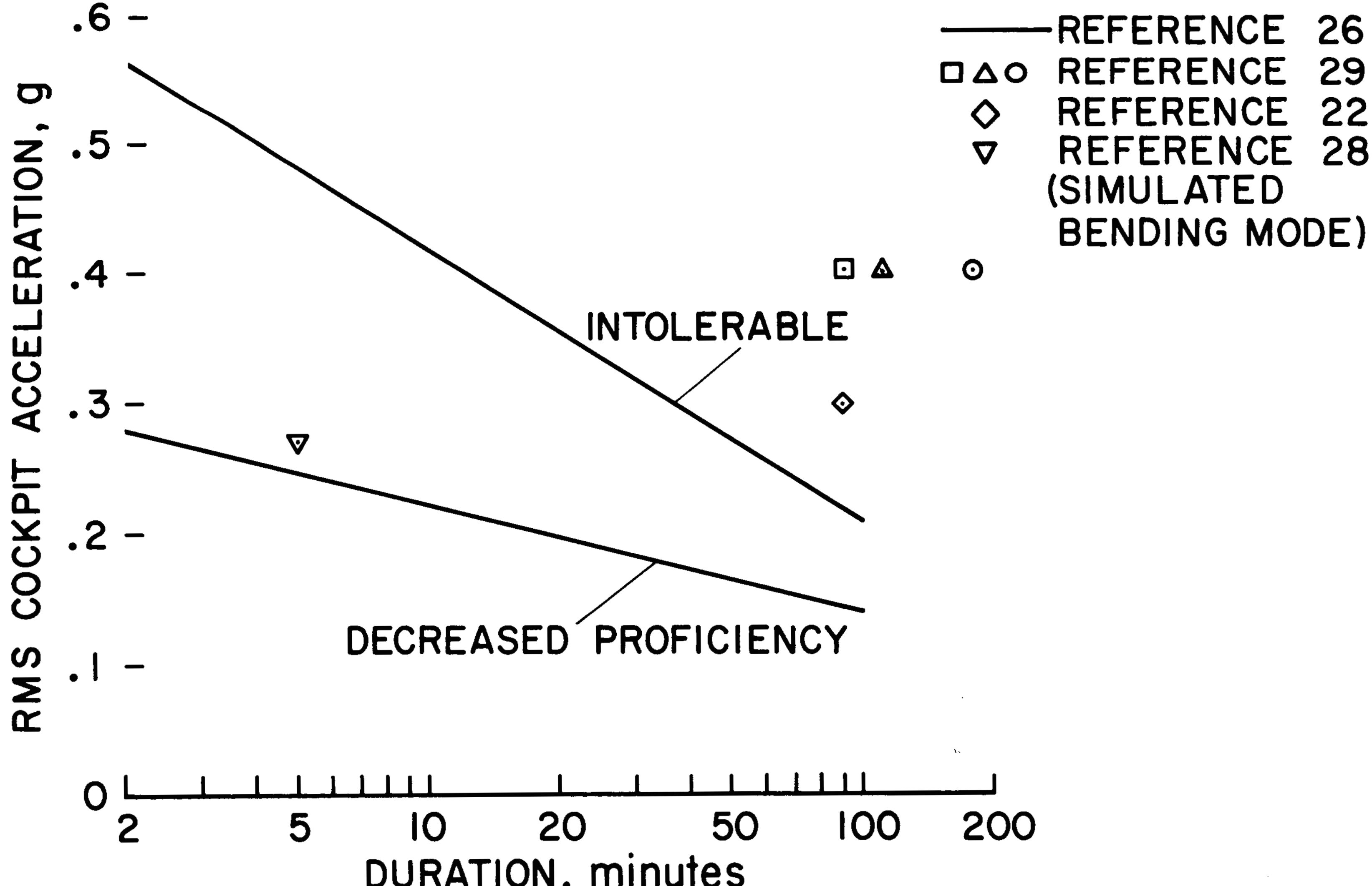


Fig. 5.- Pilot tolerance to gust-induced accelerations.

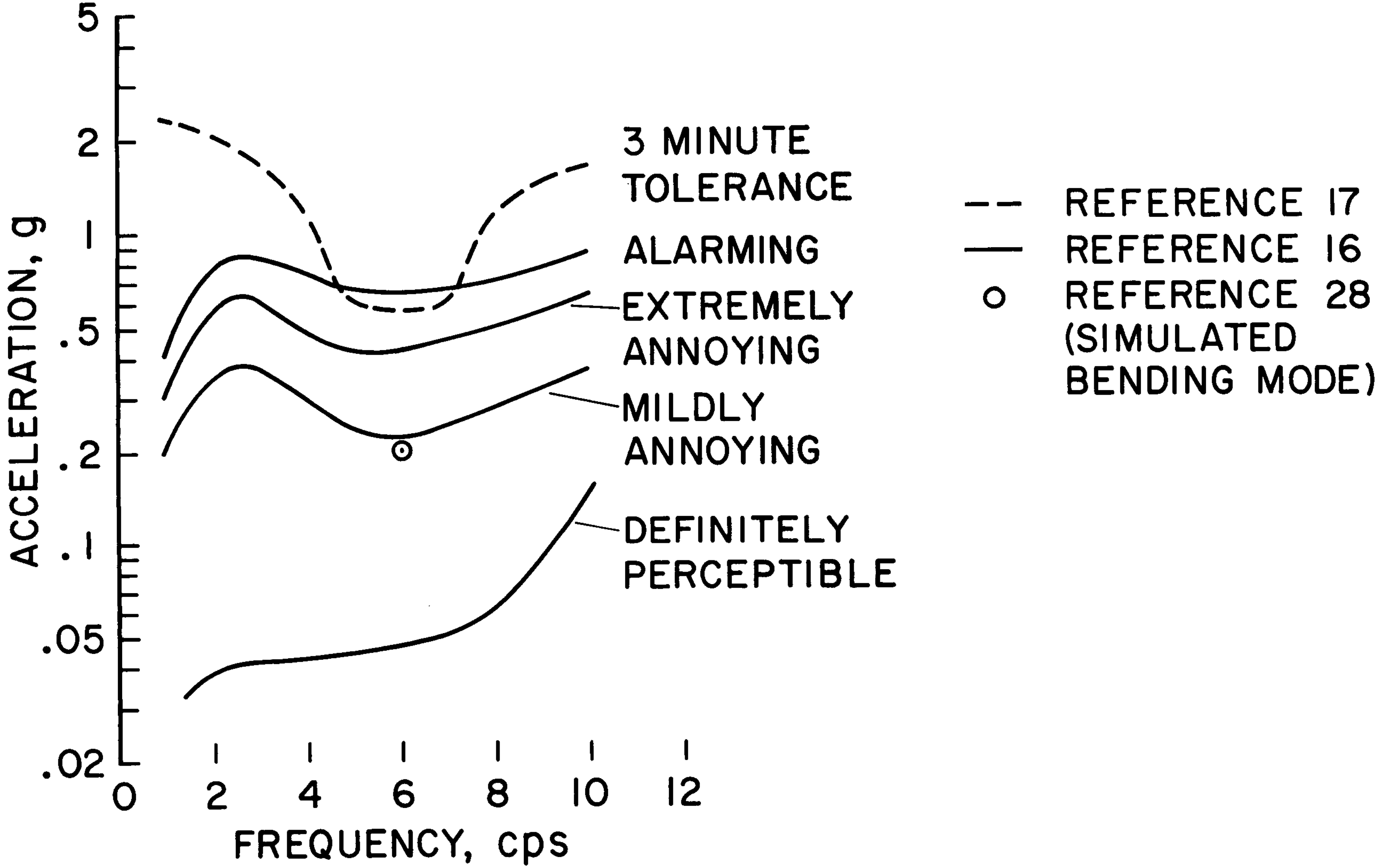


Fig. 6.- Human tolerance and subjective impressions of oscillatory accelerations.

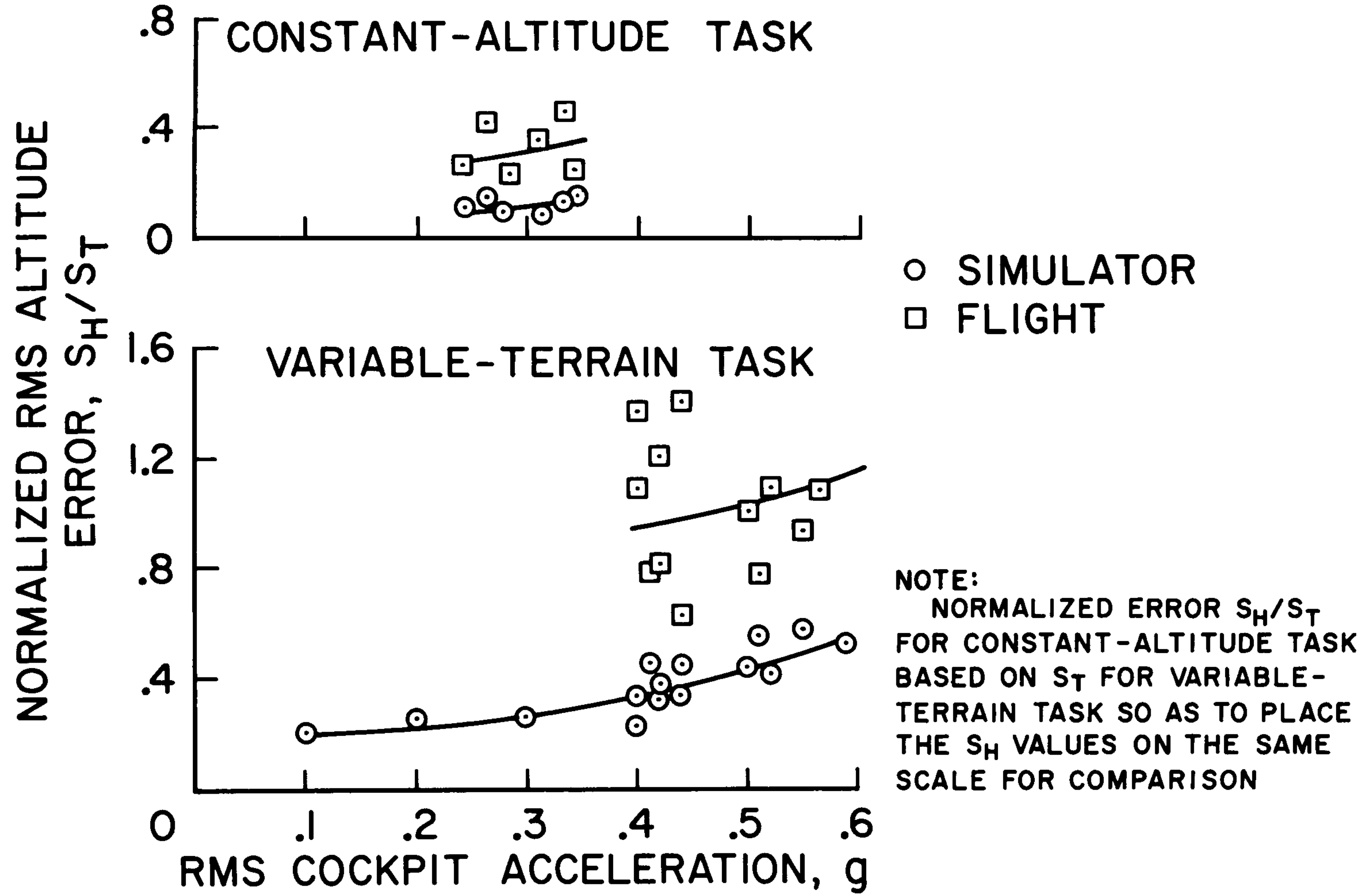
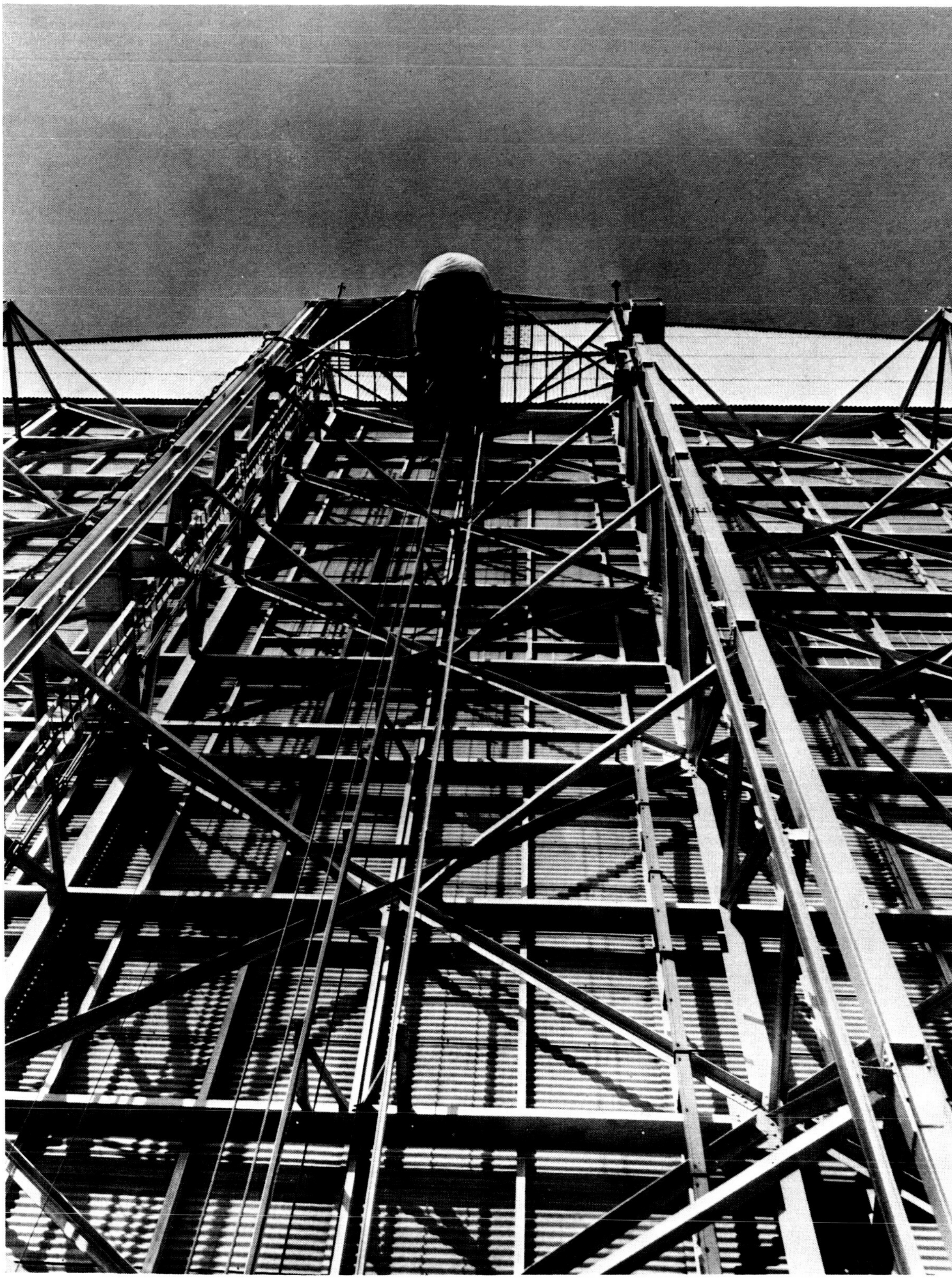


Fig. 7.- Effects of gust-induced acceleration stress on performance.



A-32206

Fig. 8.- Photograph of Ames Height Control Apparatus.

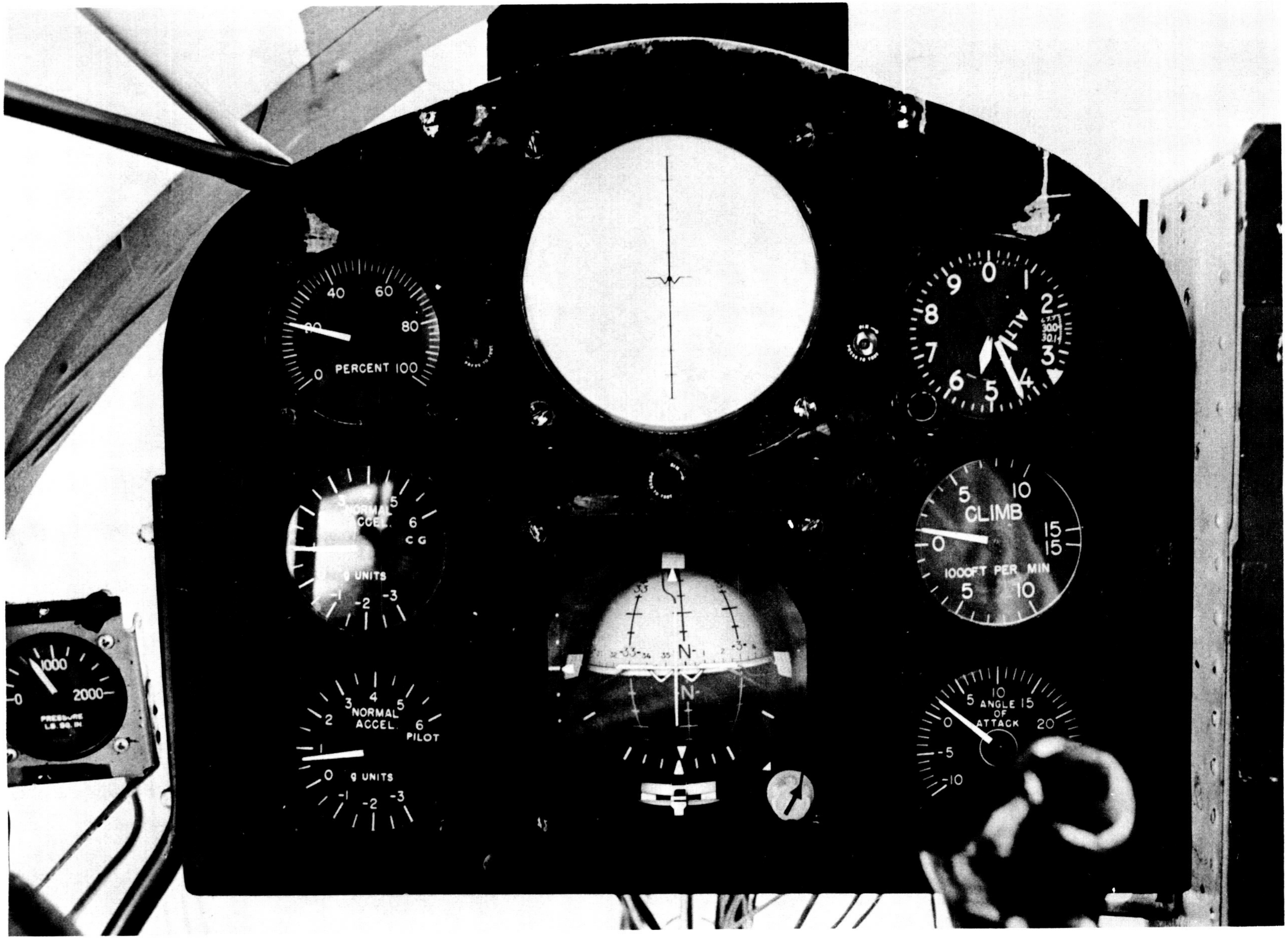


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Fig. 9.- View of simplified instrument panel used.

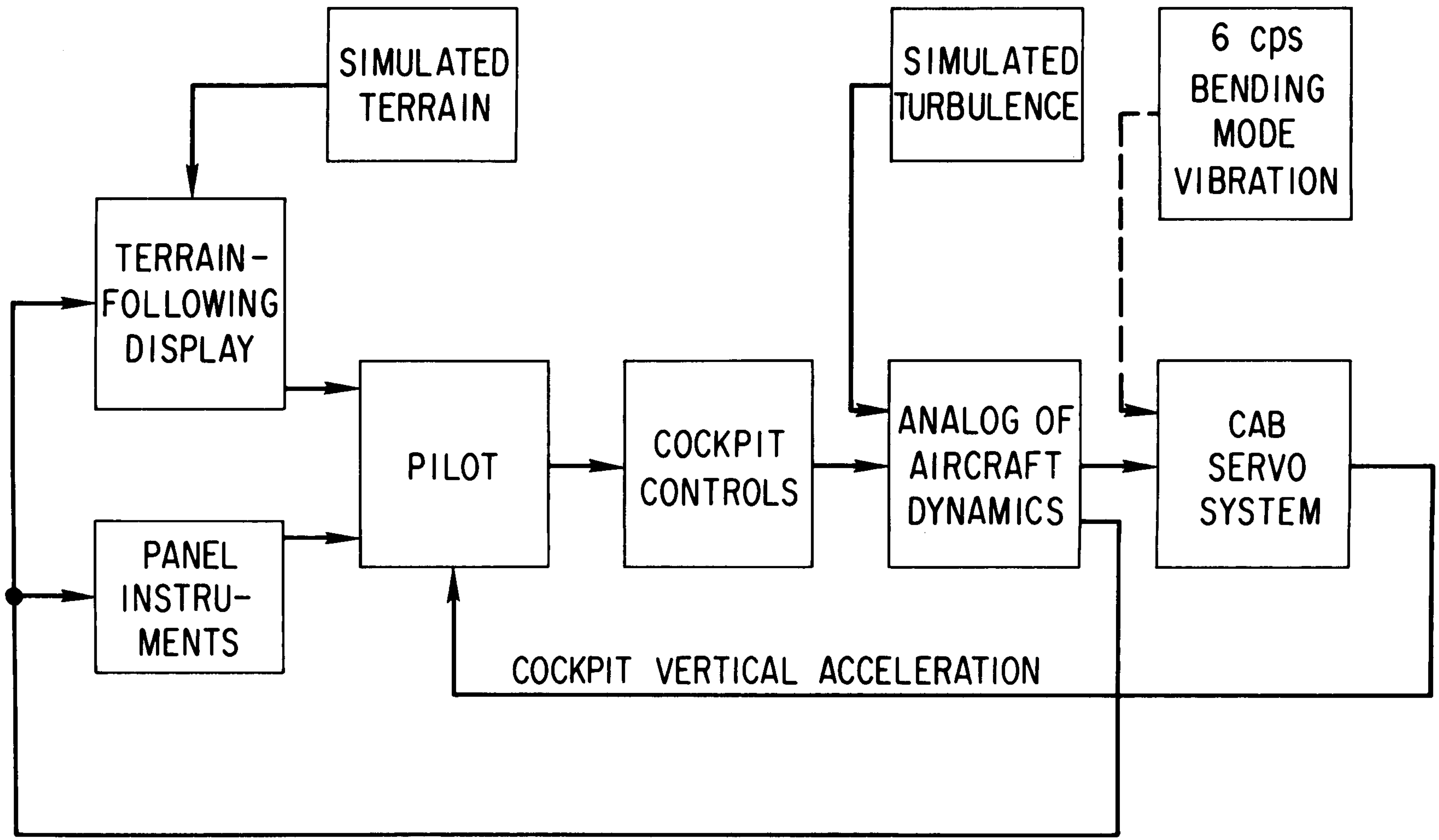


Fig. 10.- Block diagram of piloted simulator setup.

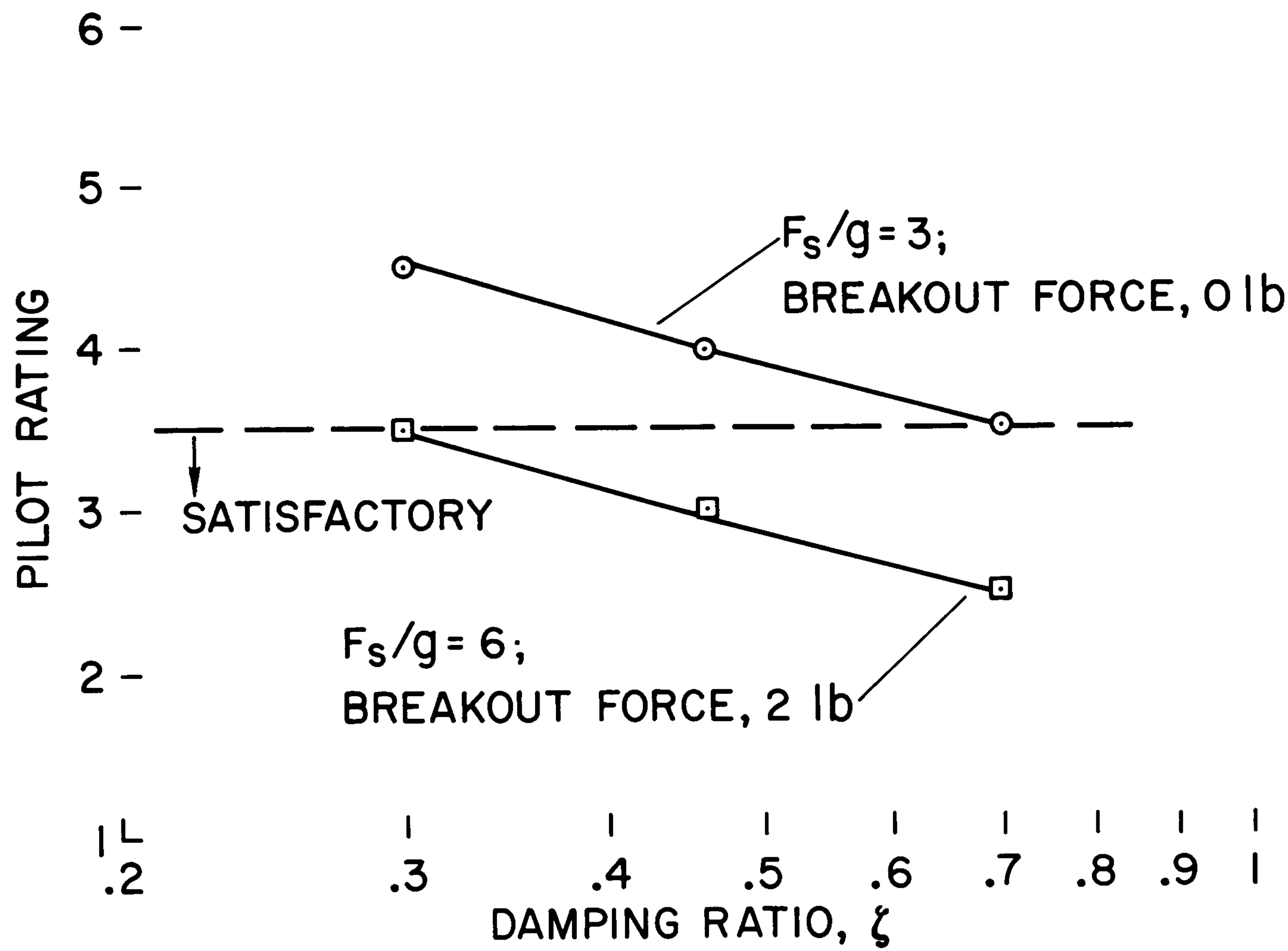


Fig. 11.- Longitudinal short-period evaluations.

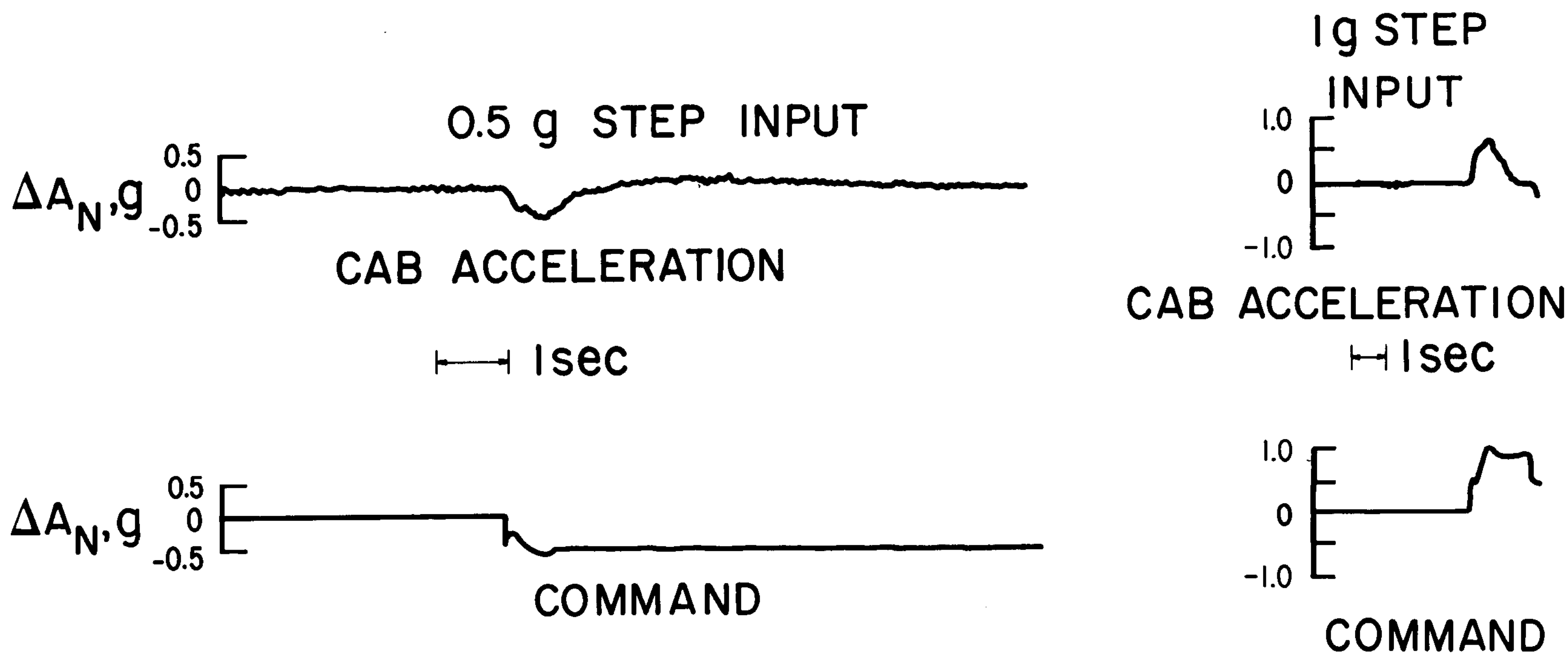
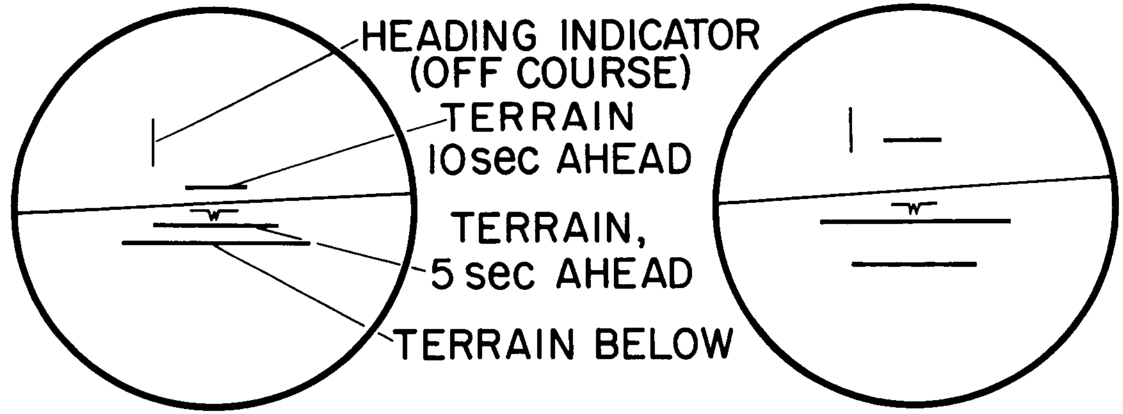
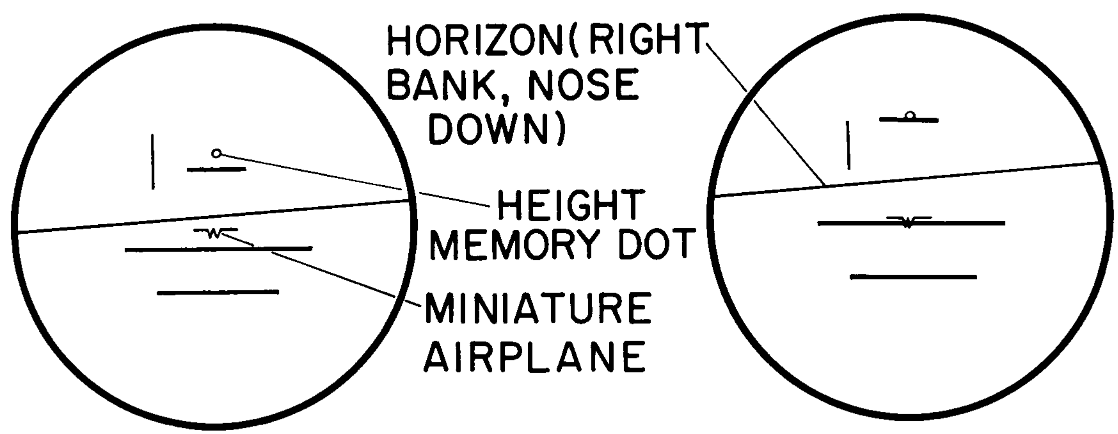


Fig. 12.- Simulator response characteristics.



DISPLAY C; ANGLES TO TERRAIN AHEAD SCALED 6°/cm; TERRAIN BELOW 333ft/cm USING HORIZON CENTER AS ZERO REFERENCE

DISPLAY D, TERRAIN AHEAD SHOWN AS RELATIVE HEIGHTS, 333 ft/cm

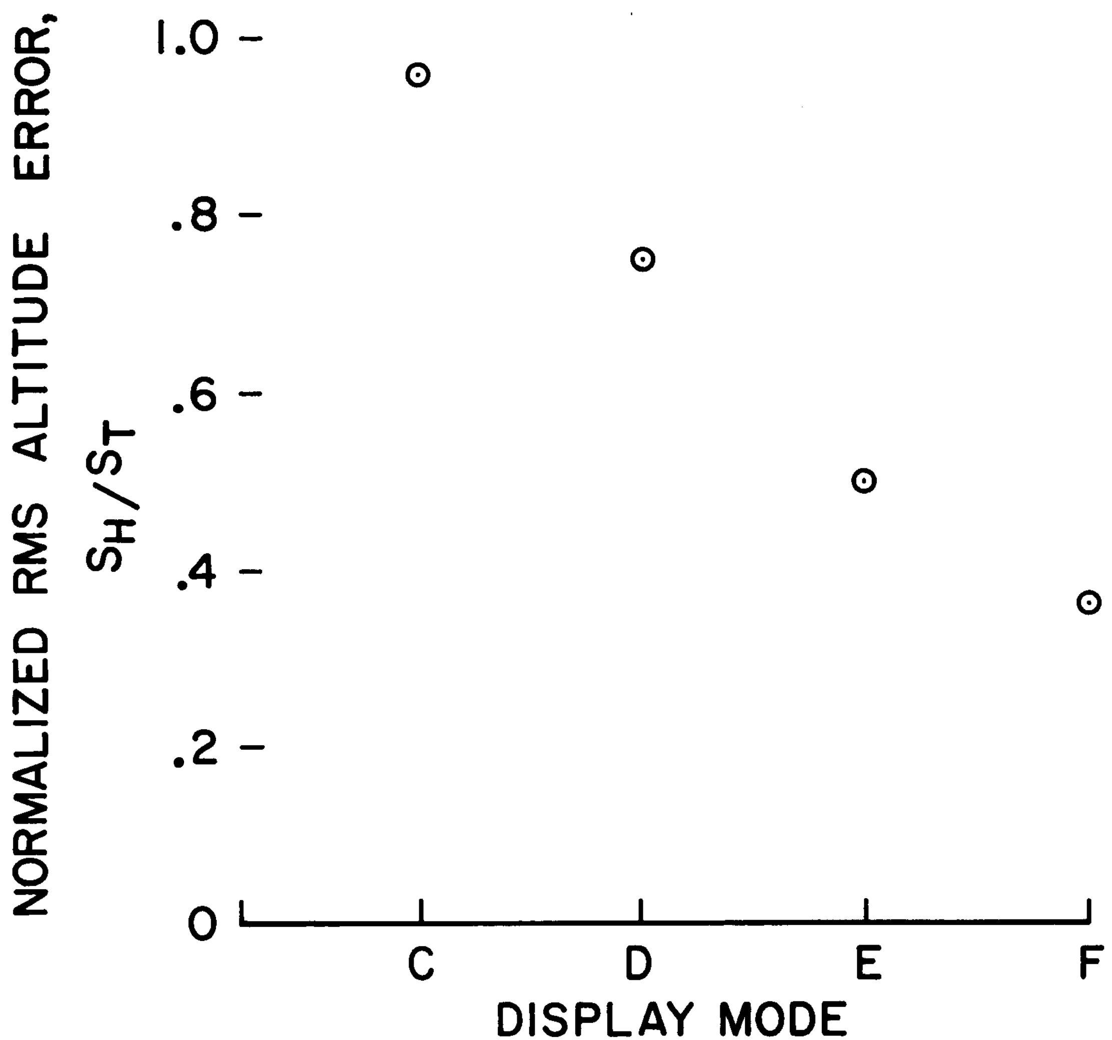


DISPLAY E, HEIGHT MEMORY DOT (MAXIMA OF TERRAIN 10 sec AHEAD) ADDED

DISPLAY F, HEIGHTS RESCALED TO 250ft/cm, PITCH ANGLE - 2.2°/cm

(a) Displays.

Fig. 13.- Terrain-following situational displays evaluated.



(b) Performance.

Fig. 13.- Concluded.

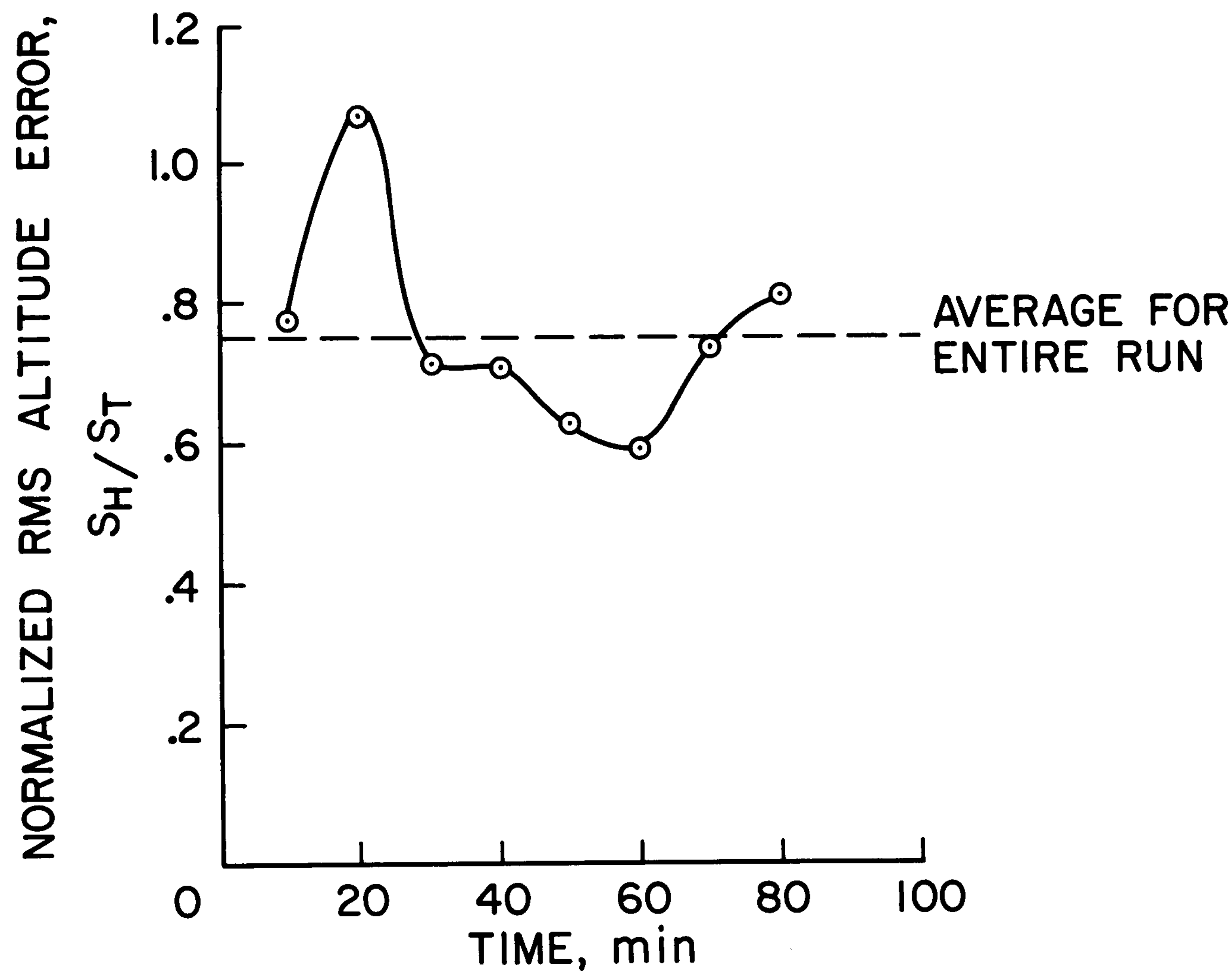


Fig. 14.- Pilot terrain-following performance (90 minutes of LASS flight).

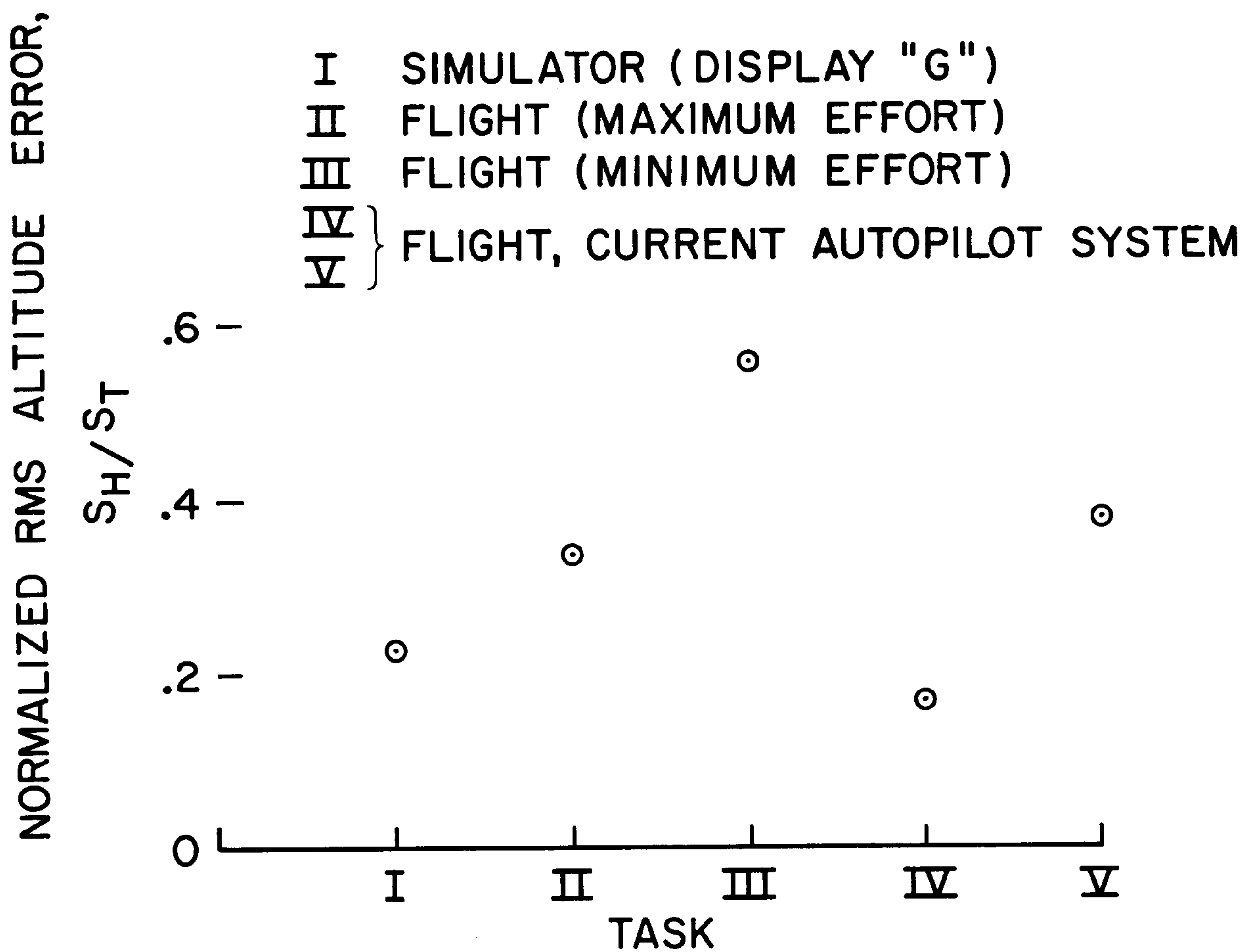


Fig. 15.- Comparison of terrain-following performance.

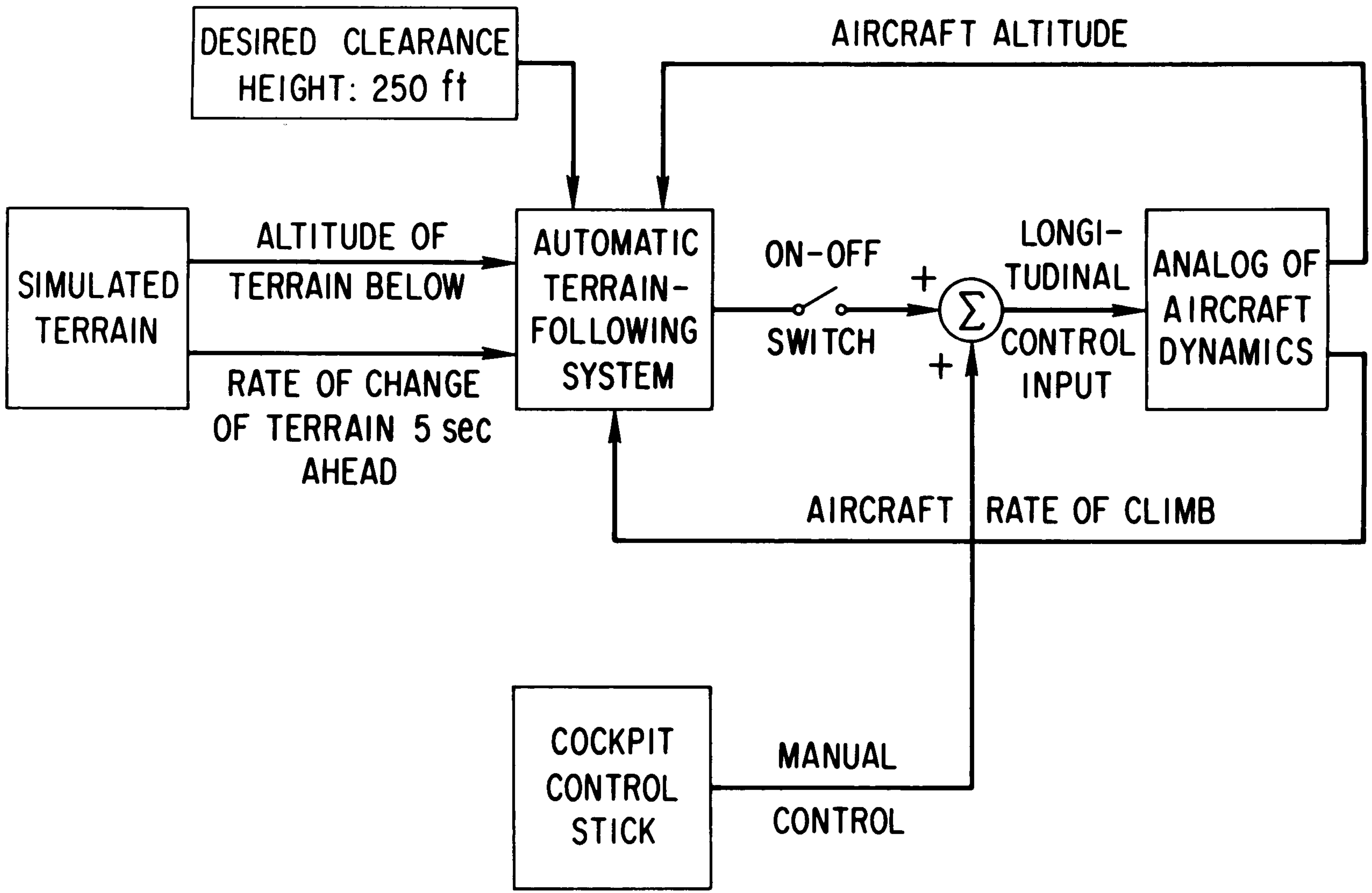


Fig. 16.- Block diagram of simulated automatic terrain-following system.

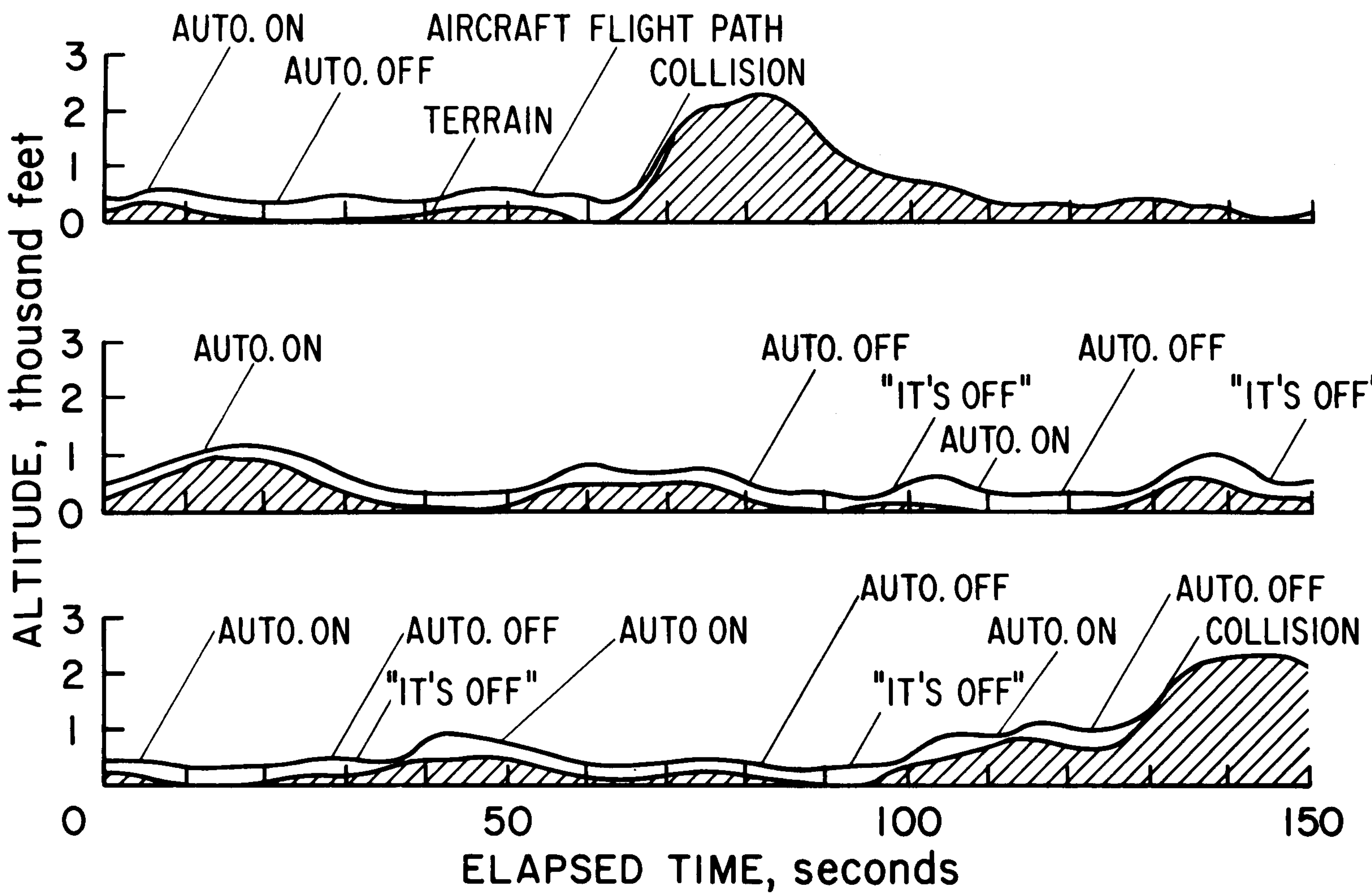
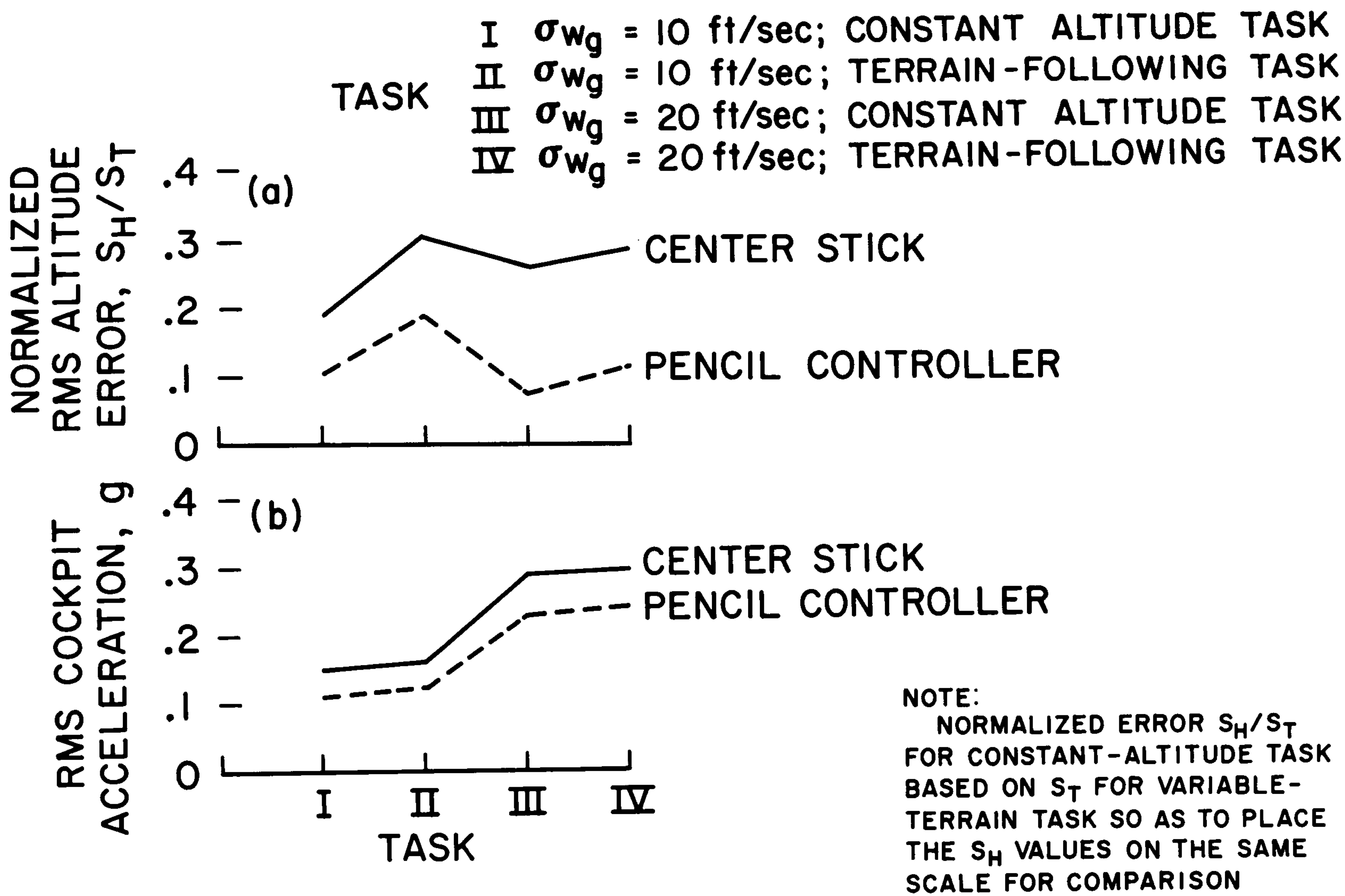


Fig. 17.- Simulated automatic terrain-following system failures.



(a) Terrain-following performance.
(b) Cockpit acceleration environment.

Fig. 18.- Comparative center stick, side-arm controller results.

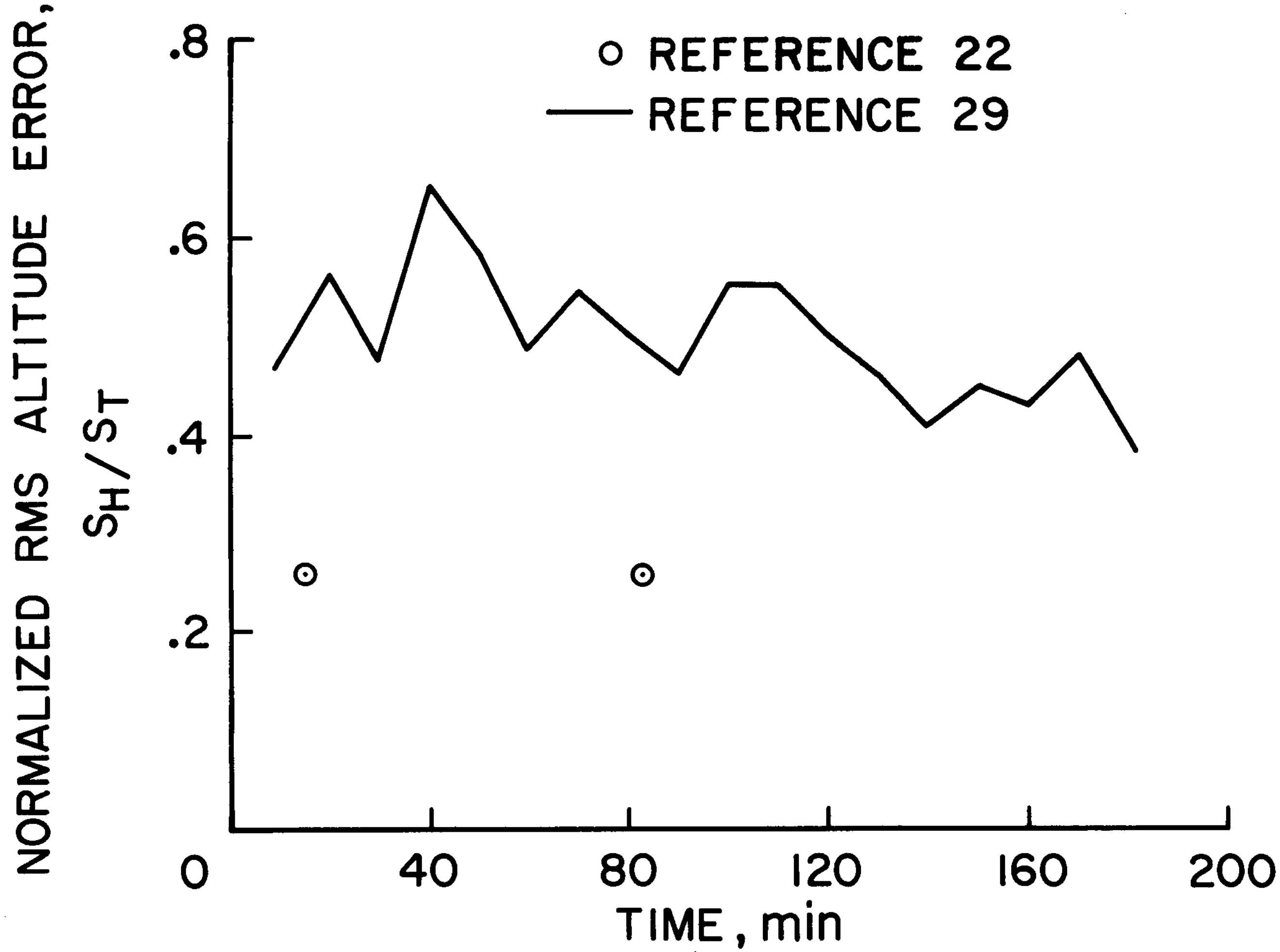
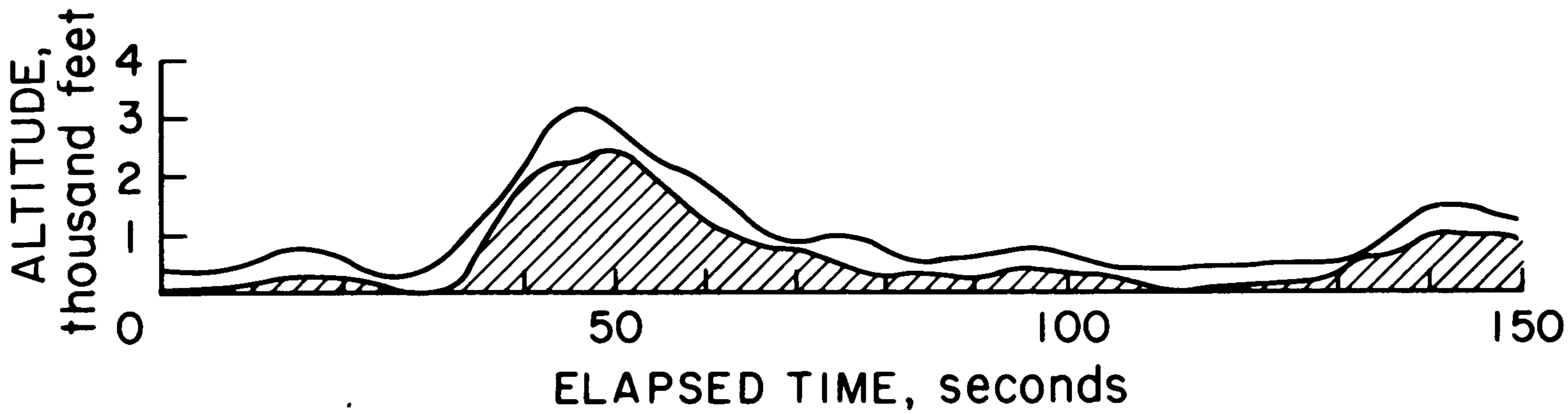
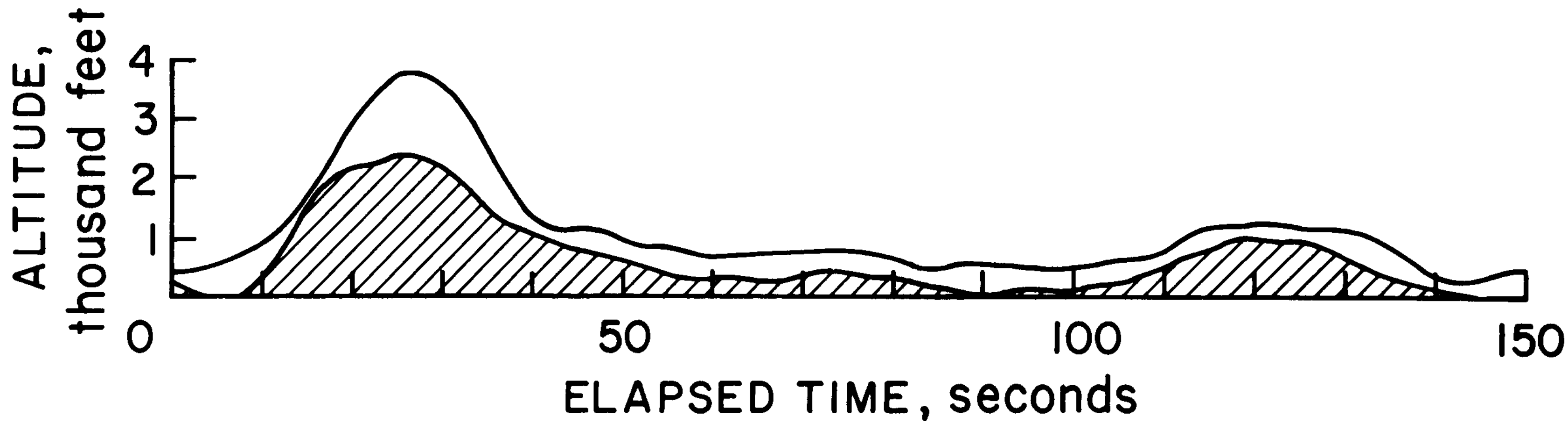


Fig. 19.- Effects of long-duration acceleration stress on pilot performance.



(a) Pilot performance (bending mode in).

Fig. 20.- Effects of simulated bending mode vibration.



(b) Pilot performance (bending mode out).

Fig. 20.- Concluded.

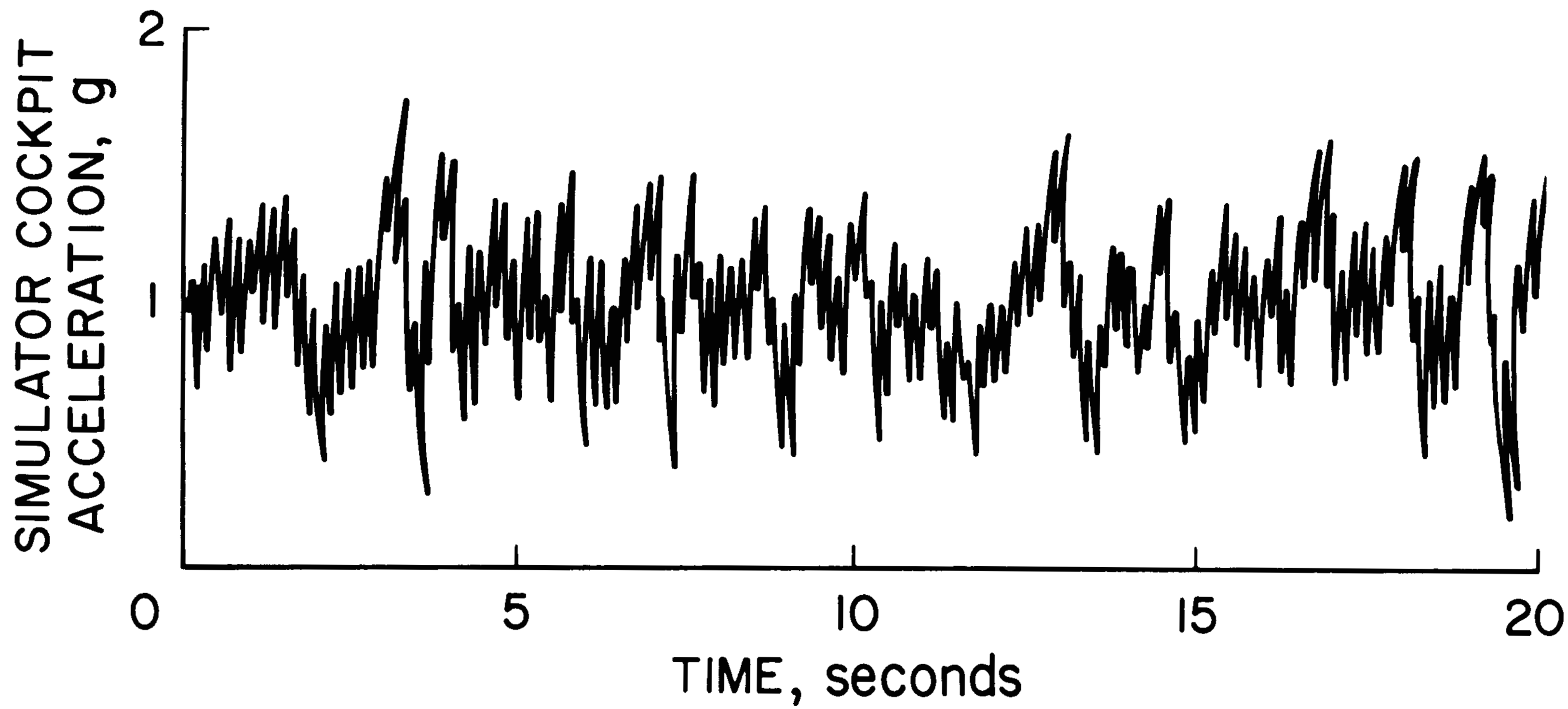


Fig. 21.- Sample of cockpit acceleration record during Fig. 20(a) run.

NASA-Langley, 1965 A-1080