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A STUDY OF A PILOT'S ABILITY TO CONTROL DURING

SIMULATED STABILITY AUGMENTATION

SYSTEM FAILURES

By Melvin Sadoff

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SUMMARY

The results presented show the effects of failure of a stability augmentation system on the pilot's ability to control while engaged in a simple tracking task. The results of failures simulated in a fixed- and moving-cab centrifuge suggest that moving cockpit flight simulators provide a more realistic evaluation of the transient effects of stability augmenter failures. In the present study, simulator motions generally interfered with the ability of the pilots to adapt to the failures. A pencil-type side-arm controller proved easier to use than a conventional center stick in coping with pitch damper failures at the higher short-period frequencies. The use of simple pilot models in the analysis and prediction of the transient effects of stability augmenter failures provided encouraging results.

INTRODUCTION

Considerable effort has been devoted in recent years to establishing basic handling qualities requirements for high-performance aircraft through the use of piloted flight simulators and variable-stability airplanes (e.g., refs. 1 to 6). The results provided by these studies delineate regions of satisfactory, acceptable, and unacceptable vehicle dynamics. It has been considered that the aircraft should be designed so that when the stability augmentation system is inoperative or has failed, the vehicle dynamics should be rated marginally acceptable by pilots. Pilot-rating boundaries have been established only for time-invariant vehicle dynamics; that is, no attempt was made to determine whether these boundaries apply for sudden stability augmenter failures. Though the pilot is a remarkably adaptive controller who can, given sufficient time, vary his own dynamics to maintain constant pilot-vehicle performance over a wide range of vehicle dynamics (refs. 1 and 7), little is known about his ability to cope with the abrupt changes in aircraft dynamics that would occur during sudden failure of the stability augmentation system (SAS). (The ability of a human to adapt to more gradual changes in vehicle dynamics, type of display, etc., is discussed in ref. 8.)

To provide some information on a pilot's ability to control a vehicle during sudden SAS failures of the longitudinal control system, a fixed- and moving-cab simulator study was conducted by Ames Research Center on the human centrifuge at the Aviation Medical Acceleration Laboratory (AMAL), Naval Air Development Center, Johnsville, Pennsylvania. In this preliminary study, the SAS failures were simulated simply by varying the vehicle dynamics, suddenly; no attempt was made to simulate "hard-over" failures.

The main objectives of this paper are: (a) to illustrate by means of vehicle response time histories and pilot-vehicle performance measures the general pattern and nature of the control problem when the pitch SAS fails, (b) to assess the effects of kinesthetic and vestibular motion cues by a comparison of results from tests in fixed-cab and moving-cab simulators, (c) to compare the pilot's ability to control with center-stick and side-arm controllers, (d) to apply simplified pilot transfer-function models to the interpretation and prediction of control problems resulting from SAS malfunction.

SYMBOLS

A_N vehicle normal acceleration factor (ratio of accelerating force to weight), g

AR amplitude ratio

C_O numerator constant in pitch transfer function, $1/\text{sec}^3$

C_1 numerator constant in pitch transfer function, $1/\text{sec}^2$

F_s pilot stick force, lb

g acceleration of gravity, 1g = 32.2 ft/sec^2

K_p pilot or pilot model static gain, δ_s/ϵ, deg/deg or F_s/ϵ, lb/deg, as indicated

s Laplace transform variable

t time, sec

T transition time required for pilot to adapt to changed vehicle dynamics, sec

T_2 divergence time to double amplitude, sec

T_L pilot model first-order lead, sec

Y_c vehicle pitch transfer functions

Y_p pilot or pilot-model transfer function

δ_s stabilizer deflection, deg

Δ incremental change in value over an appropriate time interval

ϵ tracking error, deg

$\bar{\epsilon}^2$ mean square tracking error, deg^2

ζ vehicle short-period damping ratio in pitch

θ vehicle pitch attitude, deg

θ_i target motion, deg

$\bar{\sigma}^2$ mean square target motion, deg^2

τ pilot or pilot-model visual reaction time, sec

φ phase angle, deg

ω angular frequency, radians/sec

ω_n vehicle undamped short-period natural frequency in pitch, radians/sec

SIMULATION

In this study the human centrifuge at the AMAL, Naval Air Development Center, Johnsville was used to assess the effects of normal acceleration and pitching acceleration on the pilot's ability to adapt to sudden SAS failures. A detailed description of the simulation setup is provided in reference 1. As noted in this reference, the centrifuge has disorienting effects on the pilot at normal accelerations below 3g; therefore, the moving-cab portion of the study was conducted at a bias normal acceleration level of 3g so that normal-acceleration perturbations were referred to 3g rather than 1g. The coordinate conversion system used in this study is the one described in reference 1. The purpose of the coordinate transformation analog was to transform the computed linear-acceleration signals into appropriate centrifuge responses which reproduced the desired normal-acceleration perturbations accurately, introducing a minimum of spurious motions. As indicated in reference 1, the system used was the best of 16 modes evaluated, and it resulted in centrifuge responses which were considered fairly realistic by the pilots over most of the range of aircraft short-period dynamics studied. However, at the highest short-period frequencies tested ($\omega_n = 6$) and at low damping levels, the introduction of spurious fore and aft and lateral accelerations had an adverse effect on the pilots' ability to control.

TESTS AND PROCEDURE

The test conditions for the present study are illustrated in figure 1. The five cases covered in the program are shown in relation to steady-state pilot-opinion boundaries for short-period longitudinal handling qualities provided in reference 1. The pilot rating schedule for the steady-state boundaries is presented in table I. Three of the five cases involved sudden reductions in pitch damping (A,B,C in fig. 1); the other two involved sudden reductions in static stability (D and E, fig. 1). In case D, the static stability rating was changed from 3-1/2 to about 6-1/2 for steady state; in case E, the steady-state rating was unchanged between initial and final levels. The failures illustrated in figure 1 were simulated simply by step changes in vehicle dynamics between the initial and final levels. Since SAS failures are probably most critical when the pilot is required to control precisely, the failures were initiated while the pilot was engaged in a simple pitch-attitude tracking task. The task input θ_i was the sum of four sine waves with frequency and amplitude characteristics as indicated in the table below.

Sine wave component	Frequency, radians/sec	Mean-square amplitude, arbitrary units
1	0.277	1.0
2	.741	.5
3	1.21	.15
4	1.80	.07

(For further description of the task, see ref. 9.) Pilot performance was determined from the ratio of mean-square tracking error $\bar{\epsilon}^2$ to the mean-square target motion $\bar{\sigma}^2$. This was determined from the incremental changes in $\int\epsilon^2\,dt$ and $\int\theta_i^2\,dt$ over the same time period, so that

$$\bar{\epsilon}^2/\bar{\sigma}^2 = \Delta\int\epsilon^2\,dt/\Delta\int\theta_i^2\,dt$$

Most of the tests were conducted with a force-command center stick; however, a brief re-evaluation of damper failures at the higher short-period frequencies (cases A and B) was made with a pencil-type side-arm controller with appropriate arm restraint (see ref. 1).

The test conditions described were evaluated by four experienced test pilots, including two from the NASA and one each from the Naval and

Air Force Flight Test Centers. The majority of the conditions were evaluated only by two pilots, pilots B and E of reference 1. The same two pilots were used in the present study and are identified as pilots A and B, respectively.

RESULTS AND DISCUSSION

General Pattern of Control Problem

The general pattern of the control problem encountered during sudden failure of the stability augmentation system is indicated in figure 2. A typical time history of the simulated aircraft response characteristics associated with a pitch-damper failure for case A with the centrifuge cab moving is shown in figure 2(a). Figure 2(b) presents the associated tracking-task input and the tracking error, expressed as $\int\theta_i^2\,dt$ and $\int\epsilon^2\,dt$, respectively. The time at which the pitch damper failed is easily recognized by the point in time where the aircraft responses build up rapidly (fig. 2(a)) and where the integral of the error squared increases abruptly (fig. 2(b)). As shown by these typical results, the pilot-aircraft combination tends to become unstable immediately following the damper failure; this tendency will be discussed in a later section. The results in figure 2(b) also show that a well-defined transition time is required for the pilot to adapt to the failure in terms of the time required to stabilize tracking performance. The more rapid increase in $\int\epsilon^2\,dt$ relative to the increase in $\int\theta_i^2\,dt$ indicated the pilot would have improved the situation by releasing the control.

A control problem, somewhat analogous to that described here, was indicated by analysis of some of the results of reference 8. Results of the analysis, considered pertinent to those of the present study, are provided in appendix A.

Effects of Simulator Motions

The effects of centrifuge flight simulator motions on the pilot's ability to cope with pitch damper and SAS failures are illustrated by the comparison of fixed-cab and moving-cab centrifuge results presented in figures 3 to 7. Shown are plots of pilot performance expressed as the ratio of mean-square error $\bar{\epsilon}^2$ to mean-square input $\bar{\sigma}^2$.

The results in figures 3, 4, 5, and 6 for cases A, B, C, and D, respectively, show a significant adverse effect of simulator motions on the pilot's ability to adapt to the failures. This is generally apparent both from the larger mean-square error during transition and from the longer transition times for the moving-cab results. Case C (fig. 5(b)) is of interest because of a nontypical double rise in tracking error - one at failure and one after the pilot had presumably adapted to the failure. This result may reflect the difficult adaptation required of the pilot after SAS failure for this case. Appendix B describes the time-invariant pilot adaptation (gain and lead) required for all failures considered and points out that pilot adaptation to a case C failure involved a simultaneous reduction in pilot static gain and an increase in pilot lead. Presumably, this adaptation was more difficult to attain by pilot B with the centrifuge cab moving. Results for pilot A in the moving cab (not shown) did not indicate the double rise in tracking error.

In figure 7, which presents results for failure of a static-stability augmenter (case E), a reverse trend is noted; that is, effects of motion feedback to the pilot were beneficial. In this case, the centrifuge motion may provide the pilot with additional lead information[1] required for stabilizing a lightly damped vehicle with zero static stability. (See ref. 7.) It should be noted, however, that in other cases which demanded relatively large lead of the pilot (e.g., cases C and D, figs. 5 and 6), an adverse effect of motion was observed. As noted in appendix B, these latter two cases required a simultaneous large reduction in static gain and an increase in lead which may have been more difficult to achieve with the centrifuge cab moving.

The effects of simulator motions on the transition times and tracking performance are summarized in figures 8 and 9. In general, it can be concluded that simulator motions had an adverse effect on both measures; that is, longer adaptation times were required, and the performance during transition was poorer.

These results suggest that simulator motions are generally required for a realistic assessment of a pilot's ability to cope with stability augmentation system failures. It should be noted that some of the comparisons of fixed-cab and moving-cab results presented may be contaminated by the spurious motions associated with simulation of aircraft motions on any limited degree-of-freedom simulator. In the present study, spurious motions were apparent to the pilots, particularly at the highest short-period frequencies (see section on simulation and ref. 1). Consequently, the adverse effects of motion, measured with the centrifuge, may be exaggerated, particularly for case A.

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[1]Lead information is the tracking-error rate information used by the pilot to maintain closed-loop stability. Results in reference 7 indicate the pilot develops large lead terms in order to control the pitch attitude of a lightly damped vehicle with low static stability.

Comparison of Center-Stick and Side-Arm Controller Results

A brief study was made to determine whether a pencil-type side-arm controller could reduce the adverse effects of simulator motions on the pilot's ability to adapt to damper failures. Center-stick and pencil controller tracking results with the centrifuge cab in motion are presented in figures 10 and 11. The results in figure 10 for case A show that the side-arm controller markedly improved the pilot's ability to cope with a pitch-damper failure at high short-period frequencies. The pilot appeared to adapt to the failure almost immediately with no apparent pilot-vehicle instability; whereas, with the center stick, his performance deteriorated markedly during the transition period of about 15 seconds. (In one instance (fig. 11(a)) the pilot lost control and aborted the run.) With the pencil controller the deterioriation of performance for case B was relatively small; however, the transition period was somewhat longer than that observed for the center stick.

These results indicate that the adverse effects of centrifuge motion feedback on the pilot's ability to adapt to pitch-damper failures can be reduced by the use of a side-arm controller, particularly when the failures occur at high short-period natural frequencies. As observed in the preceding section, spurious centrifuge motions, particularly fore and aft accelerations, probably interfered with the pilot's ability to adapt to damper failures at high frequencies with the conventional center stick. The improvement shown for the side-arm controller under these conditions is probably attributable to two factors: the arm restraint used helped minimize inadvertent control inputs, and the low mass and inertia of the aide-arm controller device, which was operable with the fingers, permitted smoother, more precise control inputs than those possible with the center stick.

Analysis Using Simplified Pilot Models

The transient effects of failure of a stability augmenter have been discussed with reference to the general pattern of the control problem, the effect of motion feedback to the pilot, and the effect of controller design. It is obvious that we have been discussing a closed-loop control problem; that is, the characteristics of the pilot response coupled with those of the vehicle response result in a marked transient deterioration of closed-loop performance. Methods for analyzing the performance of closed-loop systems are widely used in automatic control design. The results of extending these methods to systems with the pilot in the loop have been encouraging (refs. 1, 10, 11). We shall describe the application of these techniques, using simplified pilot models, to predict pilot-aircraft instability immediately following pitch-damper failures. The cases selected for analysis illustrate the extreme consequences of sudden damper failure.

Example cases.- Results in the preceding sections have indicated, in general, a tendency for the pilot-aircraft system to become unstable (divergent) in varying degree during the transition period following failure of the stability augmentation system. In several instances the instability progressed to the point where the pilot lost control of the vehicle. Two such cases that occurred following pitch-damper failure at high short-period frequencies are shown in figures 12 and 13. Figure 12(a) presents results for a case B (fig. 1) pitch-damper failure with the centrifuge cab moving. In this case, the failure was totally unexpected by the pilot; the failure was first encountered in a moving cab, whereas the normal test procedure was to investigate the failure first in a fixed cab. The aircraft responses following failure (fig. 12(a)) show a divergence time to double amplitude of roughly 1 second. As the normal acceleration reached about 5g, the pilot aborted the run.

In figure 13, data are shown for a case documented in flight in which control was completely lost. In this case, the pilot was flying at low altitude at high speed. There was evidence that the pitch damper failed just prior to the time for which data are shown. Here, again, the divergence time to double amplitude of the aircraft response was roughly 1 second. Since the damping of the unaugmented vehicle provided good response with controls fixed (time to one-half amplitude of about 0.2 sec), the pilot must have introduced large negative damping moments. The precise altitude control task of the pilot at the time the pitch-damper failed would, as noted earlier, tend to exaggerate the effects of the failure.

The results in figures 12 and 13 indicate that the limits of acceptable vehicle dynamics should be carefully selected to insure that the vehicle will be controllable within these limits if the stability augmentation system should fail. Evaluations obtained from tests with time-invariant vehicle dynamics should be checked by tests similar to those described here.

Pilot models.- Methods for analyzing the stability of closed-loop systems are widely used in control design and have recently been applied to pilot-airframe stability studies by appropriate assumptions of the pilot model or transfer function (see refs. 1, 10, and 11). In this section, a description is given of the application of these techniques to predict pilot-aircraft stability during the initial stages following pitch-damper failures.

The analysis procedure used was to determine the pilot model required to operate a vehicle with good dynamics (prior to damper failure) and to assume, conservatively, that this model would be initially unchanged following damper failure. The resulting closed-loop stability characteristics chould then be compared to those actually experienced. Data are analyzed for the cases in which the pilots lost control of the vehicle following failure of a pitch damper (figs. 12 and 13). The method described in reference 1 was used to deduce the required pilot dynamics. This procedure can be described briefly by means of figure 14 which shows in block-diagram form the closed-loop pilot-aircraft system considered. As indicated, the target motion or forcing function is represented by θ_i; ϵ is the tracking error; Y_p, Y_c are the pilot and vehicle transfer functions; δ_s is the control surface deflection; and θ is the aircraft pitch response. The airplane transfer-function coefficients C_o, C_1, $2\zeta\omega_n$, and ω_n^2 were adjusted to appropriate values, and the pilot model gain K_p and lead T_L were adjusted to values which resulted in a matching of the actual closed-loop performance with minimum introduction of lead. Since closed-loop performance data prior to the damper failure in flight (fig. 13) were not available, the lead term was assumed zero and the gain was adjusted to optimize closed-loop performance. The vehicle dynamics - in the present case the damping term $2\zeta\omega_n$ - were then changed to correspond to those with damper inoperative, and the resulting closed-loop stability was assessed.

Correlation of results.- Results of the analysis of the data in figures 12 and 13 by means of this simplified approach are presented in figure 15. Shown in figure 15(a) is the correlation of the predicted results and the actual results expressed in terms of the decrement in damping due to the destabilizing influence of the pilot. (The damping decrement $\Delta\, 2\zeta\omega_n$ is simply the difference between the unaugmented airplane damping and the closed-loop damping of the pilot-airframe system for an unadapted pilot model as described above.) The correlation based on the closed-loop stability, expressed in terms of divergence times to double amplitude T_2, is given in figure 15(b). Fairly good correlation of the results is shown. In addition to the analysis of the examples shown in figures 12(a) and figure 13, a run, labeled in figure 12(b) as a repeat run, was also analyzed. In this run, which followed immediately that shown in figure 12(a), the pilot was not informed whether the damper would fail again. Examination of the tracking performance data for this run, however, indicated the pilot tracked less energetically during the initial phase of the run in anticipation of a possible failure. This caution in tracking performance prior to failure (relative to the first run) corresponded to a reduction in pilot model gain of about 50 percent; consequently, milder transition characteristics were predicted for this case. (See fig. 15.) It should be noted that, if actual performance data had not been available for this run, the predicted results based on optimum performance would have been about the same as those shown in figure 15 for the initial run. These results demonstrate the need, in assessing the effects of SAS failures, for considering the type of task in which the pilot is engaged, and, hence, the tightness of control or gain he is initially using.

In view of these encouraging preliminary results, it may be desirable to check the damper authority and unaugmented damping for a given vehicle design by the procedure described to insure at least neutral closed-loop stability in the event of damper failure.

Neutral pilot-airframe stability will be assured, for example, if the unaugmented airplane damping is at least equal to the damping decrement produced by the destabilizing effect of an unadapted pilot model (see fig. 15(a)). The pilot models for the augmented vehicle may be determined as outlined above, or established by means of pilot-vehicle system surveys similar to those described in references 10 and 11.

It is emphasized that these results apply only to the initial part of transition and that the cases analyzed were selected because they reflected the extreme consequences of the type of SAS failures considered in this study. In these cases, the elements of complete surprise and the effects of motion feedback combined to interfere seriously with the pilot's ability to adapt to the failures. Considerable work remains to be done to define the precise mechanism by which a pilot adapts to SAS failures of various kinds and to determine the effects of realistic motion cues on pilot adaptation.

CONCLUDING REMARKS

The results of a brief simulator study to determine the transient effects of failure of the stability augmentation system on high-performance aircraft have been presented and discussed. The failures were initiated while the pilot was occupied with a pitch attitude tracking task, since the consequences of SAS failure were anticipated to be more serious when the pilot was required to control the vehicle attitude, altitude, or flight path precisely.

The results indicated, in general, a well-defined transition time required for the pilot to adapt to SAS failure. The transition was characterized by a marked increase in tracking errors (to levels generally higher than those observed following adaptation), and its length depended on the type of failure and whether the simulator was fixed or moving. Comparative fixed-cab and moving-cab centrifuge simulation of stability augmentation system failures indicated that simulator motions generally had an adverse effect on the pilot's ability to cope with the failures; in one case, however, the pilot had less difficulty adapting to the failure in the moving-cab simulation. These results suggest that moving-cockpit flight simulators should be used for a realistic assessment of the transient effects of stability augmenter failures. Comparative results showed that the pencil controller was more effective than the center stick in alleviations of some of the adverse effects of simulator motions on pilot's ability to adapt to SAS failures.

The use of simplified pilot models or transfer functions in analyzing and predicting extreme effects of damper failures on pilot control of a vehicle provided encouraging results, since the magnitude of the destabilizing influence of the pilot or the degree of closed-loop stability correlated fairly well with the actual results. Considerable work remains to be done to define the precise mechanism of pilot adaptation to rapid changes in control task and to determine the effect of realistic motion cues on pilot adaptation.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Aug. 20, 1962

APPENDIX A

TIME-VARIABLE HUMAN DYNAMICS

In this section, some of the results of reference 8 are recast in a somewhat different form to relate them to results in the present paper. The study conducted in reference 8 is also considered pertinent to the present investigation because it represents an initial and interesting effort to determine directly the time-variable adaptive behavior of human controllers. The experiment consisted of measuring changes in the closed-loop, human-operator dynamics associated with changes in display, process, or "vehicle" dynamics, etc. The experiments were performed with a tracking task similar to that used in the present study. The subject sat in front of a cathode-ray oscilloscope on which was displayed either task input and vehicle response (pursuit display), or only the error (compensatory display). The subject was instructed to manipulate a small controller to minimize the error.

Results are presented in reference 8 showing the changes in closed-loop human dynamics (average of eight subjects) that occurred as the vehicle dynamics were changed from unit gain ($Y_c = 1$) to pure integration ($Y_c = 1.61/s$) and vice versa for both compensatory and pursuit displays. The change in vehicle dynamics was generally completed within 6 seconds of the start of the change. Analysis of the average closed-loop operator dynamics $Y_p/1+Y_pY_c$ during the change in vehicle dynamics from unit gain to pure integration with a compensatory display revealed somewhat the same pattern of adaptation to SAS failures observed in the present study. Specifically, time histories of average tracking error (fig. 16) deduced from the results given in reference 8 are fairly similar to the results obtained in the present study (e.g., fig. 2(b)). It was necessary to determine the error indirectly from the over-all system transfer function $Y_pY_c/1+Y_pY_c$, since the total tracking-error results are not provided in reference 8. The time-variable results (60 to 120 seconds, fig. 16) are shown dotted because they are determined from data which are inherently less precise than the time-invariant results (see ref. 8). The deduced tracking error (fig. 16) shows that adaptation occurred within about 15 to 30 seconds of the start of the change in dynamics. As indicated in figure 16, the mean-squared error increased about five-fold as the vehicle dynamics changed from unit gain to pure integration. The associated open-loop human transfer function (fig. 17) indicate that the subjects reduced both gain and phase lag appreciably as they adapted to the change in vehicle dynamics.

APPENDIX B

TIME-INVARIANT PILOT MODEL CHARACTERISTICS

A summary of pilot-model characteristics, taken from reference 1, is reproduced in figure 18. These results show the time-invariant, pilot response characteristics (determined by the performance-matching technique described in ref. 1) for the wide range of vehicle longitudinal short-period dynamics covered in the reference 1 study. Also provided in figure 18 (dashed lines) are the changes in gain and lead required for the pilot to adapt to the various simulated SAS failures considered in the present study. These results show that the damper failures at high short-period frequencies (cases A and B) required primarily a reduction in gain K_p. Damper failure at low short-period frequency (case C) required a simultaneous reduction in gain and a large increase in lead. For the two cases involving failures of static stability augmenters, a simultaneous reduction in gain and increase in lead was required for case D, while case E required primarily an increase in lead.

REFERENCES

1. Sadoff, Melvin, McFadden, Norman M., and Heinle, Donovan R.: A Study of Longitudinal Control Problems at Low and Negative Damping and Stability With Emphasis on Effects of Motion Cues. NASA TN D-348, 1961.

2. McFadden, Norman M., Vomaske, Richard F., and Heinle, Donovan R.: Flight Investigation Using Variable-Stability Airplanes of Minimum Stability Requirements for High-Speed, High-Altitude Vehicles. NASA TN D-779, 1961.

3. McNeill, Walter E., and Vomaske, Richard F.: A Flight Investigation To Determine the Lateral Oscillatory Damping Acceptable for an Airplane in the Landing Approach. NASA MEMO 12-10-58A, 1959.

4. Creer, Brent Y., Stewart, John D., Merrick, Robert B., and Drinkwater, Fred J., III: A Pilot Opinion Study of Lateral Control Requirements for Fighter-Type Aircraft. NASA MEMO 1-29-59A, 1959.

5. Vomaske, Richard F., Sadoff, Melvin, and Drinkwater, Fred J., III: The Effect of Lateral-Directional Control Coupling on Pilot Control of an Airplane as Determined in Flight and in a Fixed-Base Flight Simulator. NASA TN D-1141, 1961.

6. Creer, Brent Y., Heinle, Donovan R., and Wingrove, Rodney C.: Study of Stability and Control Characteristics of Atmosphere-Entry Type Aircraft Through Use of Piloted Flight Simulators. Paper No. 59-129, Inst. Aero. Sci., 1959.

7. Hall, Ian A.M.: Effects of Controlled Element on the Human Pilot. WADC Tech. Rep. 57-509, Aug. 1958.

8. Sheridan, Thomas B.: Time Variable Dynamics of Human Operator Systems. AFCRC-TN-60-169, March 1960.

9. Sadoff, Melvin: The Effects of Longitudinal Control-System Dynamics on Pilot Opinion and Response Characteristics as Determined From Flight Tests and From Ground Simulator Studies. NASA MEMO 10-1-58A, 1958.

10. Ashkenas, Irving L., and McRuer, Duane T.: The Determination of Lateral Handling Quality Requirements From Airframe-Human Pilot System Studies. WADC TR 59-135, June 1959.

11. McRuer, Duane T., Ashkenas, Irving L., and Guerre, C. L.: A Systems Analysis View of Longitudinal Flying Qualities. WADD TR 60-43, Jan. 1960.

TABLE I.- 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

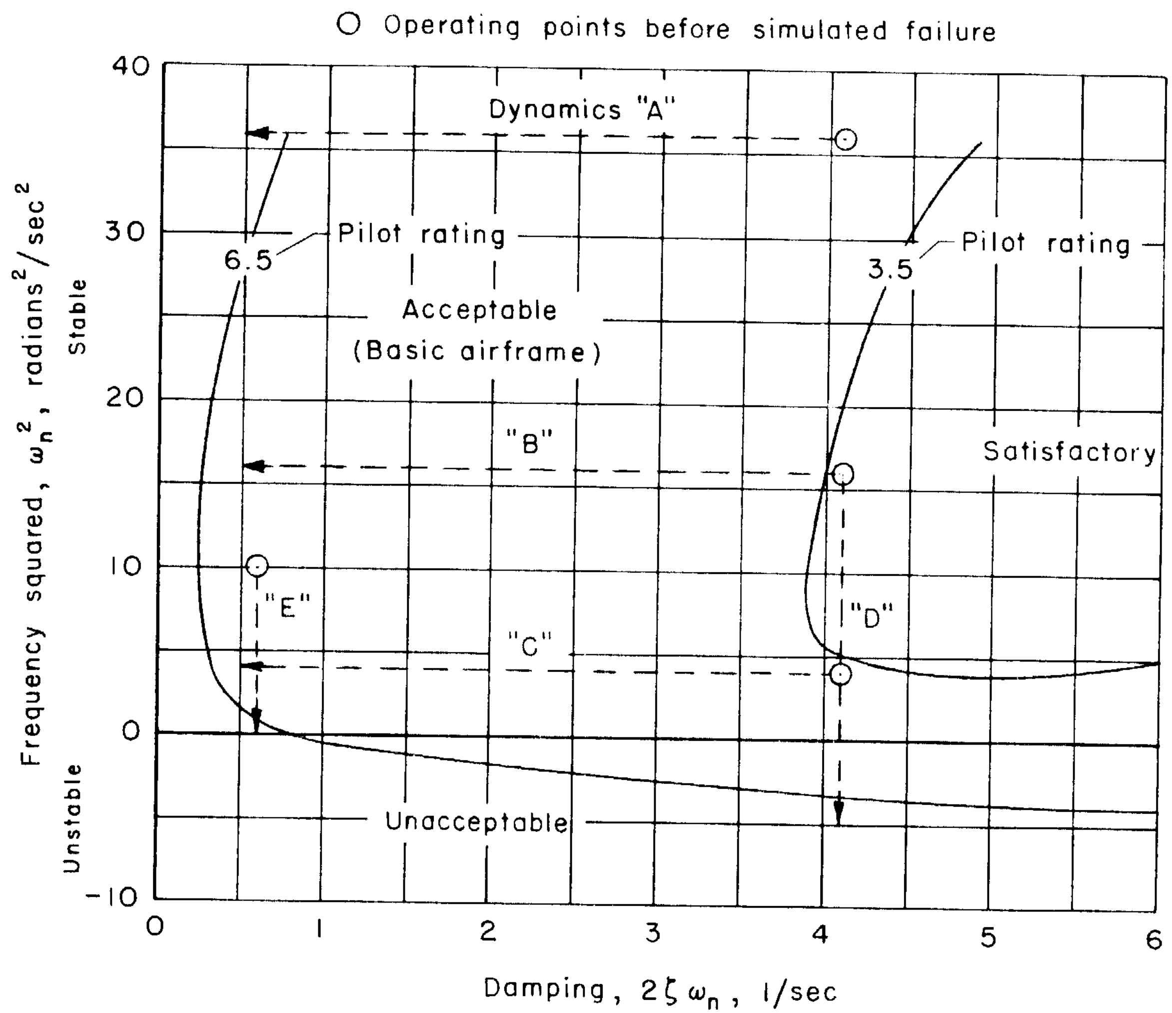
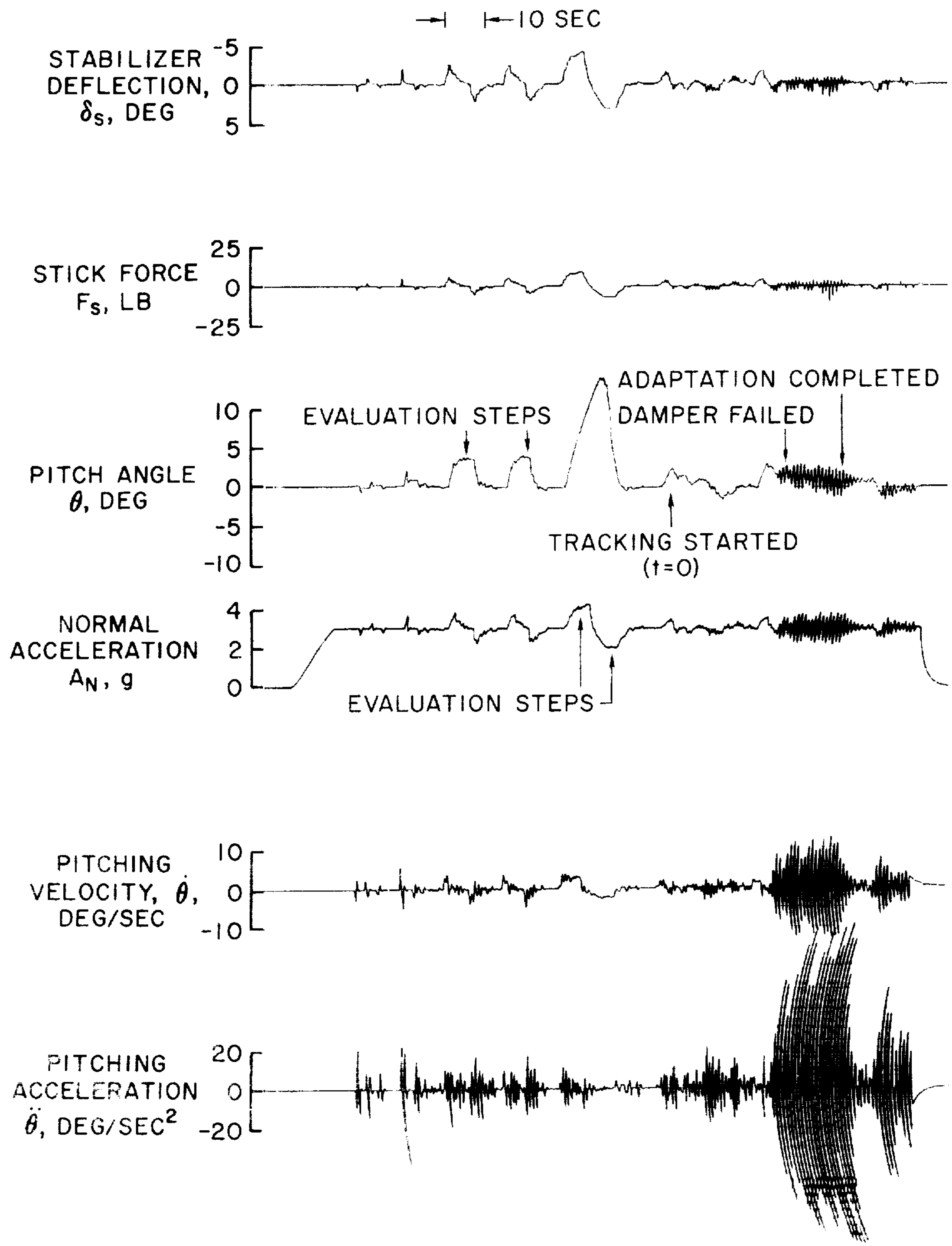
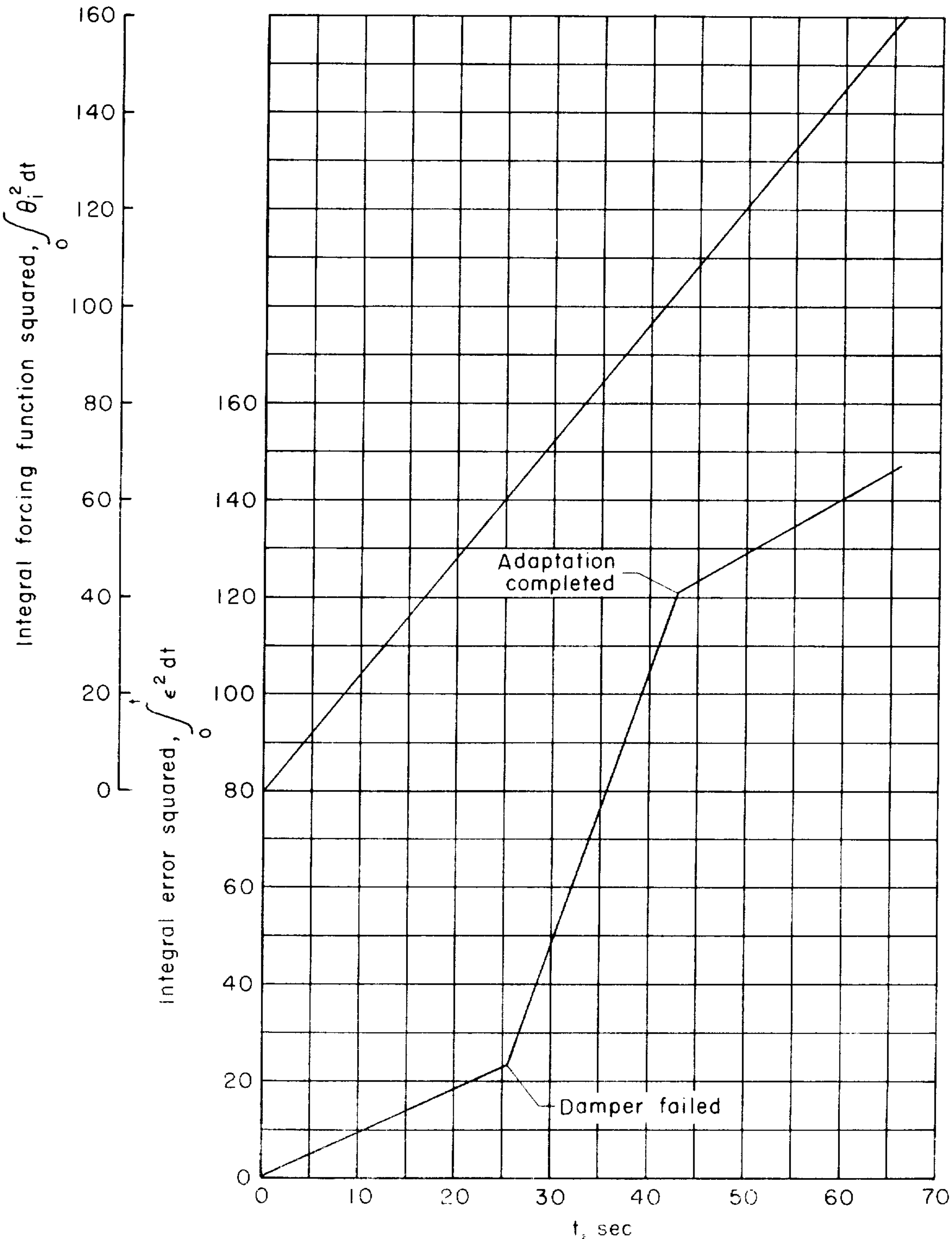


Figure 1.- Stability augmentation system failures considered in centrifuge flight simulator study.



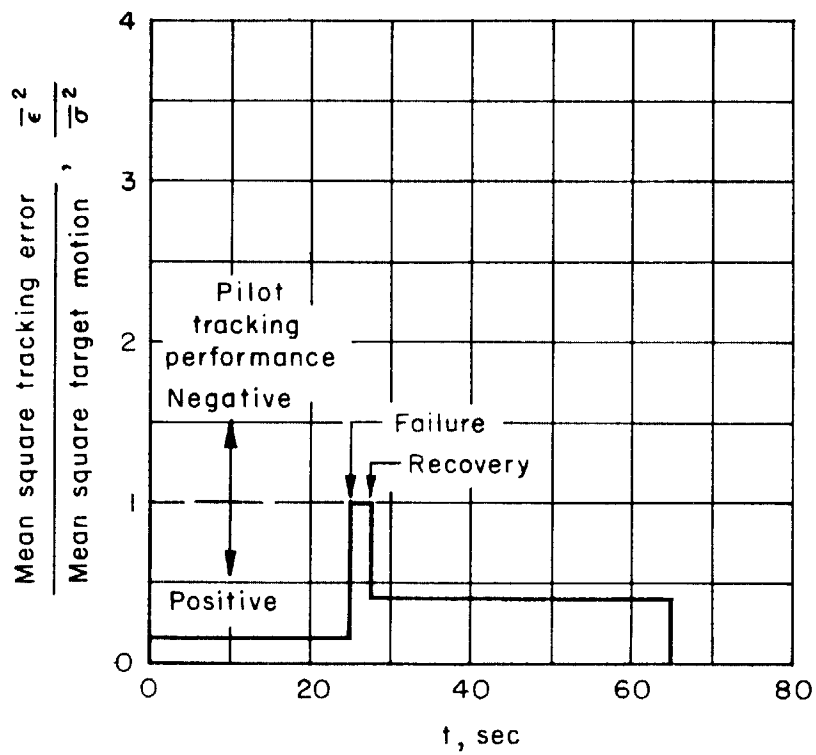
(a) Aircraft response.

Figure 2.- Time histories of typical pitch-damper failure.

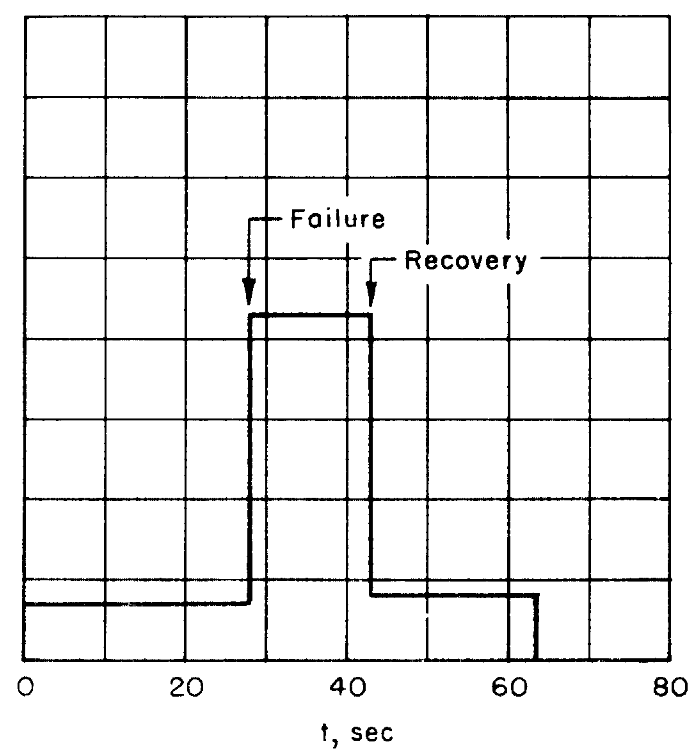


(b) Tracking performance.

Figure 2.- Concluded.

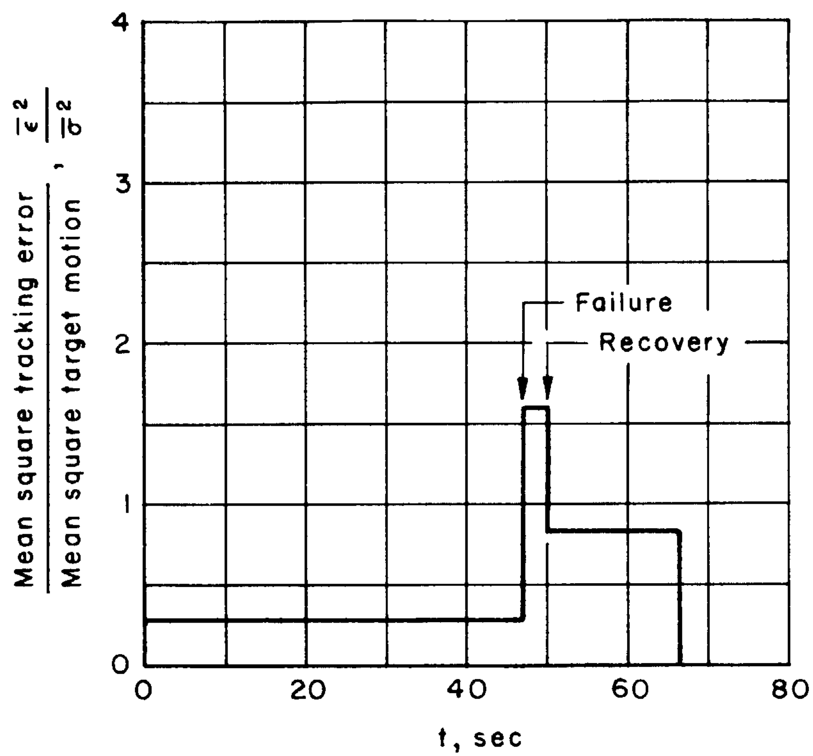


(a) Fixed cab.

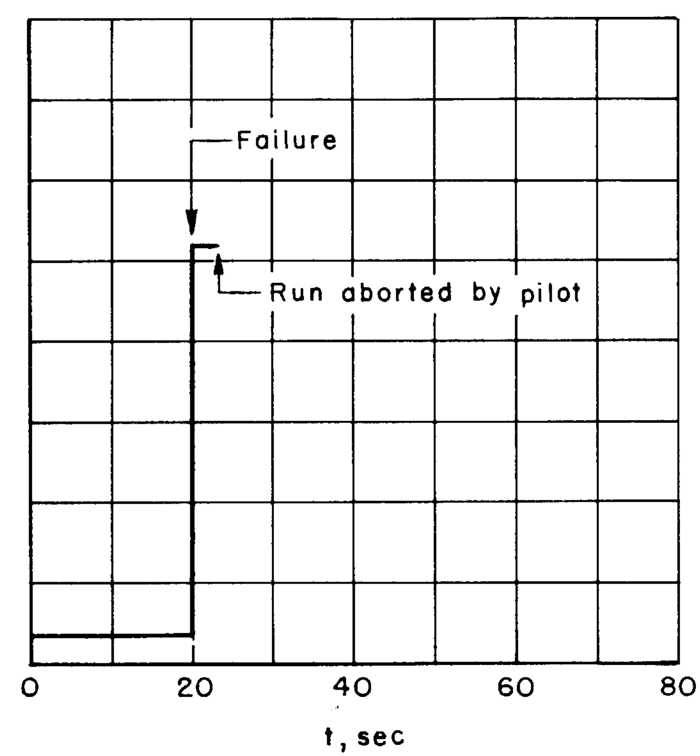


(b) Moving cab.

Figure 3.- Effect of simulator motions on assessment of control problem resulting from pitch-damper failures; case A (fig. 1), pilot A.

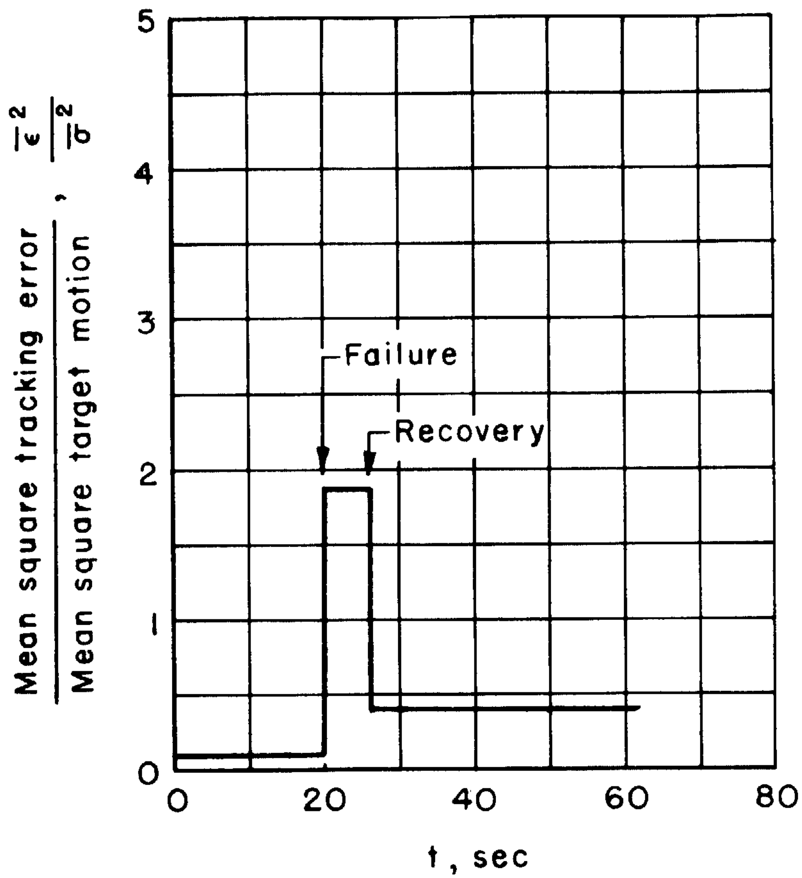


(a) Fixed cab.

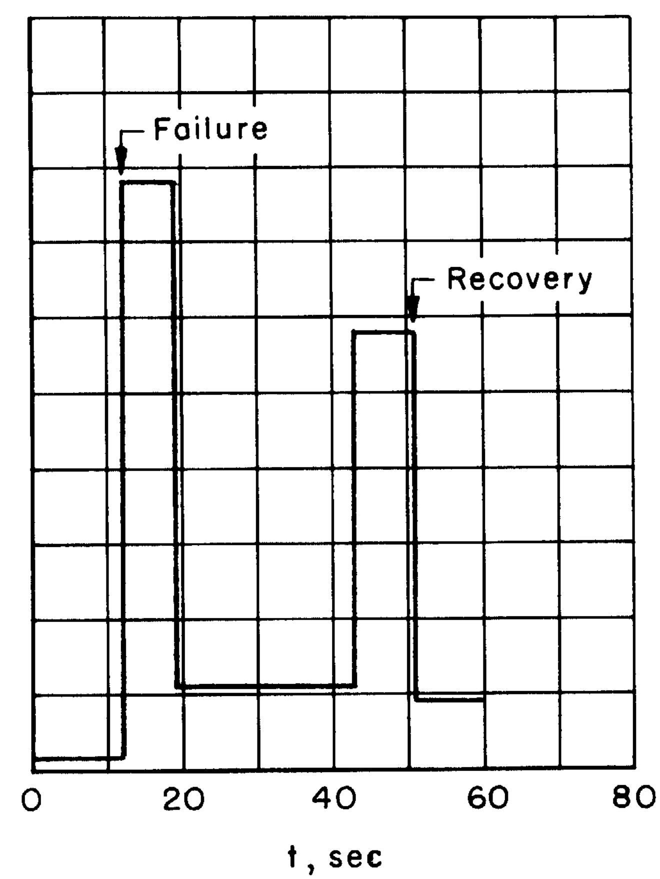


(b) Moving cab.

Figure 4.- Effect of simulator motions on pilot performance; case B, pilot B.

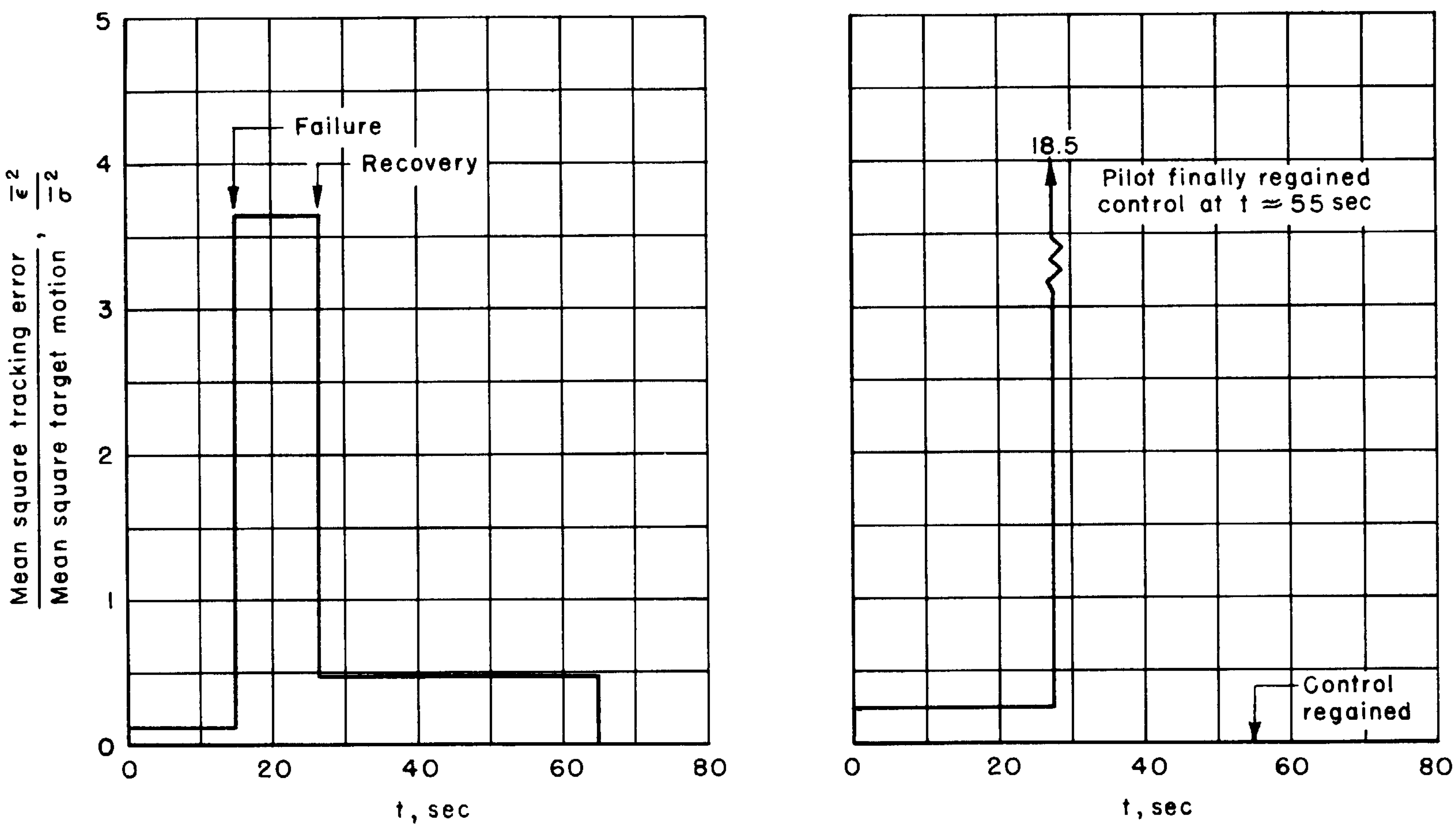


(a) Fixed cab.



(b) Moving cab.

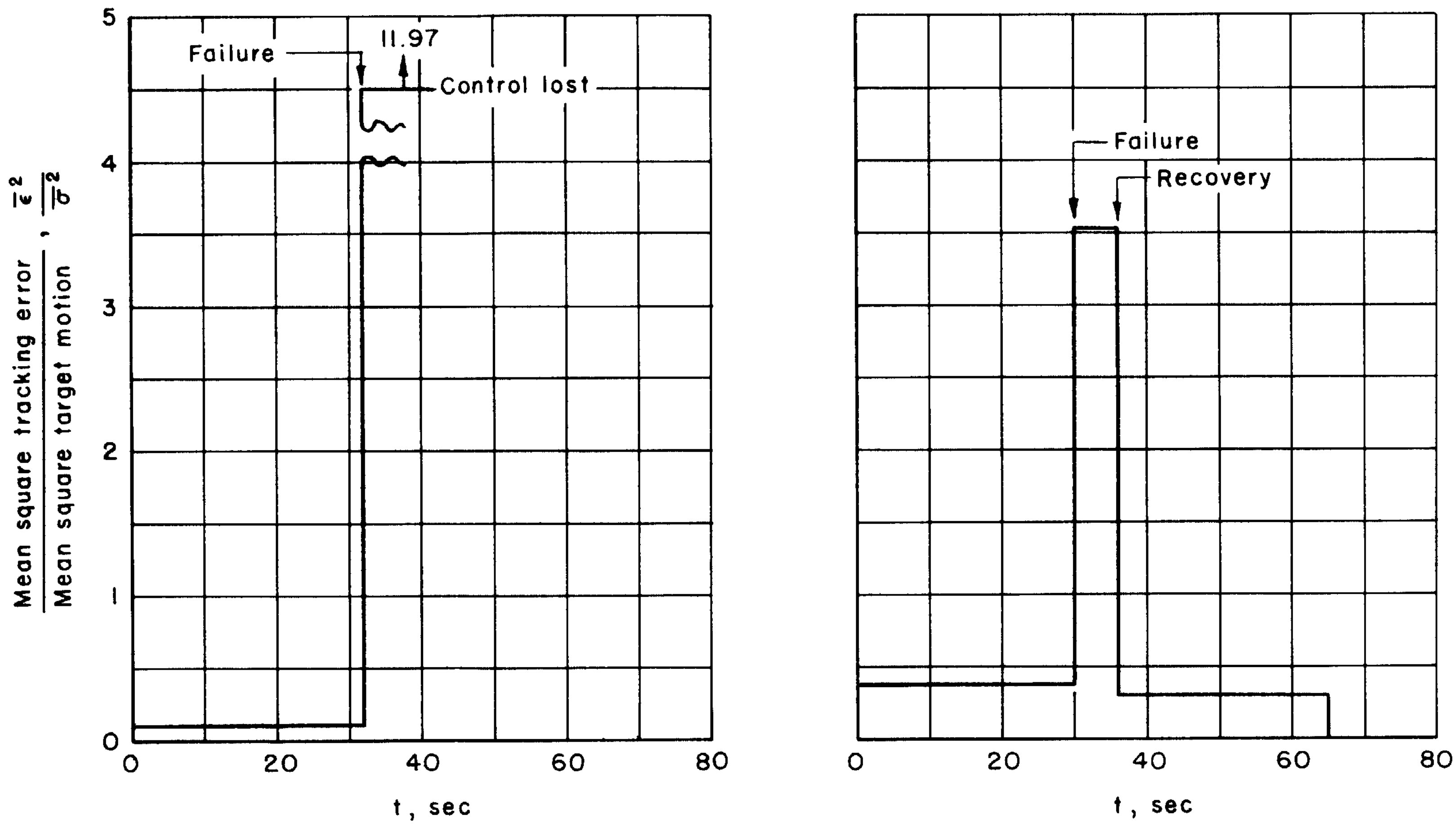
Figure 5.- Effect of simulator motions on pilot performance; case C, pilot B.



(a) Fixed cab.

(b) Moving cab.

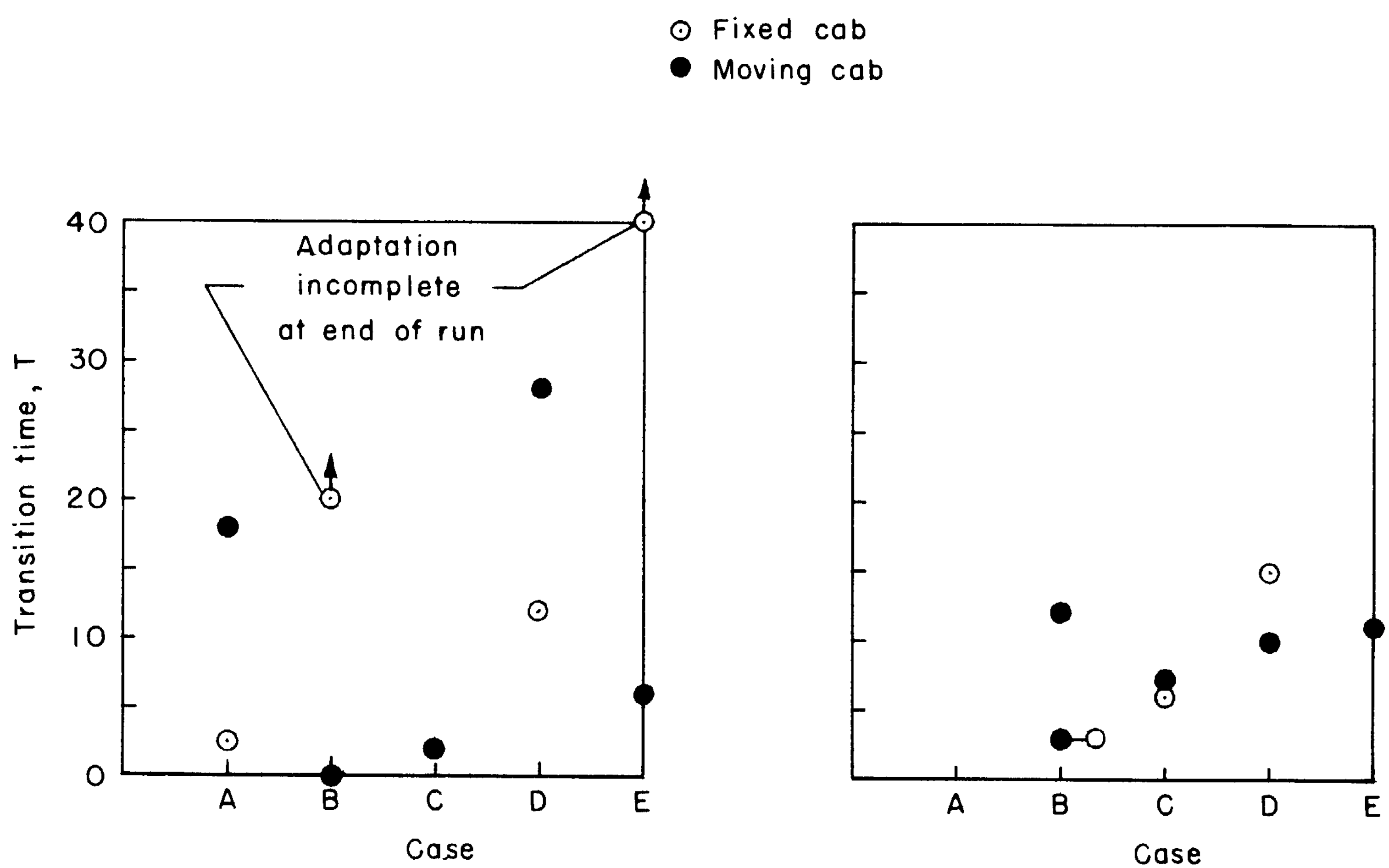
Figure 6.- Effect of simulator motions on pilot performance; case D, pilot A.



(a) Fixed cab.

(b) Moving cab.

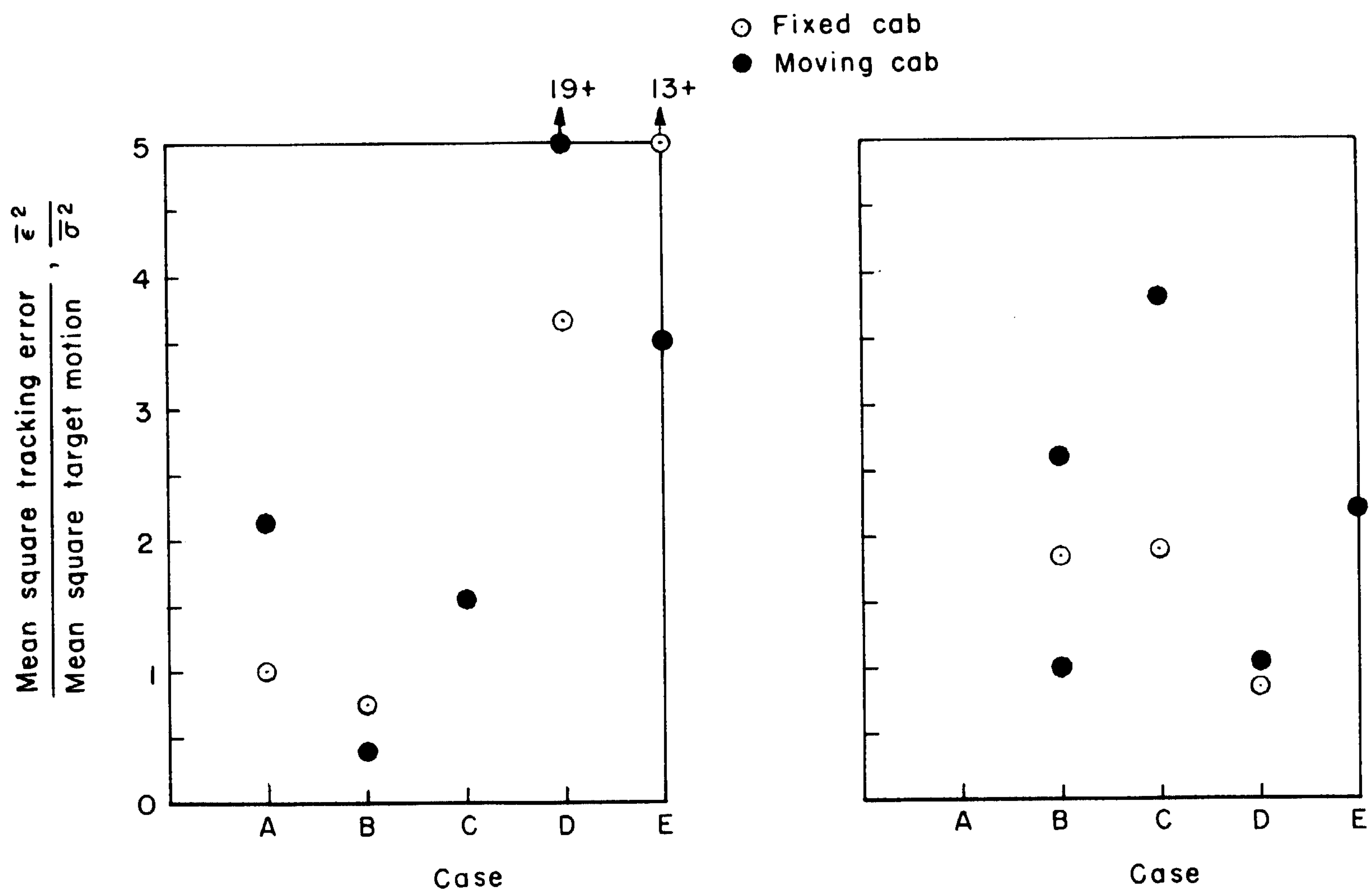
Figure 7.- Effect of simulator motions on pilot performance; case E, pilot A.



(a) Pilot A.

(b) Pilot B.

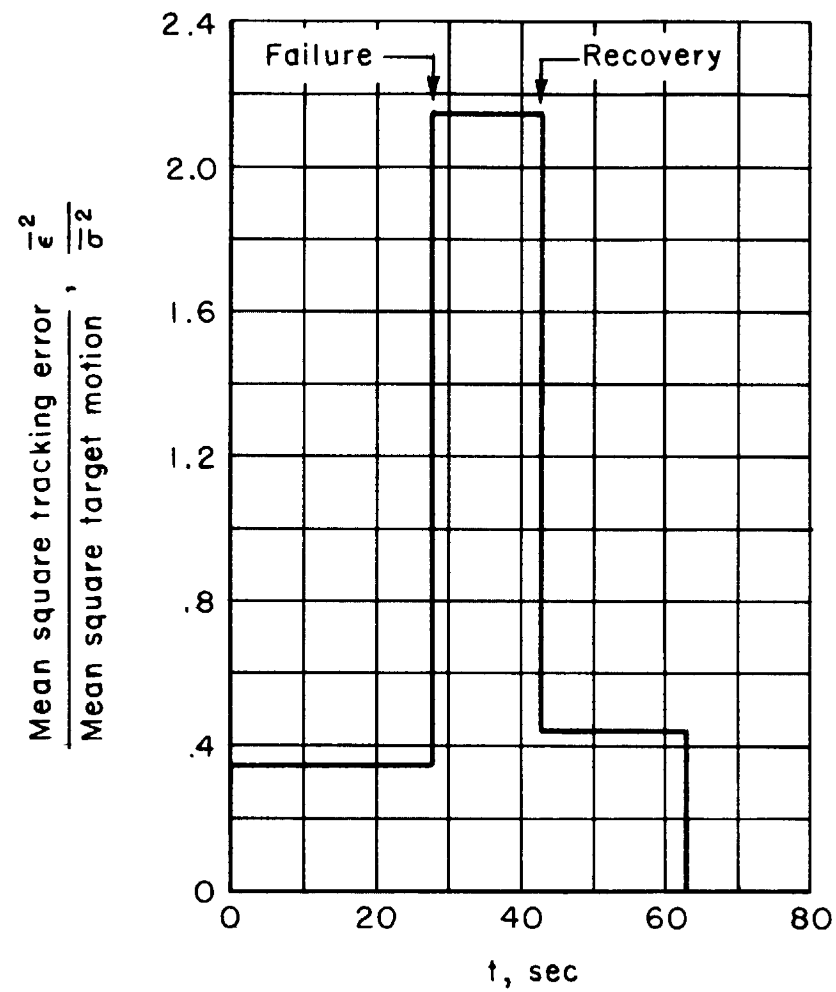
Figure 8.- Comparative fixed-cab and moving-cab pilot adaptation time.



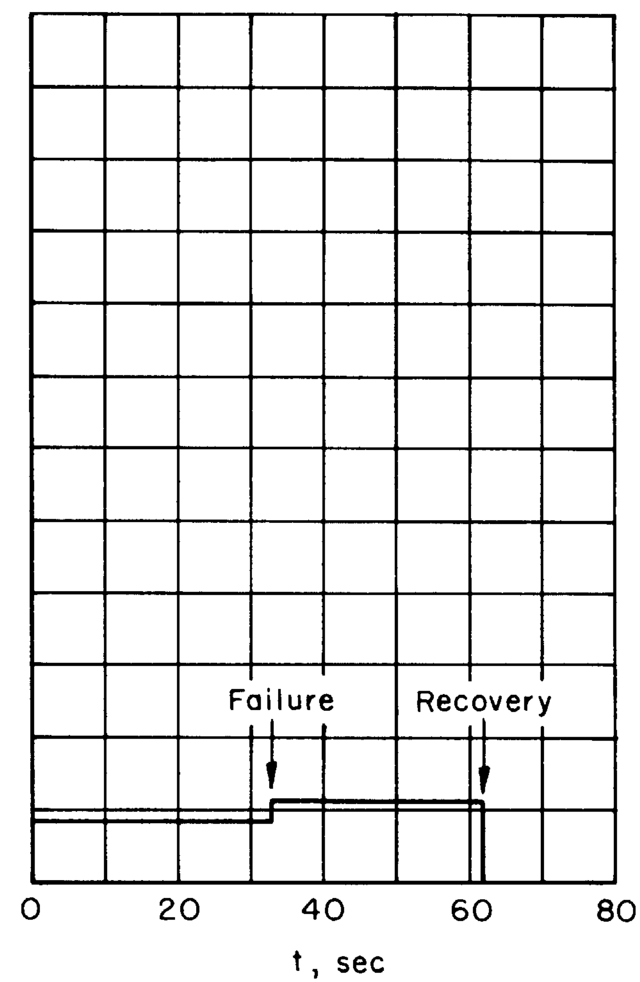
(a) Pilot A.

(b) Pilot B.

Figure 9.- Comparative fixed-cab and moving-cab tracking error during transition.

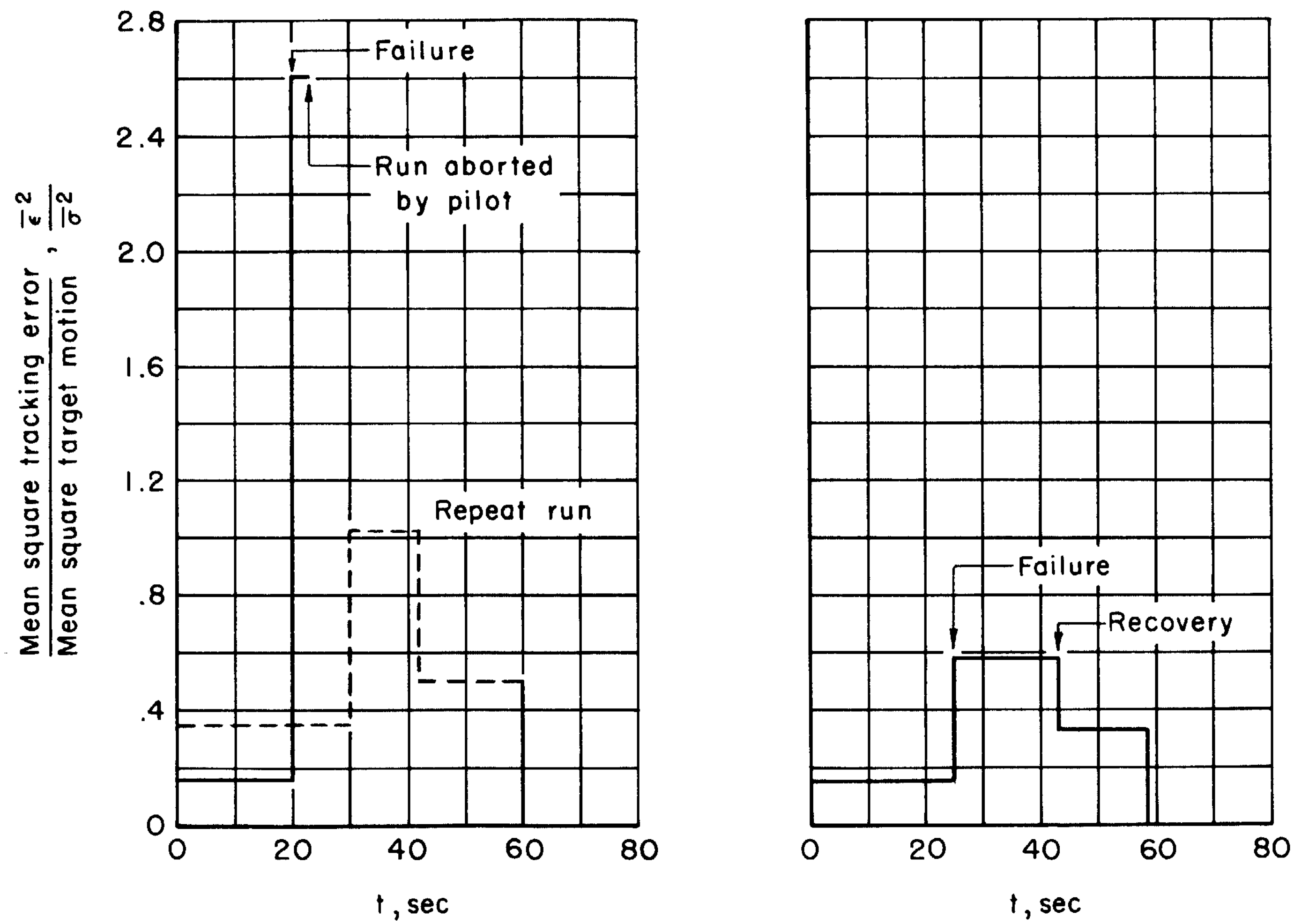


(a) Center stick.



(b) Pencil controller.

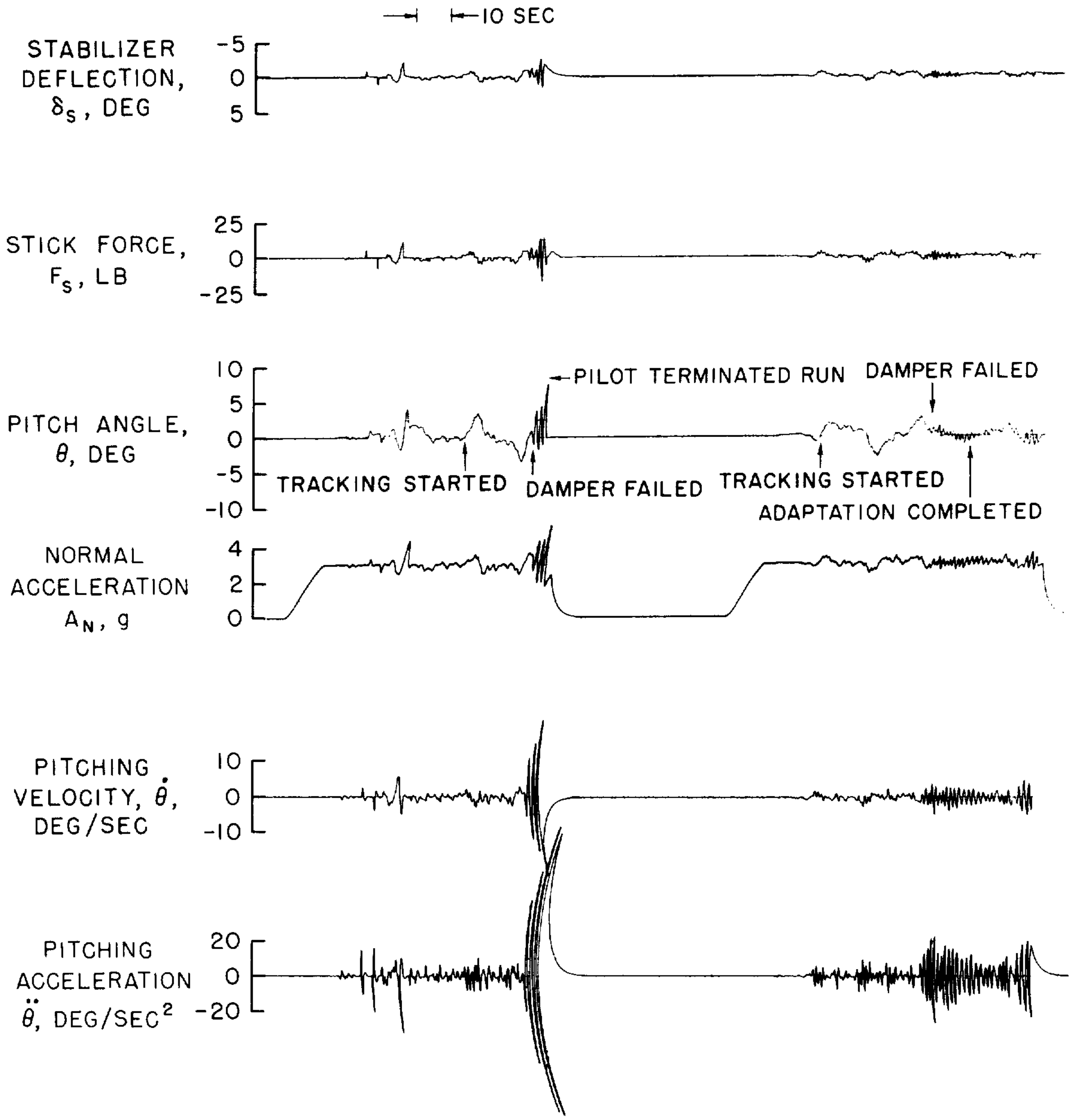
Figure 10.- Comparative pilot performance with center stick and with pencil type side-arm controller; case A, moving cab; pilot A.



(a) Center stick.

(b) Pencil controller.

Figure 11.- Comparative pilot performance with center stick and with pencil type side-arm controller; case B, moving cab; pilot B.



(a) Initial run. (b) Repeat run.

Figure 12.- Moving-simulator evaluation of pilot's ability to cope with sudden pitch-damper failure; case B (fig. 1).

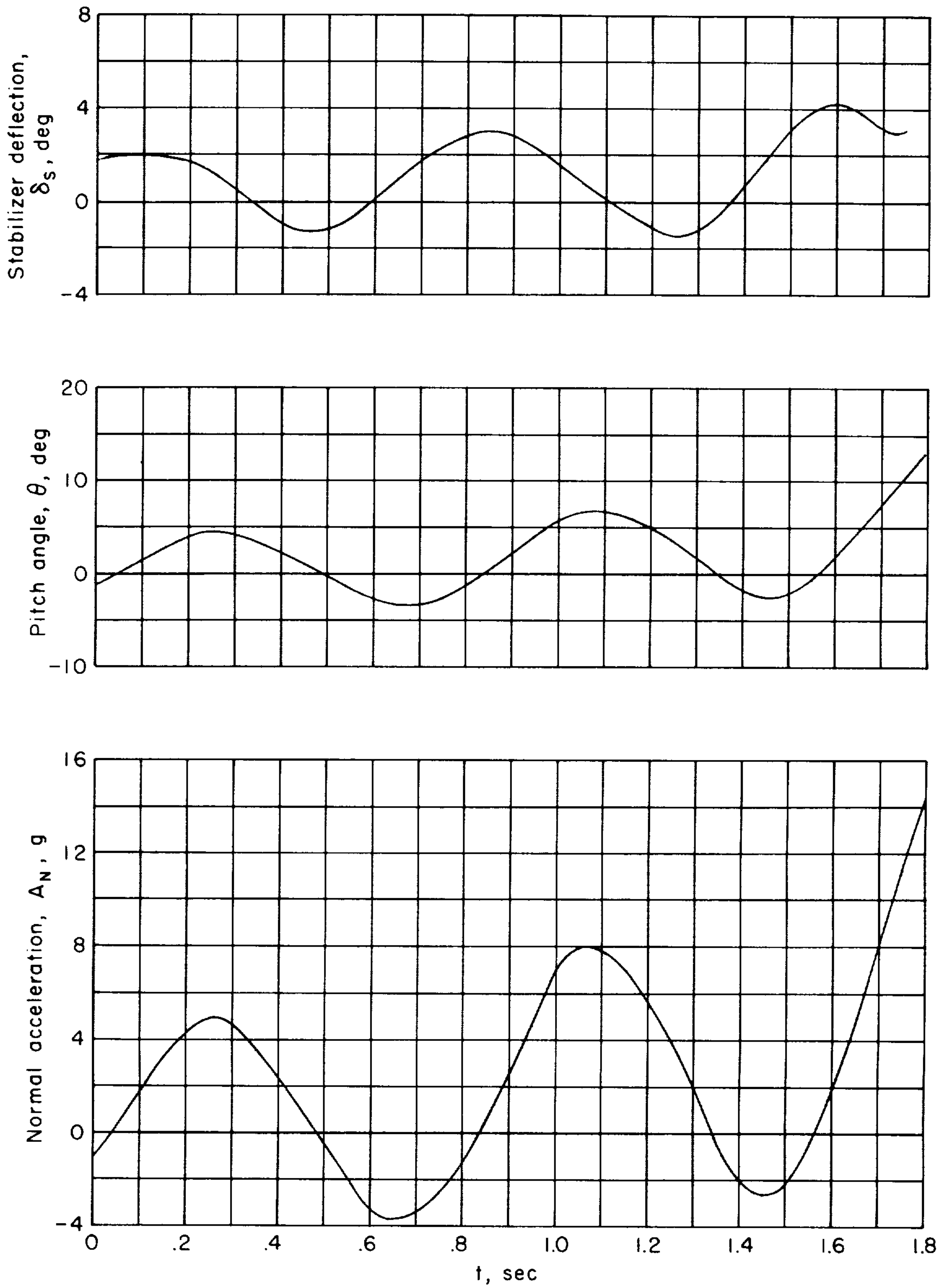
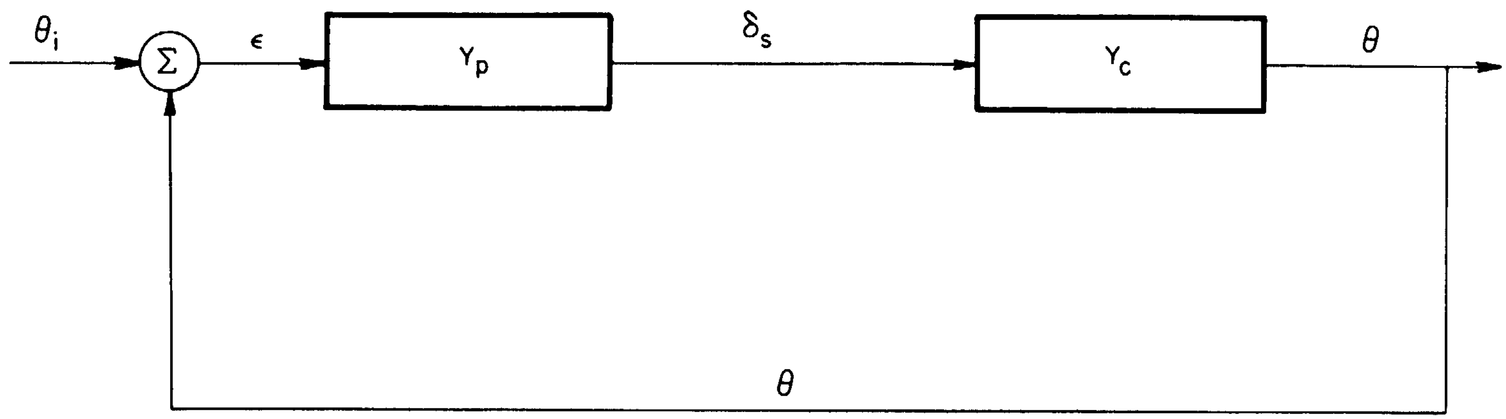
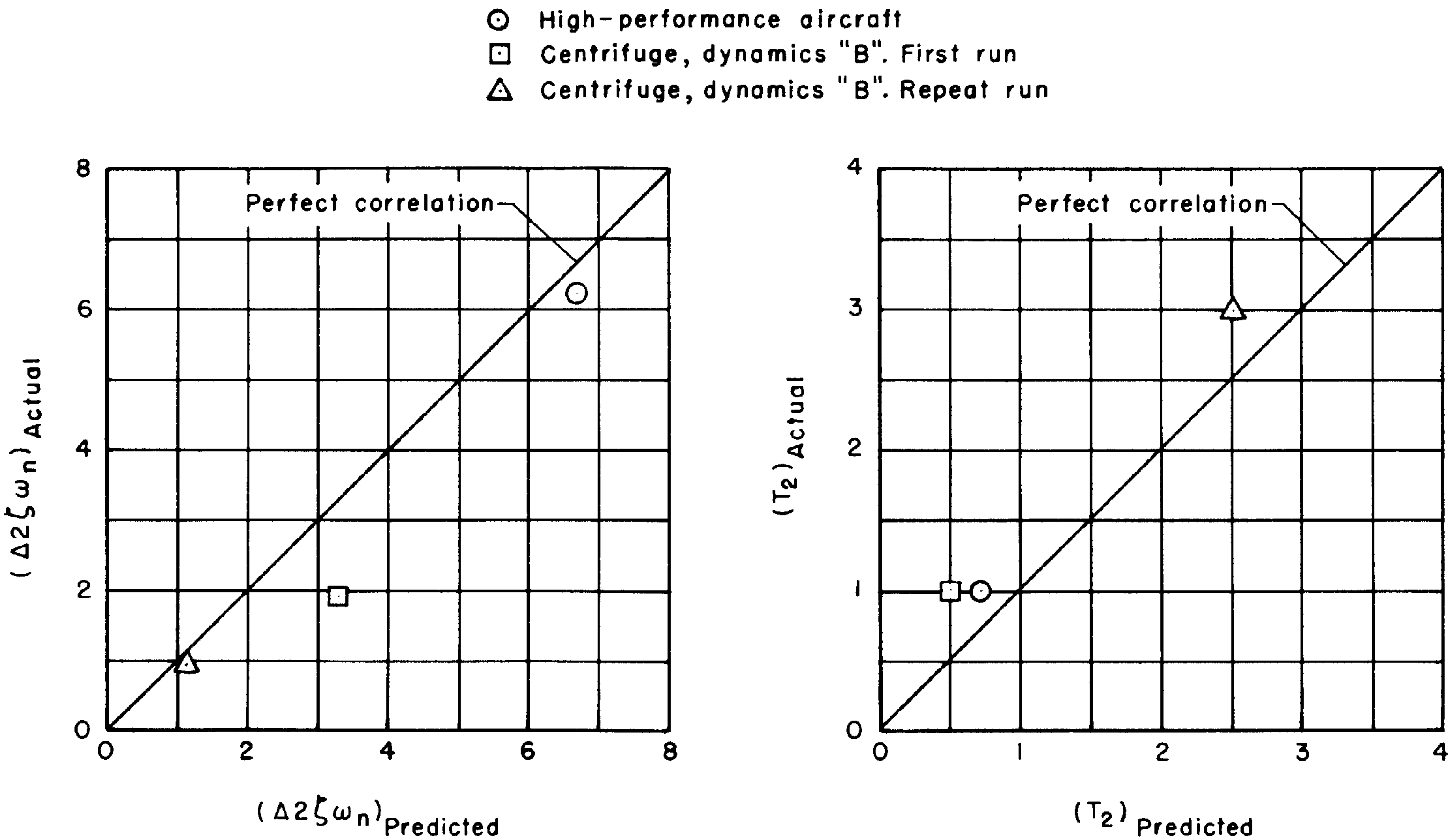


Figure 13.- Example of pilot loss of control in flight.



$$Y_p = K_p e^{-\tau s}(1 + T_L s) \qquad Y_c = \frac{C_0 + C_1 s}{s(s^2 + 2\zeta\omega_n s + \omega_n^2)}$$

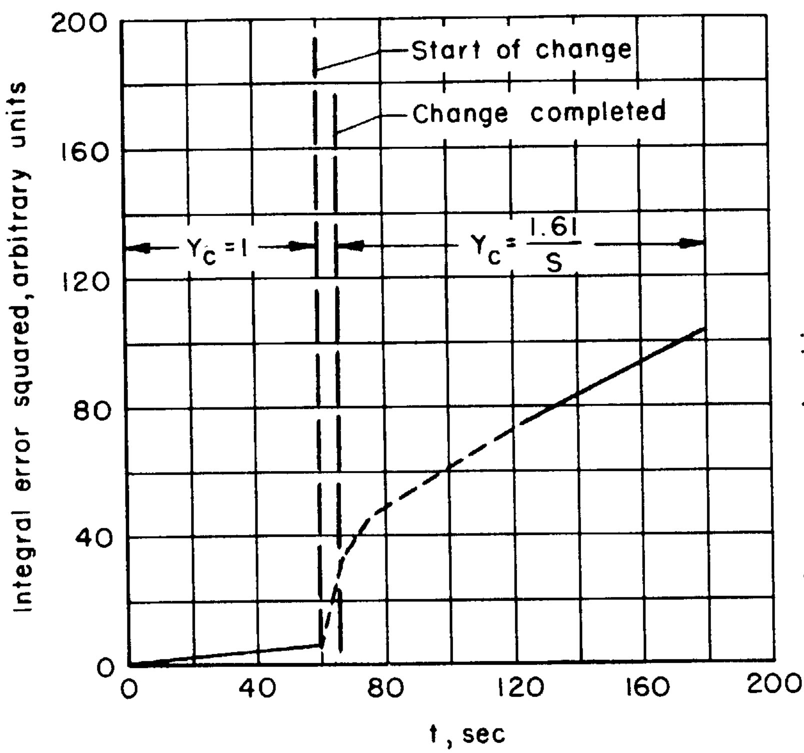
Figure 14.- Pilot-aircraft system block diagram.



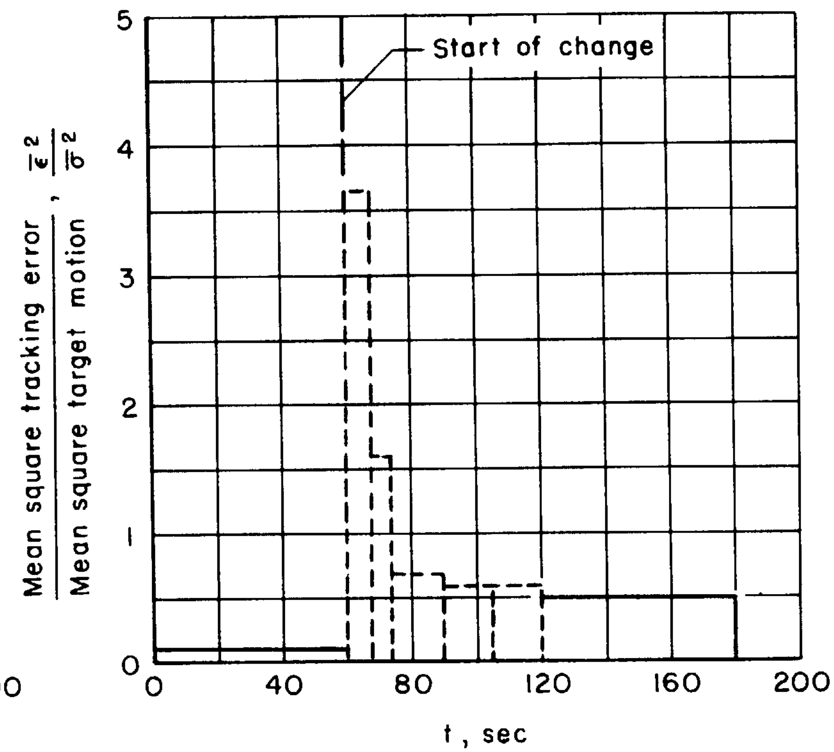
(a) Damping decrement.

(b) Divergence time to double amplitude.

Figure 15.- Correlation of predicted and actual results.

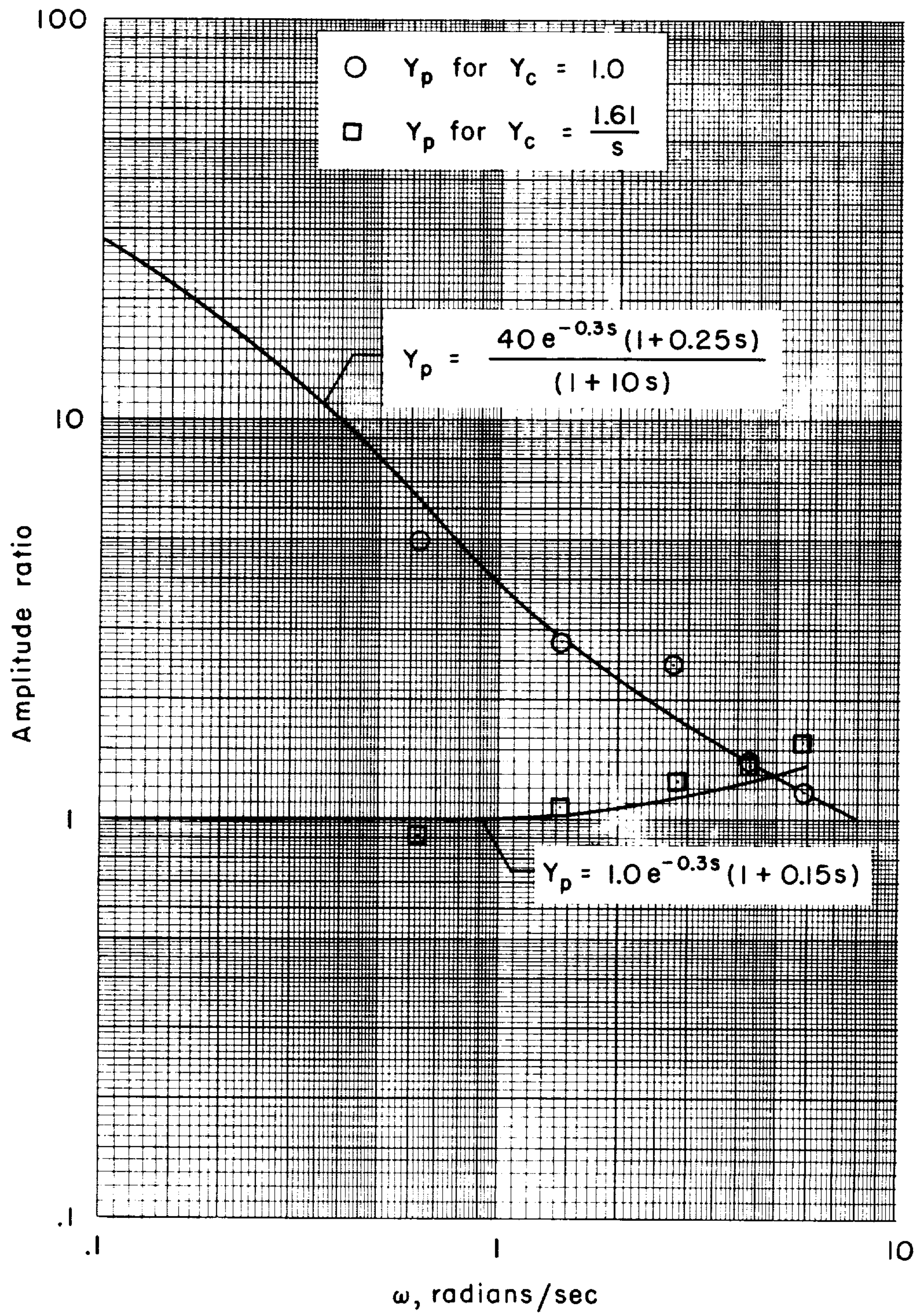


(a) Integral error squared.



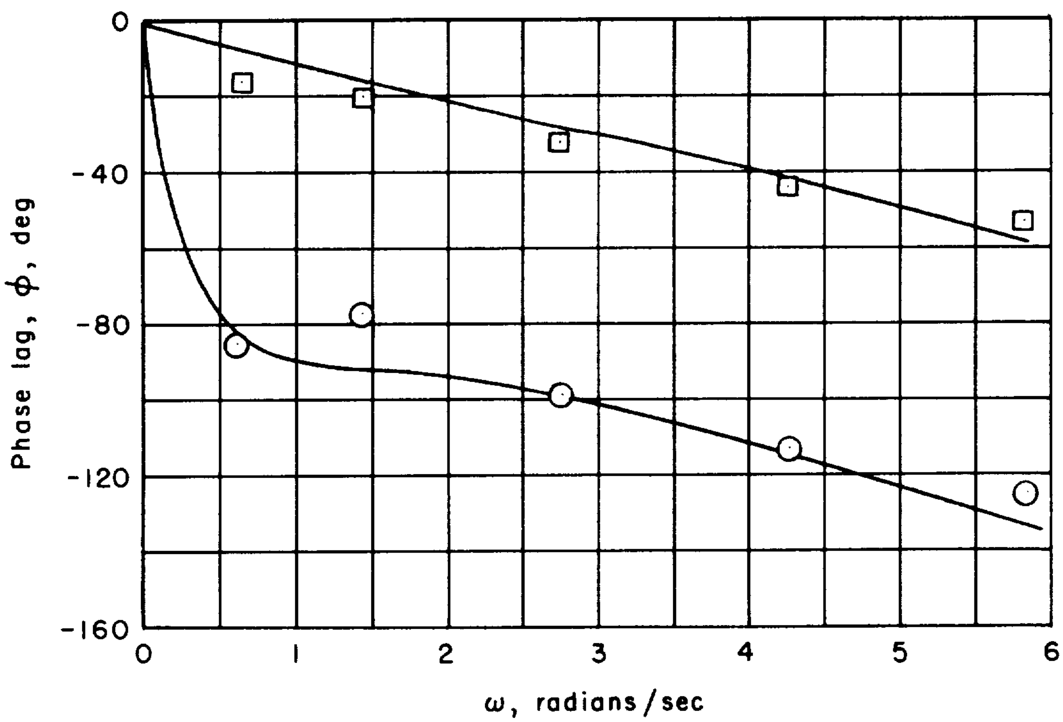
(b) Ratio of mean square error to mean square task input.

Figure 16.- Time histories of deduced tracking error during change in vehicle dynamics from unit gain ($Y_c = 1$) to pure integration ($Y_c = 1.61/s$).



(a) Amplitude ratio, Y_p.

Figure 17.- Time-invariant, open-loop transfer functions.



(b) Phase lag, Y_p.

Figure 17.- Concluded.

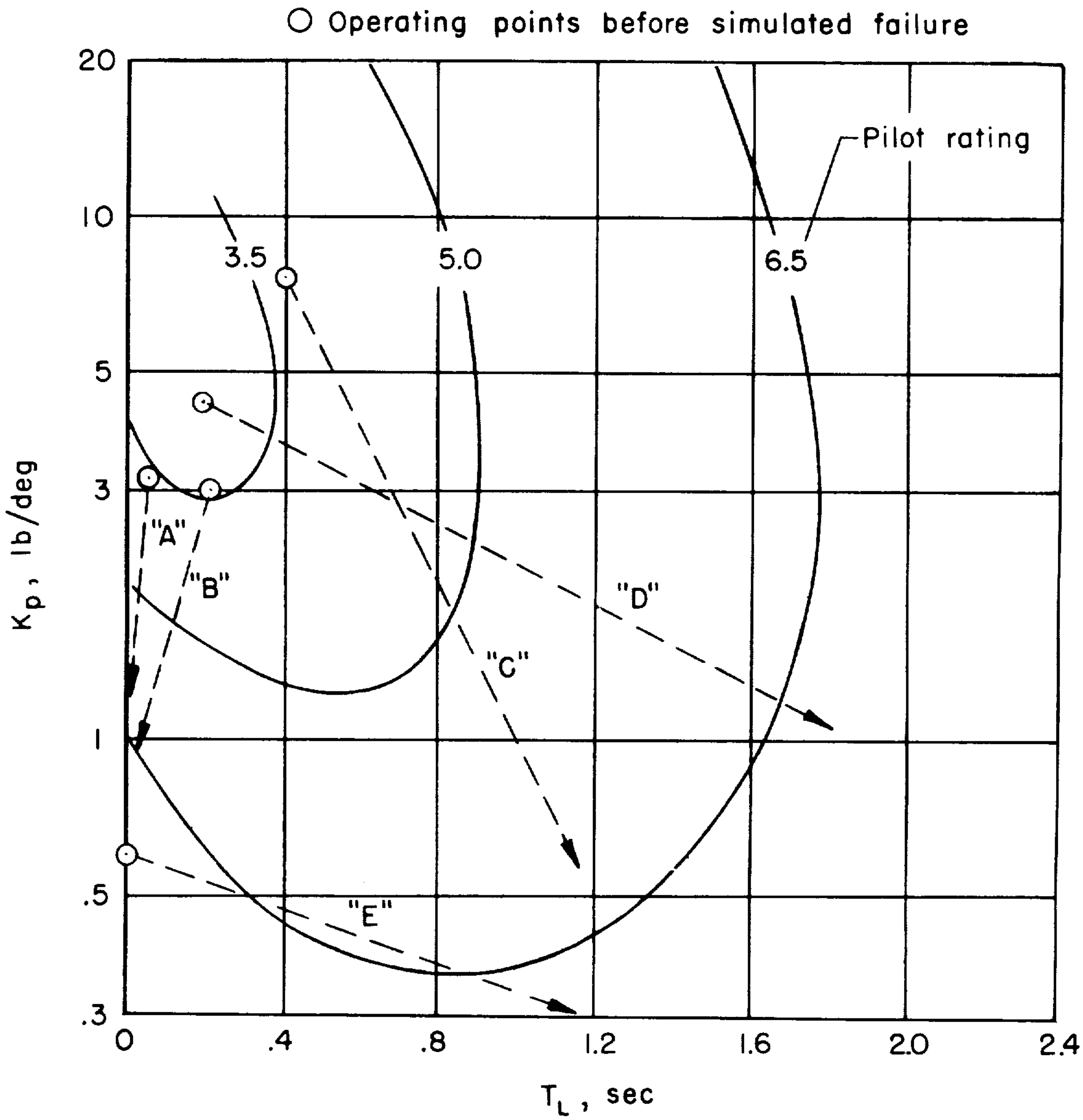


Figure 18.- Summary of time-invariant, pilot-model characteristics, including adaptive changes required for pilot to cope with the various simulated stability augmenter failures considered.