NASA TECHNICAL NOTE

NASA TN D-2710

NASA TN D-2710

EFFECT OF COMBINED LINEAR AND OSCILLATORY ACCELERATION ON PILOT ATTITUDE-CONTROL CAPABILITIES

by Constantine B. Dolkas and John D. Stewart

Ames Research Center
Moffett Field, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1965

NASA TN D-2710

EFFECT OF COMBINED LINEAR AND OSCILLATORY ACCELERATION ON PILOT ATTITUDE-CONTROL CAPABILITIES

By Constantine B. Dolkas and John D. Stewart

Ames Research Center
Moffett Field, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Office of Technical Services, Department of Commerce,
Washington, D.C. 20230 -- Price $2.00

TABLE OF CONTENTS

	Page
SUMMARY	1
INTRODUCTION	1
SYMBOLS	2
SIMULATION EQUIPMENT	3
Motion Generators	3
Vehicle Dynamics	4
Control and Display	4
Pilot Restraint Equipment	4
Tests and Procedure	4
RESULTS AND DISCUSSION	6
Pilot Opinion	6
Control-Task Performance	7
Transient Effects of Autopilot Failures	8
Effects of Engine-Servo Rate Limiting	9
SUMMARY OF RESULTS	9
REFERENCES	10
TABLES	12
FIGURES	15

EFFECT OF COMBINED LINEAR AND OSCILLATORY ACCELERATION ON PILOT ATTITUDE-CONTROL CAPABILITIES

By Constantine B. Dolkas and John D. Stewart

Ames Research Center
Moffett Field, Calif.

SUMMARY

18214

Data are presented to show the effects of superimposing vibration at 11 cycles per second on steady linear acceleration on the tracking ability of a human pilot in a stability- and rate-augmented vehicle with dynamics typical of a large high-thrust rocket. The linear accelerations ranged from 1 to 3.5 g and the oscillatory stresses varied from 0 to ±3.0 g at 11 cps. A random-appearing compensatory tracking problem was presented to the pilot in the pitch plane, although the pilot controlled both pitch and yaw. No attempt was made in this study to simulate additional pilot tasks such as monitoring of critical launch vehicle and spacecraft performance and status displays which would be required in the real situation. Various damper-failure situations were investigated, and certain characteristics due to autopilot nonlinearities were studied. Effects on the tracking efficiency of dividing the pilot's attention between pitch and yaw channels were also examined.

INTRODUCTION

AUTHOR

If man is to be used effectively and reliably in advanced aerospace guidance and control systems, more must be known about his performance in certain particularly stressful environments. The feasibility of a pilot controlling attitude in the atmosphere entry maneuver was evaluated, for example, in studies of the effects of steady linear acceleration (refs. 1 through 8). Tolerable physical limits and anticipated tracking proficiencies of human pilots were ascertained and feasible operating envelopes for such vehicles were established.

Consideration is now being given, for potential gains in system reliability, to a pilot controlling large, flexible, high-thrust launch vehicles, which superimpose a longitudinal vibration stress on a relatively steady linear acceleration. The effects of vibration have been considered separately from an aeromedical viewpoint in references 9 through 16, which contain data on the kinesthetic response and the effects on the visceral organs and visual system. However, as pointed out in reference 17, caution must be used in interpreting these types of data to establish pilot task performance criteria and operating limits. Further, little is known concerning task performance under combined linear and oscillatory stresses.

For these reasons, as part of a general program of research on environmental stress, the effects of simultaneous vibration and linear acceleration on pilot performance were studied on the five-degree-of-freedom simulator at Ames Research Center. Specifically, pilots were subjected (on an open-loop basis) to nominal longitudinal vibratory stresses at 11 cps of up to ±3.0 g superimposed on nominal steady loads of 1.0 g, 2.0 g, and 3.5 g. These stresses are typical of a class of large liquid propelled rockets. The pilots were given a random-appearing tracking task and were scored according to a root-mean-square performance criterion, in addition to noting subjective pilot opinion. The dynamics simulated consisted of closed-loop attitude and rate stabilization of the rigid body pitch and yaw modes of an advanced booster vehicle. Certain associated problems were investigated briefly, including autopilot failure (which was an extension of other work (ref. 18)) and the effects of engine thrust-axis servo rate limiting.

SYMBOLS

A_X acceleration factor in longitudinal direction, X (ratio of accelerating force to weight), g

A_Y acceleration factor in lateral direction, Y (ratio of accelerating force to weight), g

A_Z acceleration factor in normal direction, Z (ratio of accelerating force to weight), g

F pilot control force, lb

K_A airframe gain

K_E engine servo gain

s Laplace transform variable

SAS Stability Augmentation System

t time, sec

T.E. pilot tracking efficiency, $\dfrac{100\int(\theta_i^2 - \theta_\epsilon^2)dt}{\int\theta_i^2\,dt}$

δ_e error signal input to engine servo, deg

δ_H human operator control output, in. (maximum deflection of δ_H equivalent to 10° δ_s)

δ_s engine servo output, deg

θ_i task input, pitch, deg

θ_ϵ tracking error, pitch, deg

τ engine servo time constant, sec

ψ_ϵ yaw vehicle error, deg

ω angular frequency, radians/sec

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

SIMULATION EQUIPMENT

Motion Generators

The principal facility used was the five-degree-of-freedom simulator at the Ames Research Center (fig. 1). The pilot sat in a cab oriented as shown in figure 2(a) so that steady accelerations were imposed perpendicular to the plane of the subject's chest in the eyeballs-in direction, according to the convention established in reference 2. The loads were imposed on an open-loop basis (see fig. 5), and the dynamic response of the launch vehicle was apparent to the pilot only through a compensatory visual display; that is, the display showed the pilot only the error in tracking and not the vehicle attitude.

To simulate typical oscillatory stresses of 11 cps, the pilot seat was vibrated sinusoidally by an especially designed device. The device was a hydraulically driven servo which produced translational motion along the axis of the vector sum resulting from the natural force of gravity and the centrifugal force. A counterbalancing weight minimized the effect of oscillatory loads on the centrifuge. A hydraulic pump near the rotational axis of the centrifuge supplied fluid to a vertically mounted cylinder which produced the seat motion through a toggle linkage. Some movement of the counterweight was also allowed through this toggle switch. (See fig. 2(b)). A limitation of the device was that the amplitude of vibration could not equal or exceed the steady-state load (i.e., a positive force had to be present at all times).

The accelerations of the chair in the X direction, A_X, resulting from the operation of this device are described in figure 3. The outputs of accelerometers fixed to the chair were fed into a spectrum analyzer to detect the actual amplitudes and frequencies present in the records. The nominal input amplitudes of acceleration values are as shown in the figure legend and the actual outputs from the analyzer are plotted on the ordinate. The data show the existence of energy at higher frequencies. The algebraic sum of the actual outputs from all the frequencies is shown in figure 4 as a function of the nominal input values. The discrepancies from the nominal values are assumed due to phase differences in the components of vibration. It is emphasized that the values of steady state or vibratory g in the figures of this report are the nominal input values. The actual values can be obtained from figure 4.

Vehicle Dynamics

The vehicle dynamics simulated (fig. 5) were typical of large high-thrust booster rockets, and the flight condition simulated was a high-altitude first-stage situation. The airframe itself was unstable (see fig. 5); however, it was aided in the pitch and yaw channels by an autopilot with typical parameters as shown in figure 5. Except for a brief series of runs, the engine position servo (thrust axis) was rate limited at $\pm 20^{\circ}$/sec and position limited at $\pm 10^{\circ}$. Some tests were made with rate limits of $\pm 5^{\circ}$/sec and $\pm 50^{\circ}$/sec.

Control and Display

Figure 6 is a general view of the cab showing the display and controller. The force-deflection characteristics are presented in figure 7. The controller was designed to allow pitch and yaw control but to prevent the 11 cps longitudinal vibrations from being fed through to the pilot output by making the pitch and yaw controls perpendicular to the A_X acceleration. Analysis of a run through a spectrum analyzer shows that there was very little energy present at that frequency.

The compensatory display is shown in figure 6. The horizontal flight direction needle nearest the pilot was driven to indicate pitch attitude error (θ_{ϵ} in fig. 5) with a scaling of 10° error per inch. The vertical line moved to present the heading with no additional closed-loop problem. The airplane symbol and ball remained fixed as references for the moving elements.

Pilot Restraint Equipment

The pilots were restrained by an Air Force B-5 harness, with thigh straps to couple the legs to the seat pan. The harness was tight enough to prevent body movement relative to the seat pan. The subjects also wore Mercury full pressure suit helmets with appropriate liners sized for individual fit. A Navy Mark IV pressure suit communication system was used, and the helmet was attached to the standard neck ring which, in turn, was attached by straps from around the subject's torso. Balsa wood spacers were used for adjusting the eye height to the instrument panel angle for each subject.

Tests and Procedure

The test conditions for this investigation are outlined in table I. All five subjects were NASA research pilots who had extensive experience with the Ames five-degree-of-freedom simulator without the oscillatory environment. All the pilots were tested through the complete steady 2 g series. Because of time limitations, only pilots A and B performed through most of the remaining portion of the program, and only pilot B was tested for the series of sudden pitch damper failures at the highest test g levels in both vibratory and steady-state environments.

Except for unannounced damper failures later in the program, the parameters of the vehicle remained constant and only the stress environment of the pilot was varied. The task presented to the pilots was identical in each case; however, there was no evidence of pilots committing the task to memory.

To ascertain any residual effects of a high stress environment, the pilot was given the task of tracking for 60 seconds under a static 1 g EBD condition immediately before and after the 45-second dynamic run. Since there was no significant difference, this procedure was discontinued toward the latter portion of the program in order to reduce pilot fatigue.

The motion simulator was brought up to speed gradually and the pilot was asked to track throughout the dynamic portion of the run; however, the computation and evaluation (or scoring) was done only in the 45-second portion when the motion simulator was up to speed. Figure 9 illustrates a typical run.

The random-appearing task was a summation of four sine waves, according to the following table. It was identical to that used in reference 8 so that it would have continuity with previous investigations. Positive direction pilot pitch control was programmed to be in the same direction as positive θ_ϵ (as shown in fig. 5).

Sine wave component	Frequency, radians/sec	Relative mean square amplitude
1	0.28	1.0
2	.74	.5
3	1.21	.15
4	1.80	.07

The task input signal, used only in the pitch channel, was scaled so that its maximum excursion corresponded to 5° vehicle attitude, which also corresponded to half of the full display height. Figure 8 shows the power spectrum of the task input signal. The efficiency of the pilot in performing the tracking task was computed quantitatively by the analog computer. The computer used an efficiency circuit determined from the ratio of difference of the mean square task input, $\overline{\theta_i^2}$, and mean square error, $\overline{\theta_\epsilon^2}$, to the mean square of the task input (see ref. 8) or

$$\frac{\frac{100}{T}\int_0^T (\theta_i^2 - \theta_\epsilon^2)dt}{\frac{1}{T}\int_0^T \theta_i^2\, dt}$$

Because of the integration over time, T, the expression for T.E. tends to smooth out variations in efficiency. However, some rapid changes in error, due possibly to momentary pilot inattention or confusion, did occur. Now, the human being in the loop is considered to be a generator of a random process which, in many cases, does change with time. This is essentially a nonstationary time process. However, the T.E.'s obtained and plotted were averaged values for a run and can be considered as results of a quasi-stationary time series. As such, then, the trends of these results are applicable.

To judge the vehicle handling qualities the pilots used the Cooper pilot-rating system, reference 19 (table II). Before the runs were made, the pilots were asked to consider that they were controlling a high-thrust launch vehicle.

RESULTS AND DISCUSSION

Pilot Opinion

Before considering the effects of increasing acceleration loads, it is interesting to compare the pilot opinions of the present high-thrust launch vehicle with those for a conventional airplane with similar dynamics. In the normal 1 g environment with no vibration, and with the pitch and yaw autopilots operating (the vehicle is unstable otherwise), the average pilot rating was about 3 (refer to table II). Reference 2 presents results based on the same piloting task of the present paper, but for a configuration with a wide range of dynamics whose perturbations of motion were also imposed on a centrifuge. The comparison in figure 10 indicates that for the one fixed set of dynamics tested, the pilots rated the launch vehicle the same as an airplane with similar dynamic behavior.

The effect of increasing steady linear acceleration alone is shown in figure 11. As would be expected from reference 2 and elsewhere, there was a moderate degradation in subjective rating to the "unsatisfactory" level at the test limit of 3.5 g. The effect of superimposing the vibrational stress is shown in figure 12. The average opinion degrades to "unacceptable," reaching a value of 9.0 at the test limits, 3.5 g ±3 g. The vibration is obviously the predominant factor, and becomes unacceptable in the region of ±1.0 to ±1.5 g.

The individual ratings for each subject are shown in figure 13. Satisfactory levels (i.e., pilot ratings of 3.5 or better) were not achieved except for subjects B and C. The spread in opinion between the subjects is considered reasonable in view of the relative novelty of the environment and the situation being evaluated.

Some effects of SAS configuration on acceptability were also investigated (fig. 14). Piloted runs were made with the yaw SAS in and out. All other conditions were the same. With no SAS control feedback in the yaw channel, any inadvertent control motion of the pilot into the yaw channel allowed the yaw error to grow. Previously, with the pitch and yaw autopilot in operation, the pilot could devote all his attention to controlling in the pitch channel, whereas with the yaw autopilot out some of his attention had to be diverted to that channel, with a resulting degradation in opinion rating of about two points.

Control-Task Performance

Considering first the effects of steady acceleration alone, the averaged tracking efficiencies for all subjects are again compared in figure 15 with the results from reference 2. The data from the present study show little significant effect of steady acceleration alone to the limit of 3.5 g, as would be expected from previous investigations. The present "launch vehicle" data are generally between the well-damped and lightly damped "airplane" data from reference 2, except for the relatively low value of tracking efficiency at 2 g. The latter results from the particular test procedure. It was considered prudent to order the tests so that the pilots were first exposed to some steady acceleration (2.0 g) and then built up progressively in both acceleration and vibration. Thus, by the time the pilots were tested at 3.5 g without vibration, they had accumulated considerable specific task experience. Repeating the 2.0 g runs at the end of the program was not considered warranted.

The effects of superimposing vibration are shown in figure 16 with the data plotted by subject to show the spread in individual performance. The trends shown in this figure agree with the pilot opinion data of figures 12 and 13. The vibration is the predominant effect at the high oscillatory vibration levels and the performance degrades markedly above the level of about ±1.5 g (fig. 16). The pilots tracking efficiencies were quite low for the higher steady-state level (3.5 g) and at the test limit of ±3.0 g.

An interesting conjecture as to the reason for the degradation of tracking efficiency with increasing vibration was brought out by the pilots' comments during the test program. Without vibration, the pilots were able to follow the target motion (directional needles in the task display) and easily perceive reversals and rate of motion of the needles. In other words, they were getting "rate" information visually by noting how fast the needles were moving. As vibration was introduced, the actual position of the target became a blur and only the maximum excursions or peak-to-peak amplitudes were sensed; the rate information was lost. The probable effect would be that the pilot anticipation lead time constant, usually up to 2 seconds, in the human transfer function (see ref. 20), was removed with the resulting decrease in tracking effectiveness.

This conjecture appears to be reasonable inasmuch as references 8 and 21 have shown that tracking with the vehicle dynamics used in the present problem generally requires significant amounts of lead to be generated by the pilot. Normally, this effect would be substantiated quantitatively by deducing the pilot transfer function from the present test data and comparing the lead terms required with and without vibration. However, as can be seen in some of the time histories to be considered later to describe the autopilot study, one additional effect of vibration environment was that the pilot frequently encountered the booster engine position and rate limits of the present control system. This introduced nonlinearities which complicated the analysis of the pilot describing function. This point has been emphasized in this report so that future experiments in this environment can be designed with this problem in mind.

The effect on control task performance of removing the yaw stability augmentation system is summarized in figures 17(a) and (b). Except for unique (or unexpected) performance of pilot B at ±3.0 g vibration condition, a comparison of the averaged values showed a definite degradation in performance due to the diversion of the pilots' attention, which correlates well with the pilot opinion data presented in figure 14. Comparative time histories are presented in figure 18 where the yaw SAS was removed to compare with a normal situation of pitch and yaw SAS in.

Transient Effects of Autopilot Failures

The effects of unannounced pitch damper failures were also briefly investigated. The rate feedback signal in the pitch channel was made to fail while the pilot was in a normal tracking run. This was done during a static run as well as at higher g levels (up to 3.5 g with ±3.0 g vibration). Typical results (fig. 19) show a definite decrease in tracking efficiency which becomes much more severe as the stress level increases.

The period of pilot adaptation, shown in figure 20(a), is the time required for the pilot performance to stabilize after the damper fails. The integral of the forcing function squared is plotted as a function of time. The two dashed curves are for the task input and for the baseline showing the pilot tracking in the unstressed condition with no damper. The difference between the two is the reduction in error due to the pilot's effort in tracking. In this case adaptation was achieved in about 5 seconds. The typical failure run (3.5 g ±2.0 g vibration) shows the pilot initially tracking normally (with the same slope as the "baseline" in Fig. 20(b)); then his performance begins to drop but still maintains substantial effectiveness. When damper failure occurs his effectiveness drops to nearly zero (parallel to the integral of the input squared) then recovers after 15 seconds temporarily after the period adaptation. It can be argued that the pilot does not truly adapt; however, this case does illustrate his attempt to adapt during the rapid deterioration in performance (fig. 19) after the failure. The 15-second period would be fairly typical for these data; however, many more subjects and test runs must be considered before significant data can be presented for an analysis of system failures. Further discussion of experimental and analytical approaches to the adaptation process is contained in reference 22.

Effects of Engine-Servo Rate Limiting

The engine-servo rate and position limits were chosen to simulate a typical large high-thrust booster rocket. The problem often arises in a study of the present type that the vehicle and control dynamics are not compatible with the "standard" task, however, that task has been selected so that comparisons may be made with previous studies. The highest frequencies of the present task are somewhat too high for the airframe-autopilot combination used and it would be expected that increasing the engine-servo rate limit would permit the pilot to improve his performance. Limiting the rapidity with which the control system under the pilot's direction can act also prevents him from tracking rapidly. Hence, the portion of the input not filtered by the system, the remnant, would tend to increase the error.

To determine the magnitude of this effect in the present study a series of runs were made for three values of servo rate limits under 1 g static conditions using one above-average pilot. These data in sample time history form, figure 21, indicate an improvement between 5°/sec and 20°/sec with a modest improvement up to 50°/sec.

SUMMARY OF RESULTS

An investigation of the effects of simultaneous vibration at 11 cps (0 to ±3.0 g) and linear acceleration (1 to 3.5 g) on the ability of the human pilot to perform a tracking task using vehicle and control dynamics typical of a large high-thrust booster rocket has indicated the following:

Both performance measures and subjective opinion indicated substantial degradation in pilot tracking effectiveness above vibration levels of ±1.5 g at 11 cps. The pilots were almost completely ineffective at ±3.0 g vibration.

Under vibration, the pilots reached the engine-servo-rate and position-limit stops often enough that a linear analysis of the pilot describing function was difficult. Pilot comments indicate that they could not perceive rate information from the visual display (rate of needle motion). It is therefore assumed that the pilots were unable to generate the lead time constant usually necessary in this type of tracking.

A brief investigation of the pilot's ability to cope with sudden changes in the controlled element was made by simulating pitch damper failures. A period of temporary adaptation required was approximately 15 seconds at a 3.0 g steady and ±2.0 g vibration EBI condition, while for a 1 g static EBD condition, it was 5 seconds.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Dec. 10, 1964

REFERENCES

1. Woodling, C. H.; and Clark, Carl C.: Studies of Pilot Control During Launching and Reentry of Space Vehicles, Utilizing the Human Centrifuge. Rept. 59-39, Inst. Aero. Sci., Jan. 1959.

2. Creer, Brent Y.; Smedal, Harald A., Capt. USN (MC); and Wingrove, Rodney C.: Centrifuge Study of Pilot Tolerance to Acceleration and the Effects of Acceleration on Pilot Performance. NASA TN D-337, 1960.

3. Smedal, Harald A., Capt. USN (MC); Creer, Brent Y.; and Wingrove, Rodney C.: Physiological Effects of Acceleration Observed During a Centrifuge Study of Pilot Performance. NASA TN D-345, 1960.

4. Rogers, Terence A.; and Smedal, Harald A., Capt. USN (MC): The Ventilatory Advantage of Backward Transverse Acceleration. Paper presented at Aerospace Med. Assn. Meeting, Chicago, Ill., April 25, 1961. Aerospace Med., vol. 32, no. 8, Aug. 1961, pp. 737-40.

5. Vykukal, Hubert C., Lt. USAF; Gallant, Richard P.; and Stinnett, Glen W.: An Interchangeable, Mobile Pilot-Restraint System, Designed for Use in High Sustained Acceleration Force Fields. Aerospace Med., vol. 33, no. 3, March 1962, pp. 279-85.

6. Creer, Brent Y.; Stewart, John D.; and Douvillier, Joseph G., Jr.: Influence of Sustained Accelerations on Certain Pilot-Performance Capabilities. Presented at Aerospace Med. Assn. Meeting, Atlantic City, N. J., April 9-12, 1962. Aerospace Med. vol. 33, no. 9, Sept. 1962, pp. 1086-93.

7. Smedal, Harald A., Capt. USN (MC); Rogers, Terence A.; Duane, Thomas D.; Holden, George R.; and Smith, Joseph R., Jr.: The Physiological Limitations of Performance During Acceleration. Paper presented at Aerospace Med. Assn. Meeting, Atlantic City, N. J., April 9-12, 1962. Aerospace Med., vol. 34, no. 1, Jan. 1963, pp. 48-55.

8. Sadoff, Melvin: Effects of High Sustained Acceleration on Pilots' Performance and Dynamic Response. NASA TN D-2067, 1964.

9. Goldman, David E.; and Von Gierke, Henning E.: The Effects of Shock and Vibration on Man. Lecture and Review Series No. 60-3, Naval Medical Research Institute, Jan. 8, 1960.

10. Parks, Donald L.; and Snyder, F. W.: Human Reaction to Low Frequency Vibration. Tech. Rept. 1, The Boeing Company, Wichita, Kansas, July 24, 1961.

11. Parks, Donald L.: A Comparison of Sinusoidal and Random Vibration Effects on Human Performance. Tech. Rept. 2, The Boeing Company, Wichita, Kansas, July 28, 1961.

12. Besco, Robert O.: The Effects of Cockpit Vertical Accelerations on a Simple Piloted Tracking Task. Human Factors, vol. 3, no. 4, Dec. 1961. North American Aviation, Inc., Los Angeles, NA-61-47, April 13, 1961.

13. Catterson, A. D., M.D.; Hoover, G. N., Ph.D.; and Ashe, W. F., M.D.: Human Psychomotor Performance During Prolonged Vertical Vibration. Aerospace Med., vol. 33, no. 5, May 1962, pp. 598-602.

14. Linder, Gerald S., M.D.: Mechanical Vibration Effects on Human Beings. Aerospace Med., vol. 33, no. 8, Aug. 1962, pp. 939-50.

15. Grande, Donald L.: Some Effects of Random Turbulence on Weapon-System Performance. Aerospace Eng., vol. 21, no. 10, Oct. 1962, pp. 35-43.

16. Faubert, Denis; Cooper, Bruce; and Clark, C. C.: Tolerance and Performance Under Severe Transverse ($\pm G_X$) Vibration. ER 12838, Martin-Marietta Corp., Space Systems Div., Feb. 1963.

17. Krendel, Ezra S.; and Bloom, Joel W.: The Natural Pilot Model for Flight Proficiency Evaluation. Tech. Rept. NAVTRADEVCEN 323-1, Franklin Inst., Philadelphia, Penn., April 1963.

18. Sadoff, Melvin: A Study of a Pilot's Ability to Control During Simulated Stability Augmentation System Failures. NASA TN D-1552, 1962.

19. Cooper, George E.: Understanding and Interpreting Pilot Opinion. IAS Paper No. 683. Aeronautical Eng. Rev., vol. 16, no. 3, March 1957, pp. 47-51.

20. Graham, Dunstan; and McRuer, Duane: Analysis of Nonlinear Control Systems. John Wiley and Sons, Inc., 1961.

21. 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 the Effects of Motion Cues. NASA TN D-348, 1961.

22. Young, Laurence R.; Green, David M.; Elkind, Jerome I; and Kelly, Jennifer A.: The Adaptive Dynamic Response Characteristics of the Human Operator in Simple Manual Control. NASA TN D-2255, 1964.

TABLE I.- SUMMARY OF RUNS

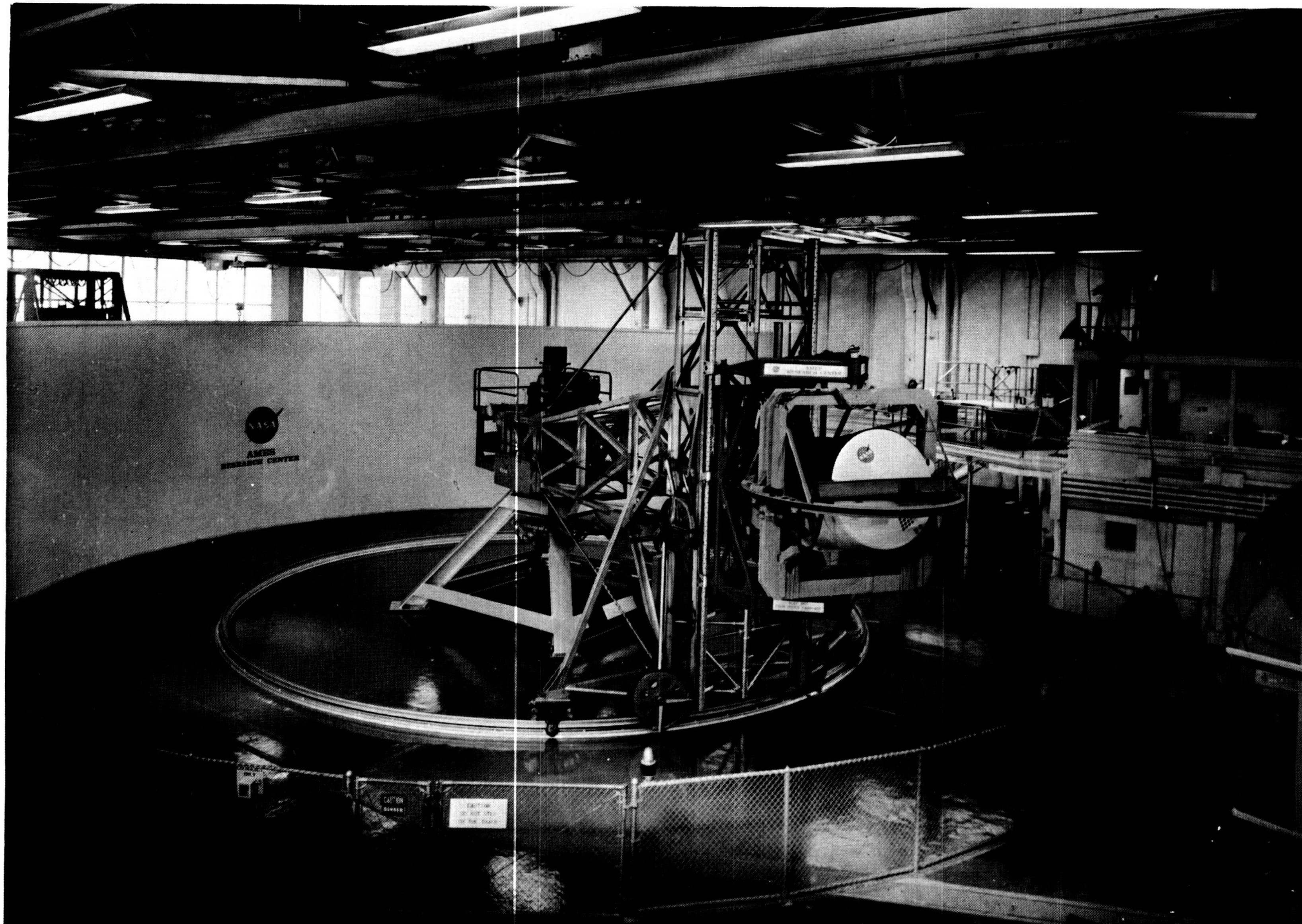
Environment						
Nominal steady, G	Nominal vibration, ± G	Pitch SAS in, Yaw SAS in	Pitch SAS in, Yaw SAS out	Pitch SAS out, Yaw SAS in	Pitch damper out, Yaw SAS in	Pitch damper failure, Yaw SAS in
1(EBD)	0	A,B,C,D,E	A,B,C	A,B,C	[1]B	
2(EBI)	0	A,B,C,D,E	A,B	B		
2(EBI)	0.5	A,B,C,D,E	A,B	A,B		
2(EBI)	1.0	A,B,C,D,E	A,B,C	A,B,C		
2(EBI)	1.5	A,B,C,D,E	B,C	A		
3.5(EBI)	0	A,B	A,B		[2]B	B
3.5(EBI)	1.5	A,B	A,B		[2]B	B
3.5(EBI)	2.0	A,B	A,B			B
3.5(EBI)	3.0	A,B	A,B			

[1]T.E. = 86 percent, with engine-rate limit: 50°/sec
[2]T.E. essentially zero, with engine-rate limit: 50°/sec

TABLE II.- PILOT OPINION RATING SCHEDULE

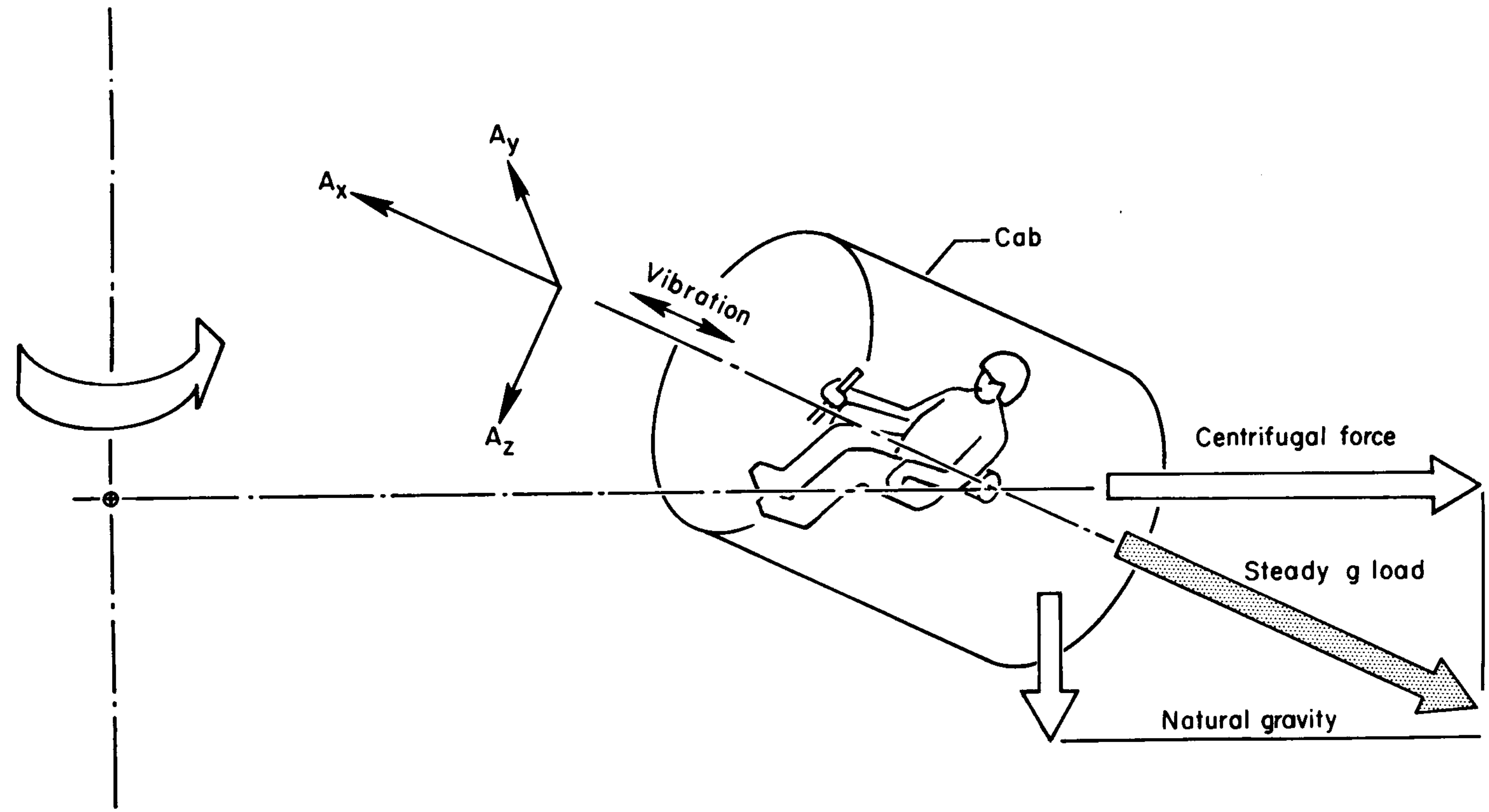
	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	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



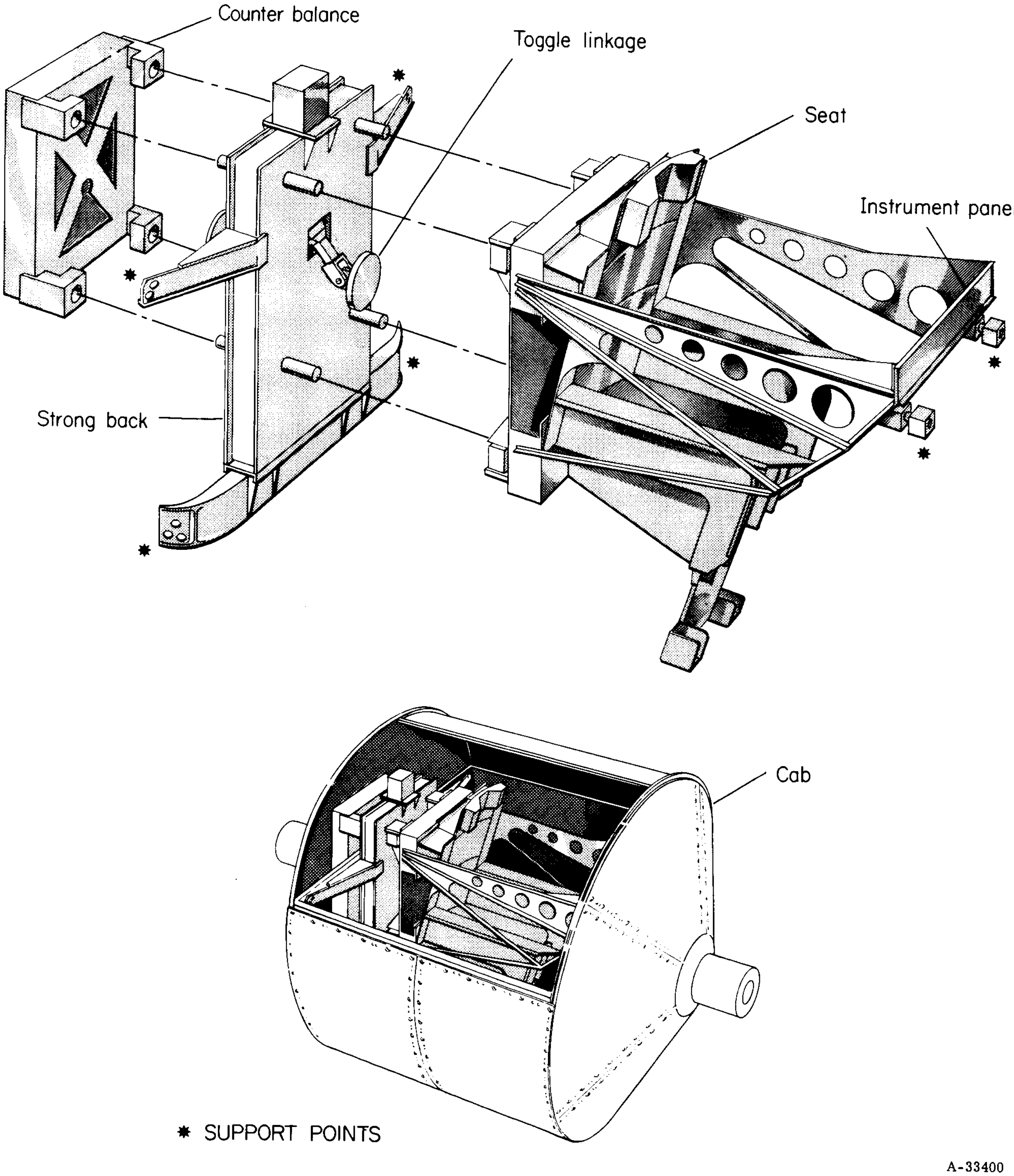
A-31542

Figure 1.- Five-degree-of-freedom simulator at the Ames Research Center.



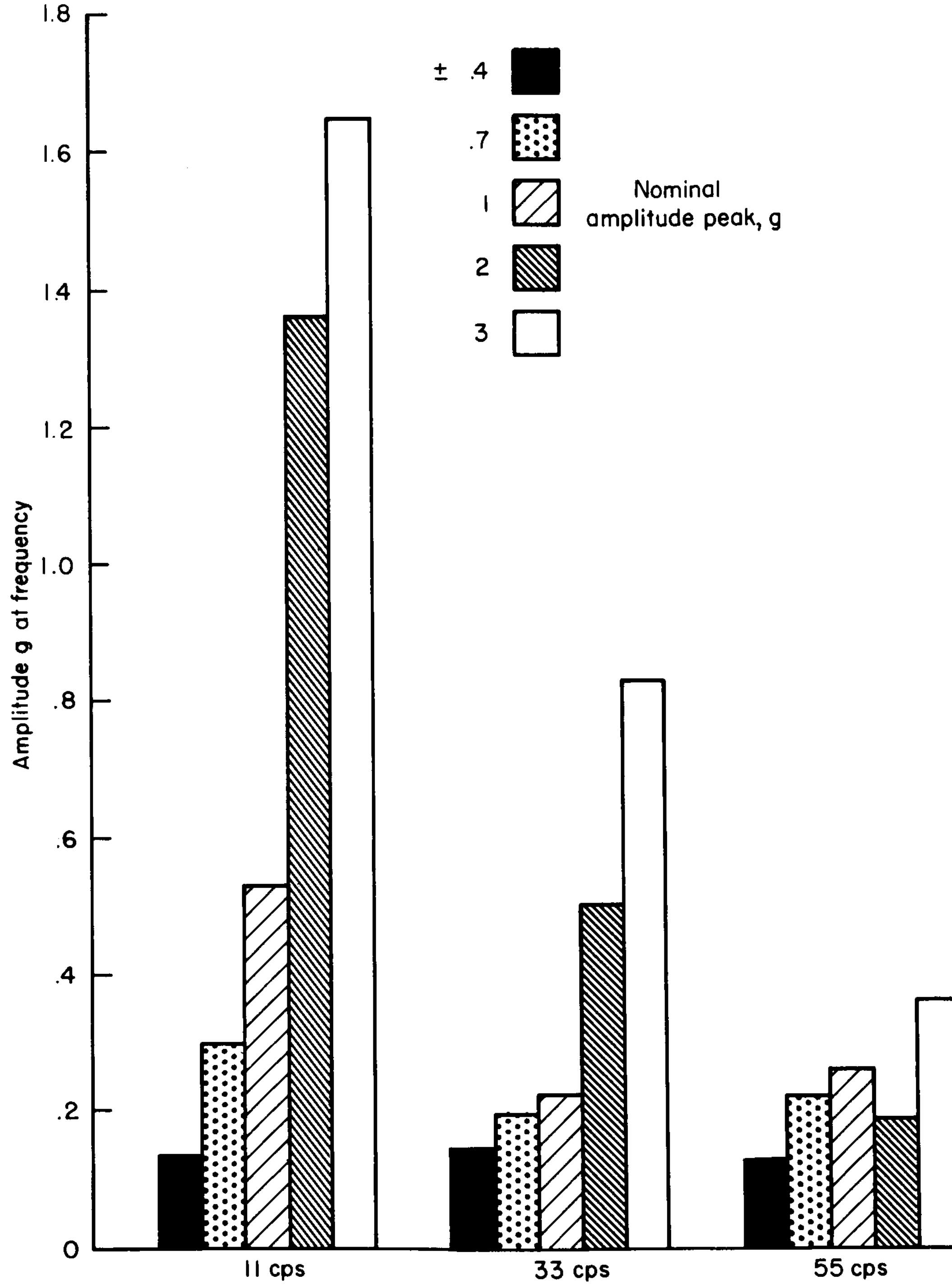
(a) Forces on subject during centrifuge operation, eyeballs-in orientation (EBI).

Figure 2.- Man carrying vibration device.



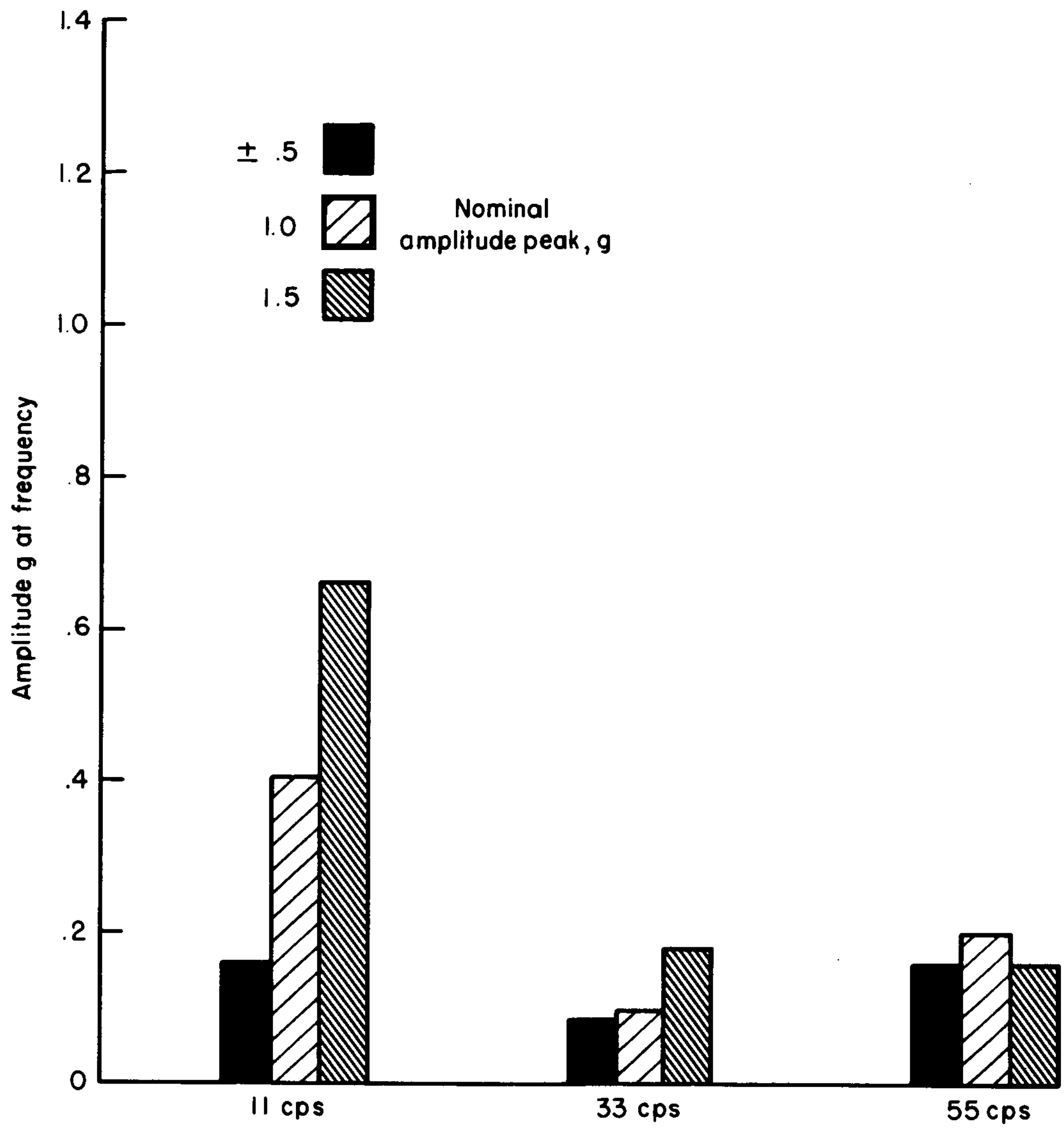
(b) Model 1.

Figure 2.- Concluded.



(a) Nominal steady-state acceleration, 3.5 g.

Figure 3.- Accelerations of centrifuge chair produced by the vibration device.



(b) Nominal steady-state acceleration, 2 g.

Figure 3.- Concluded.

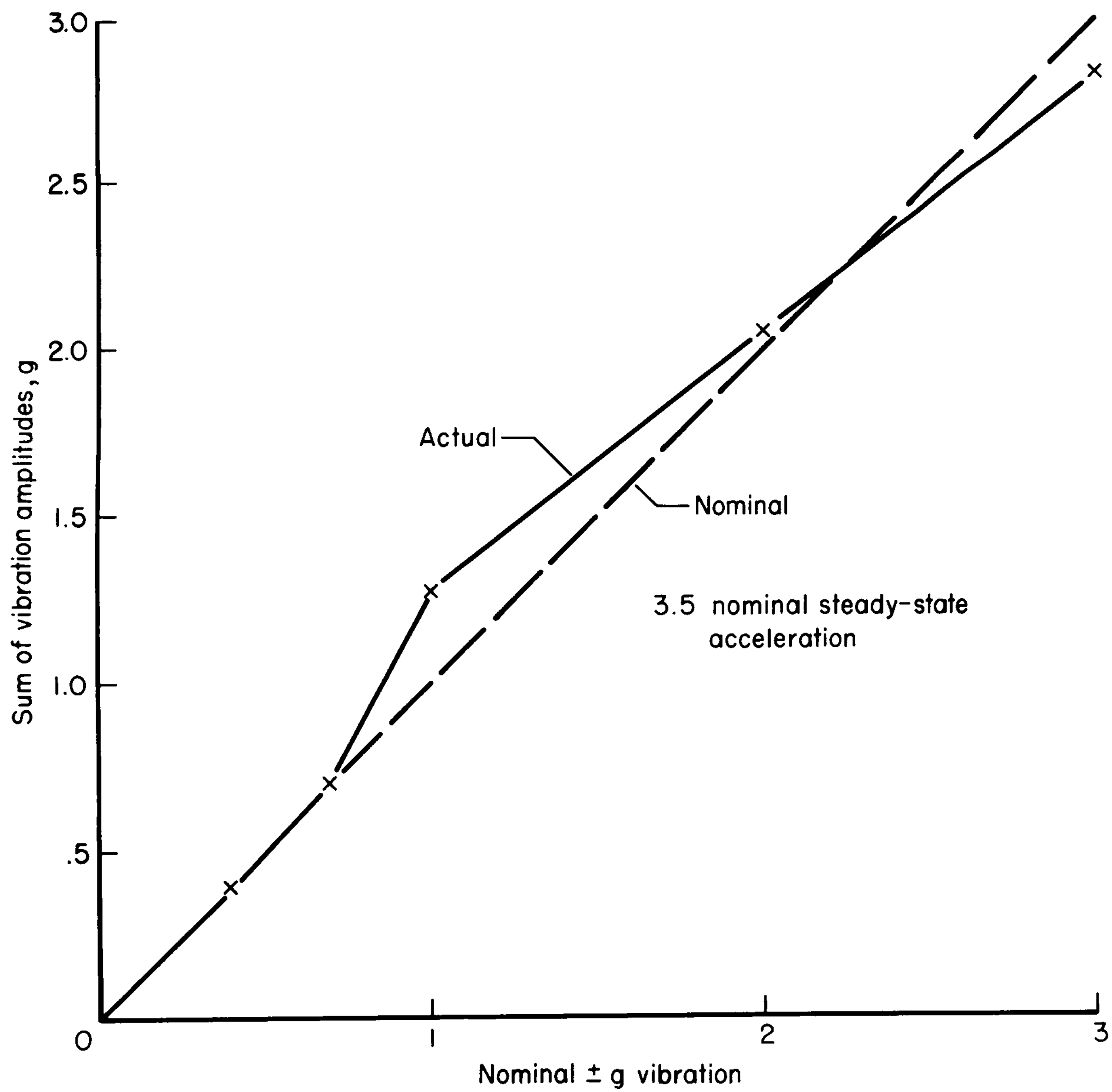
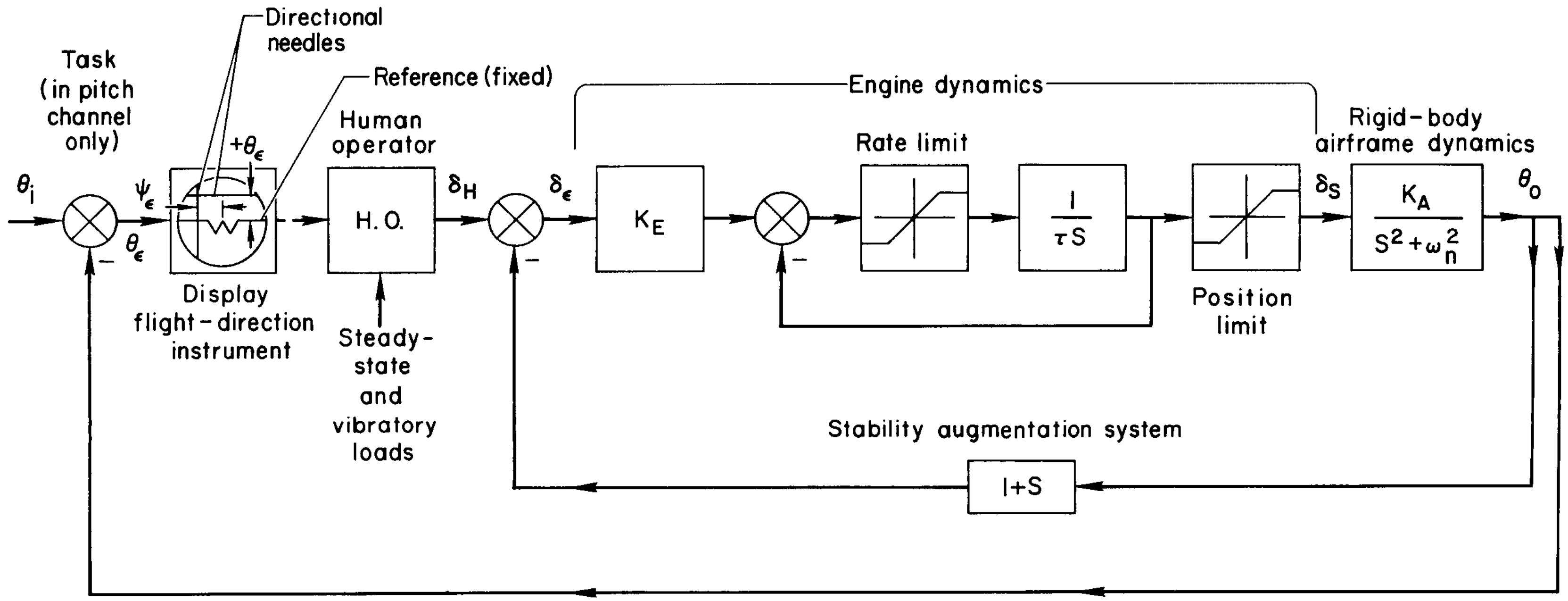


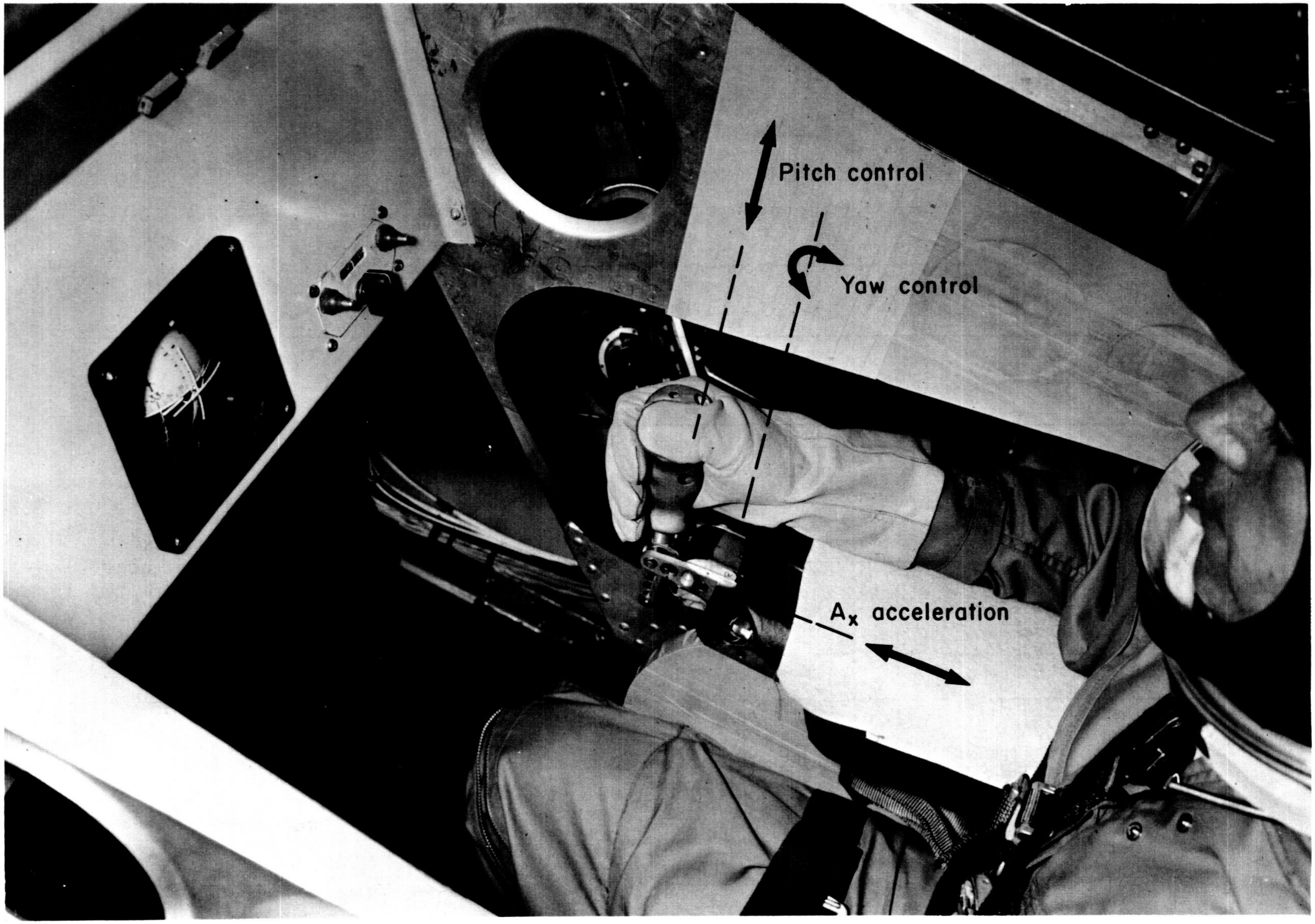
Figure 4.- Comparison between the nominal value of accelerations and the summation of actual chair accelerations at different frequencies.



$K_A = 1.22$, $\omega_n^2 = -.3\,\text{rad}^2/\text{sec}^2$, $\tau = .035\,\text{sec}$, $K_E = 1$

Note: Yaw directional channel same as above except no task input

Figure 5.- Block diagram of the longitudinal directional channel of the pilot-vehicle-control system.



A-31192-3.1

Figure 6.- Pilot in position using controller and display.

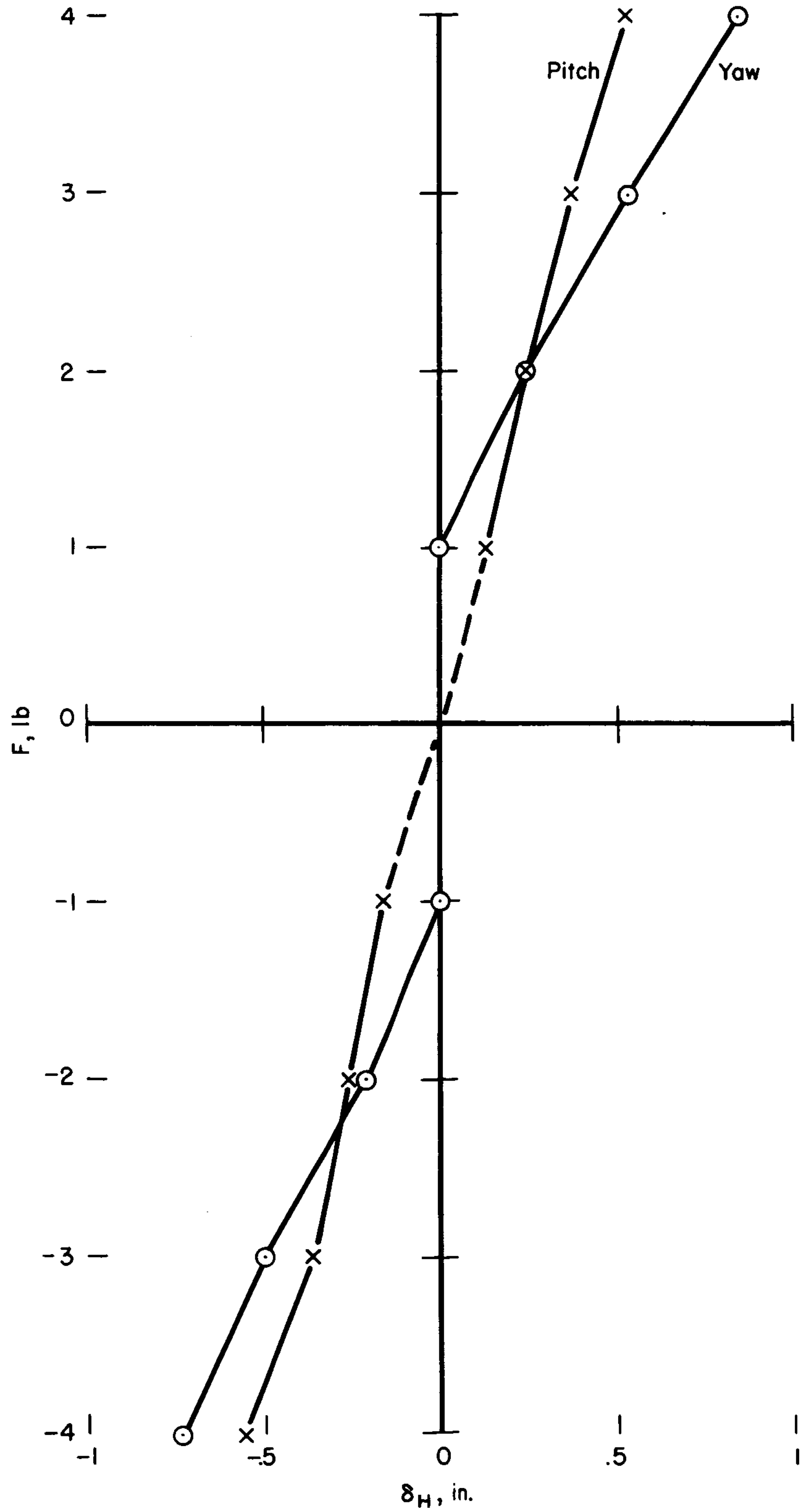


Figure 7.- Force-deflection characteristics of side-arm controller.

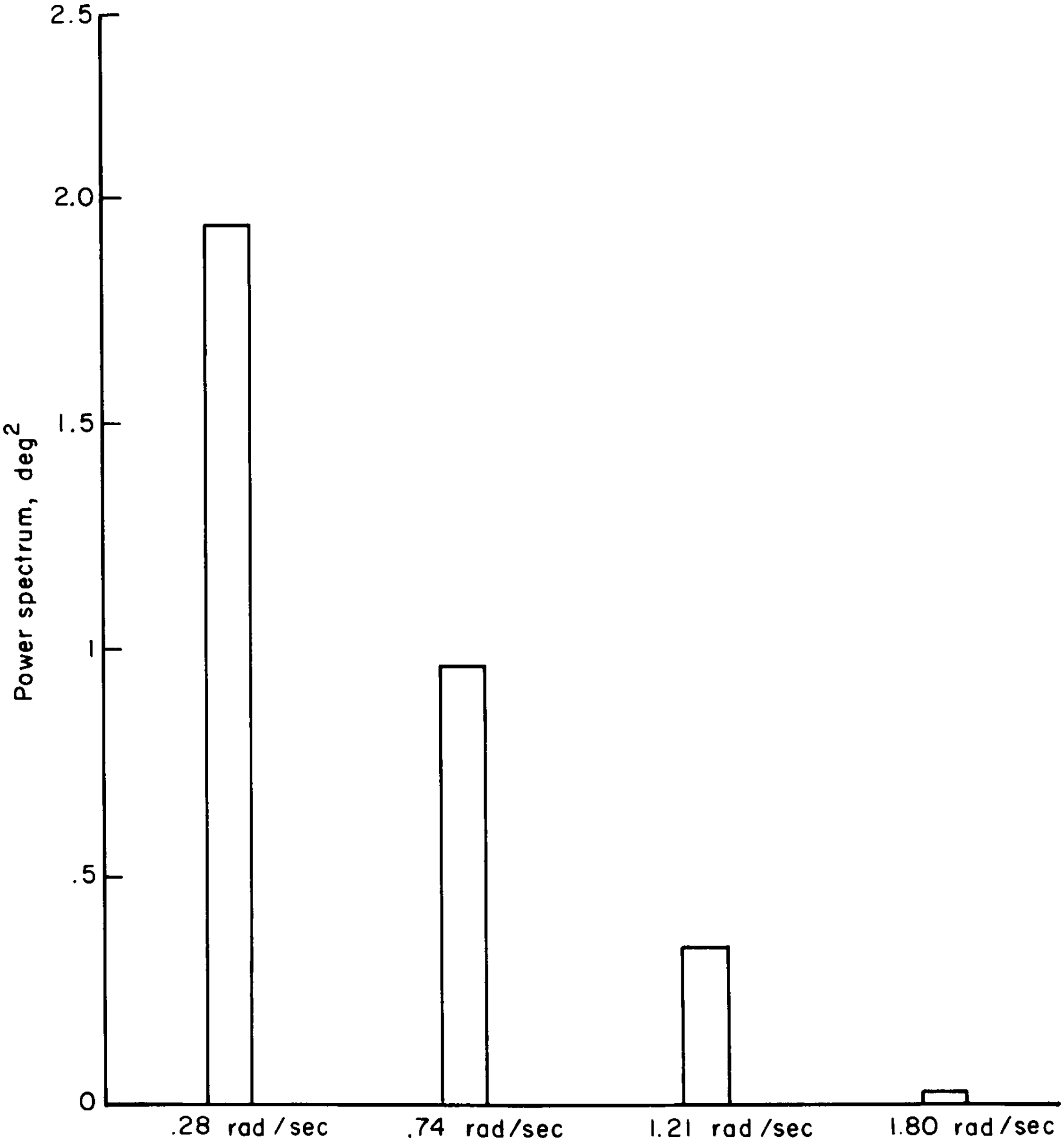


Figure 8.- Power spectra of the task input function.

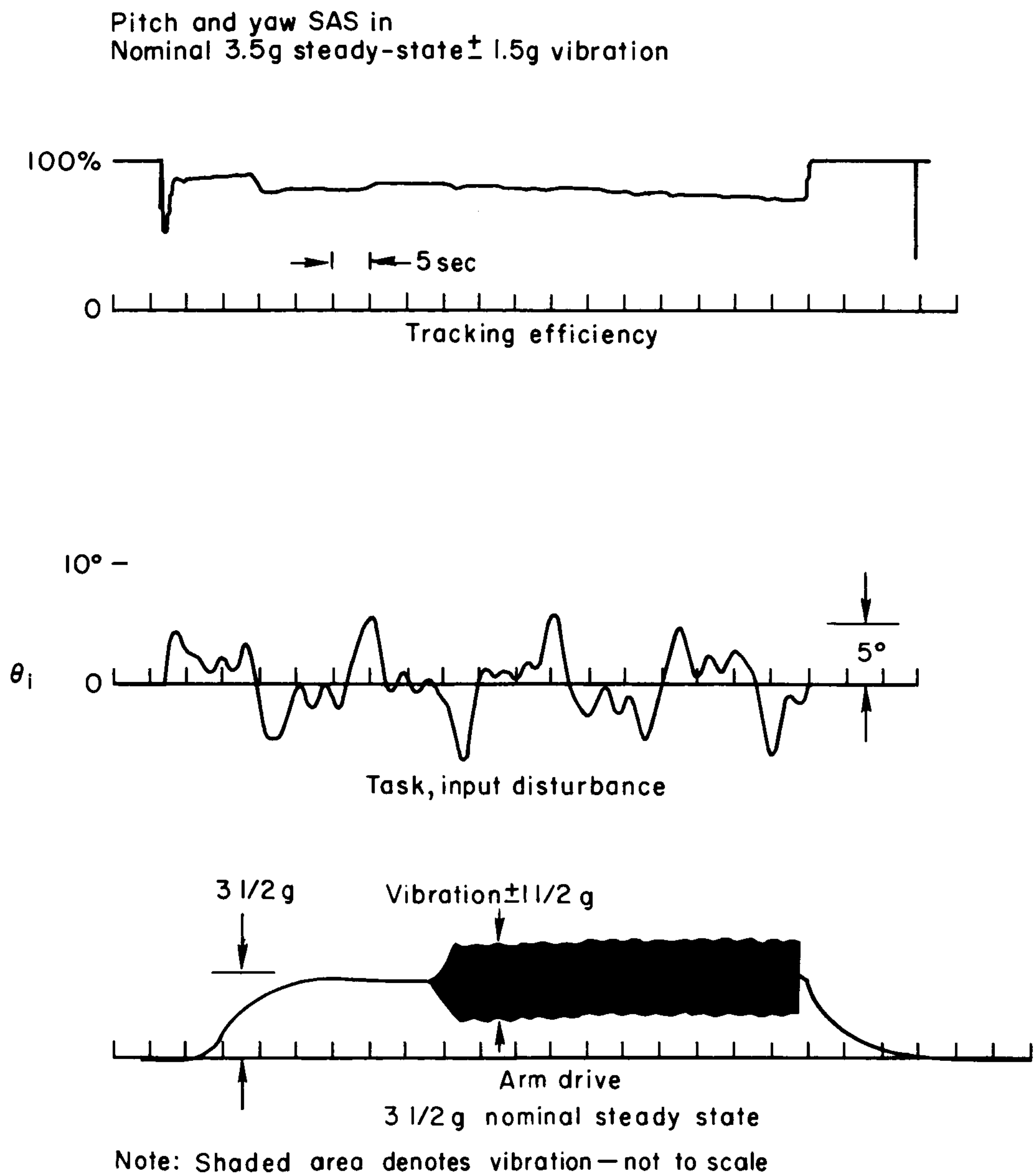


Figure 9.- Typical time history of steady-state acceleration (arm drive), task input, and pilot tracking efficiency.

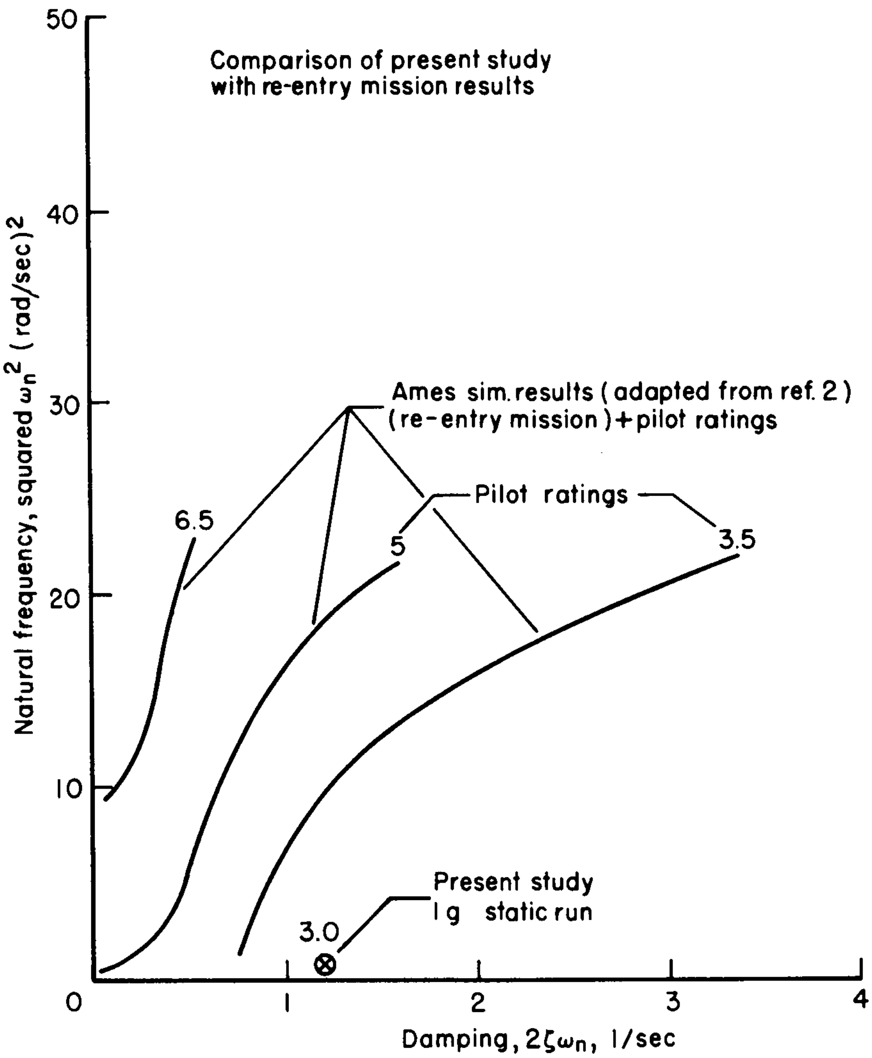


Figure 10.- Comparison of pilot opinion of the present launch vehicle dynamics with previous studies of airplane configurations.

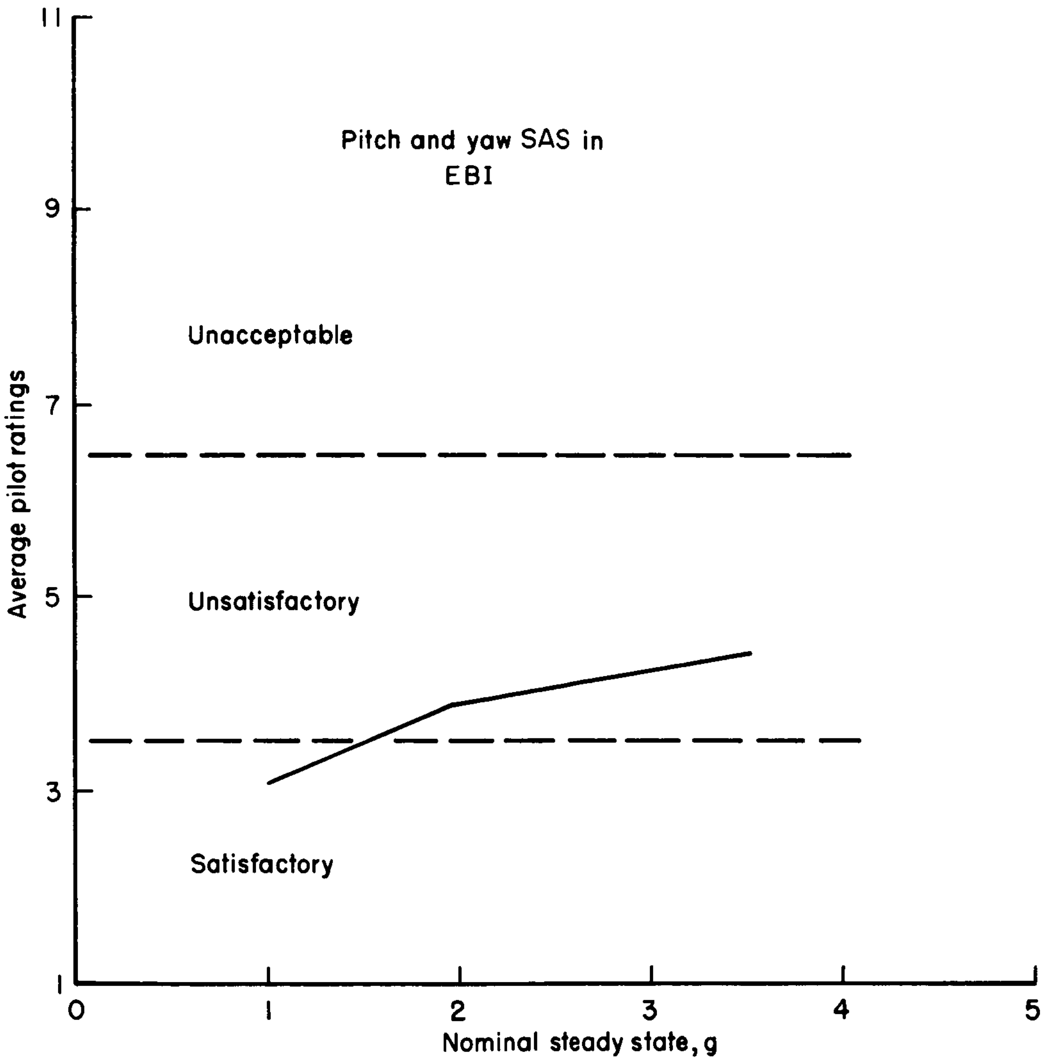


Figure 11.- Effect of increased steady linear acceleration alone on pilot opinion.

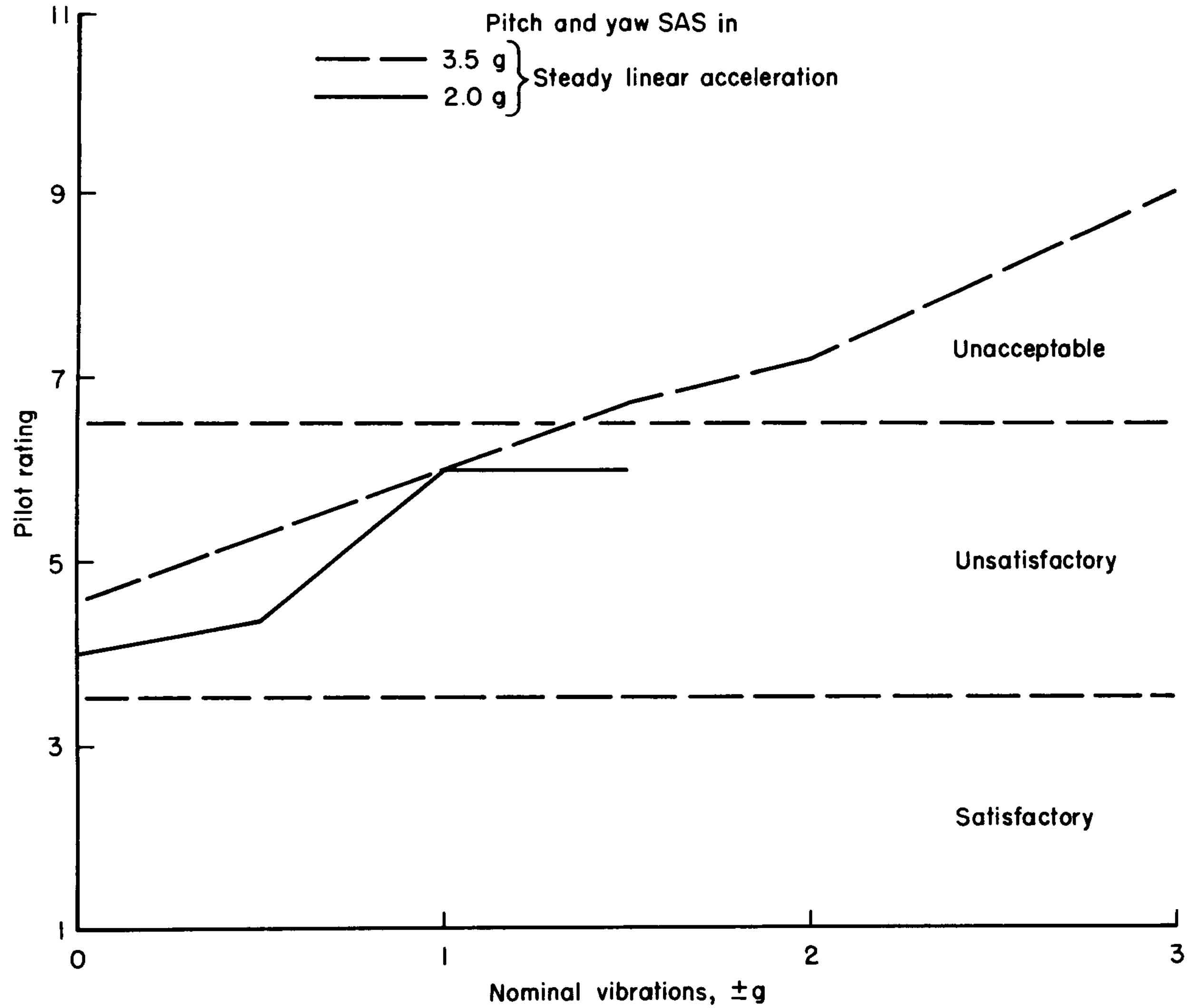


Figure 12.- Effect of combined linear and oscillatory accelerations on pilot opinion.

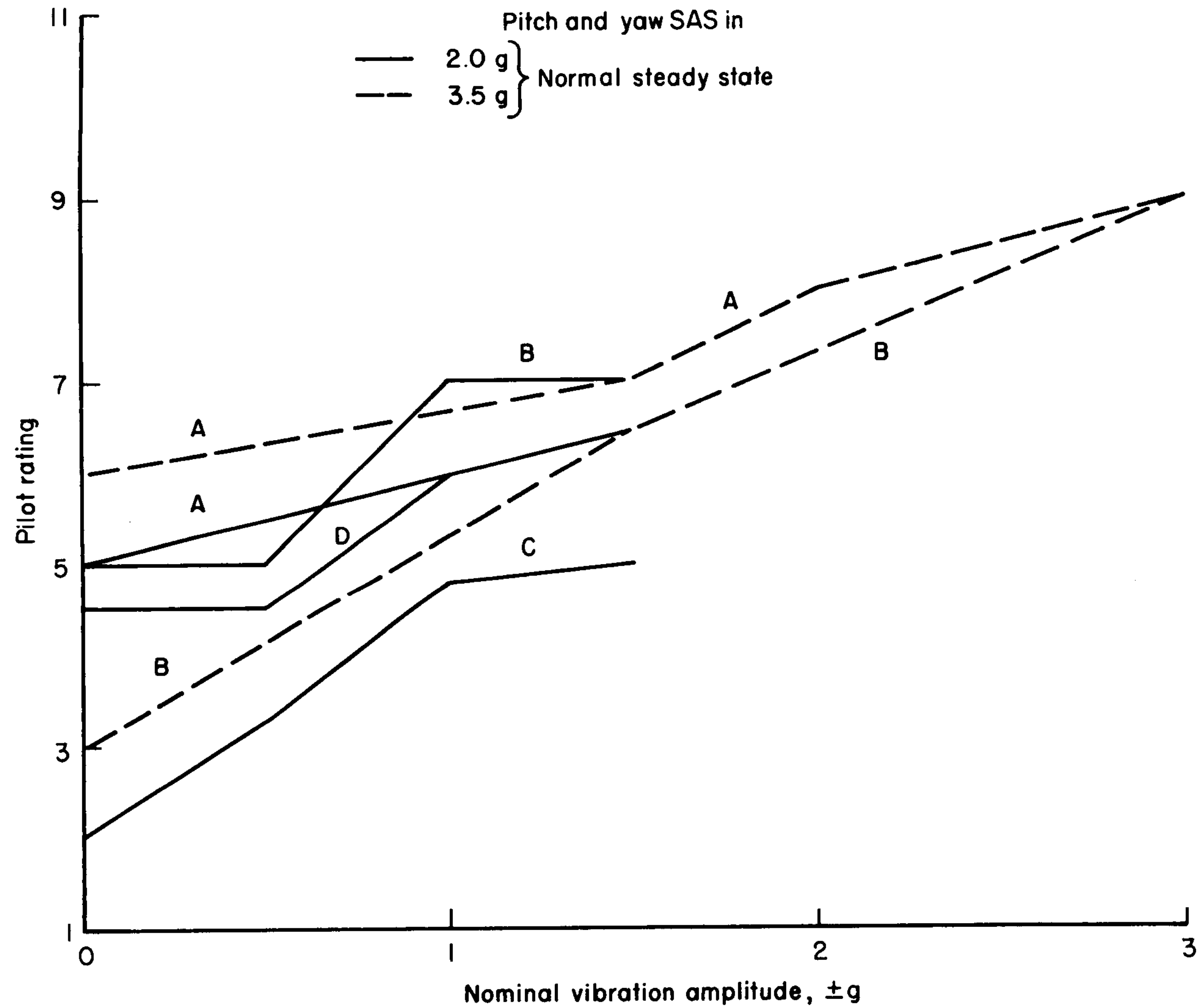


Figure 13.- Pilot opinions by individual subject under combined linear and oscillatory accelerations.

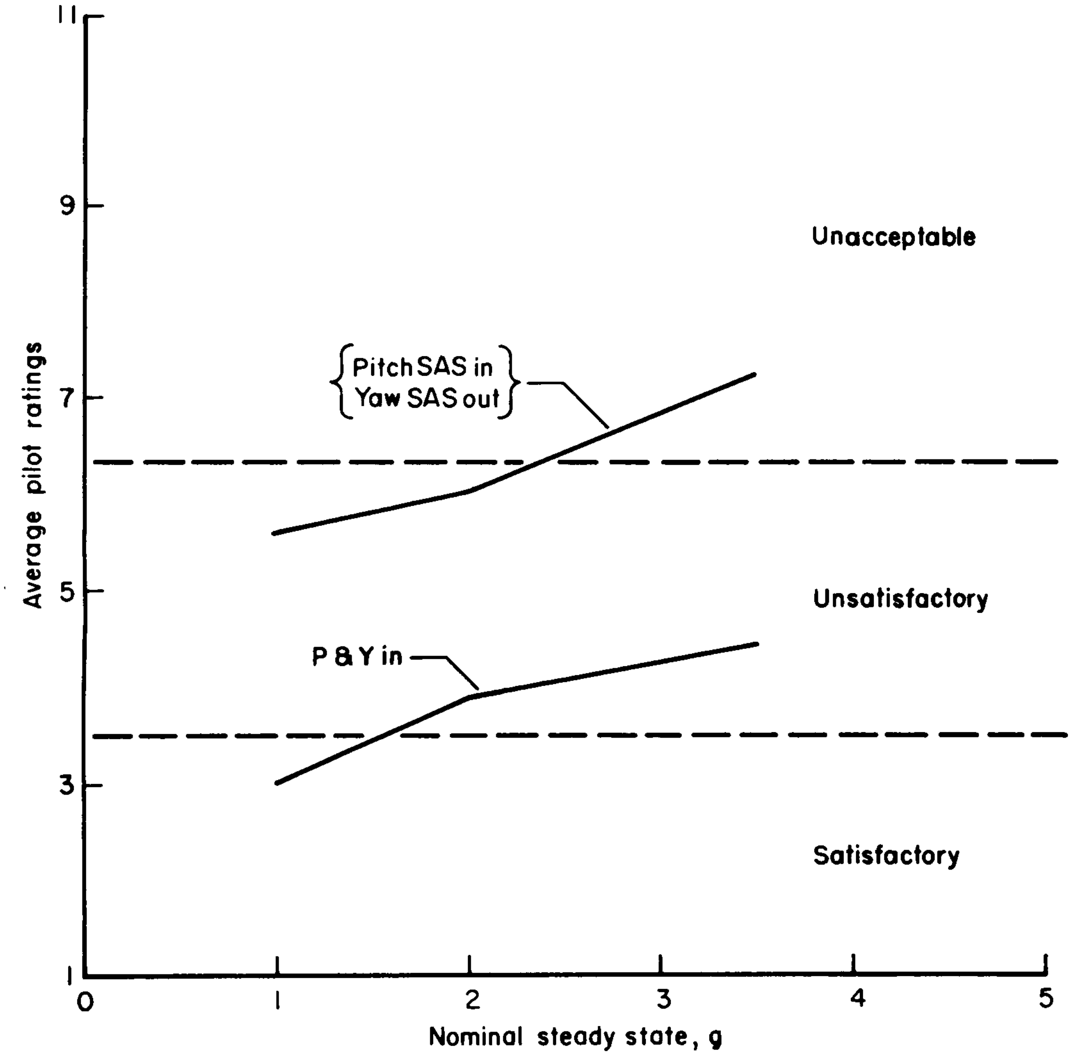


Figure 14.- Effect of autopilot configuration on pilot opinion under linear acceleration only.

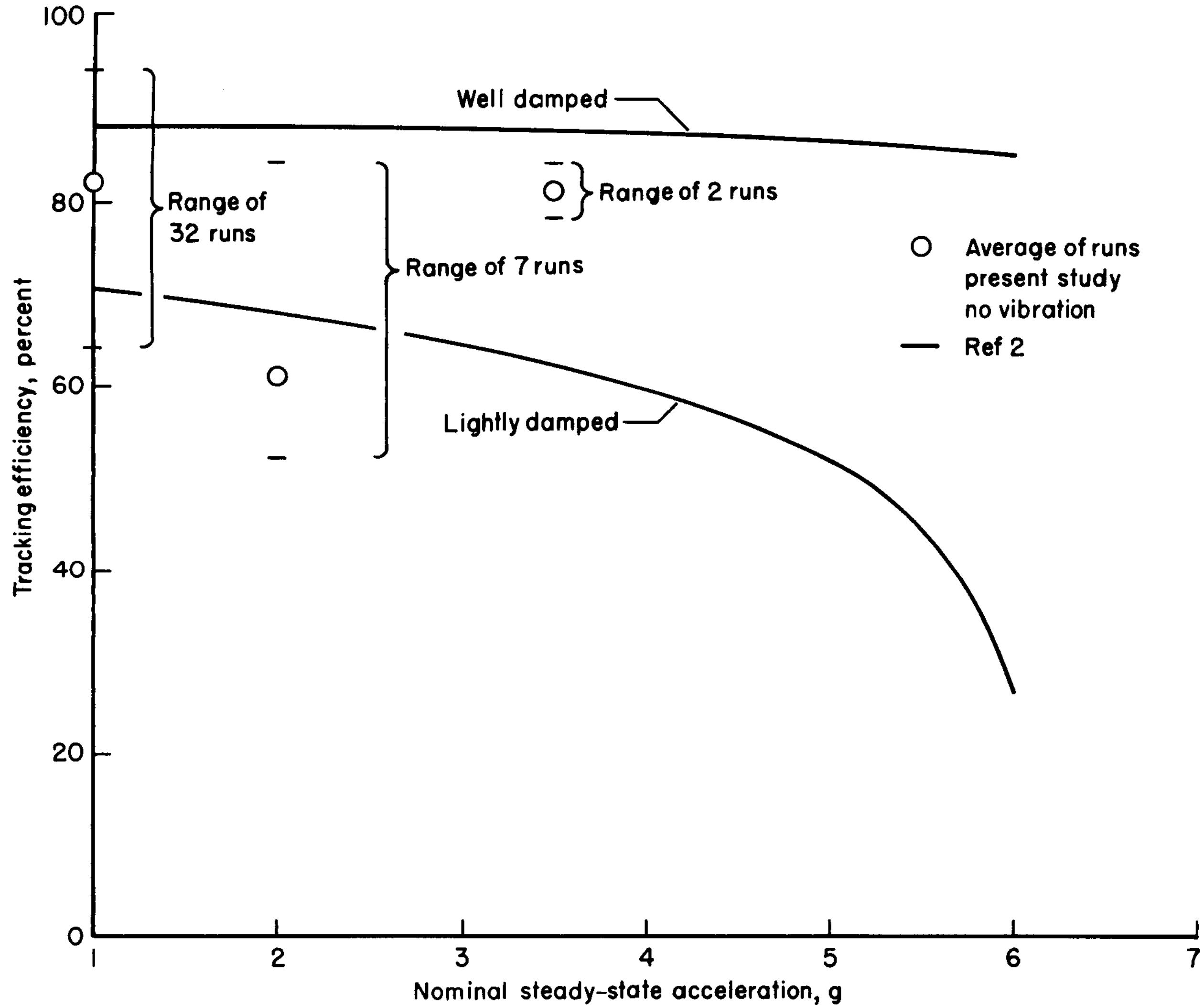


Figure 15.- Comparison of pilot tracking performance on the present launch vehicle with previous studies of airplane configurations.

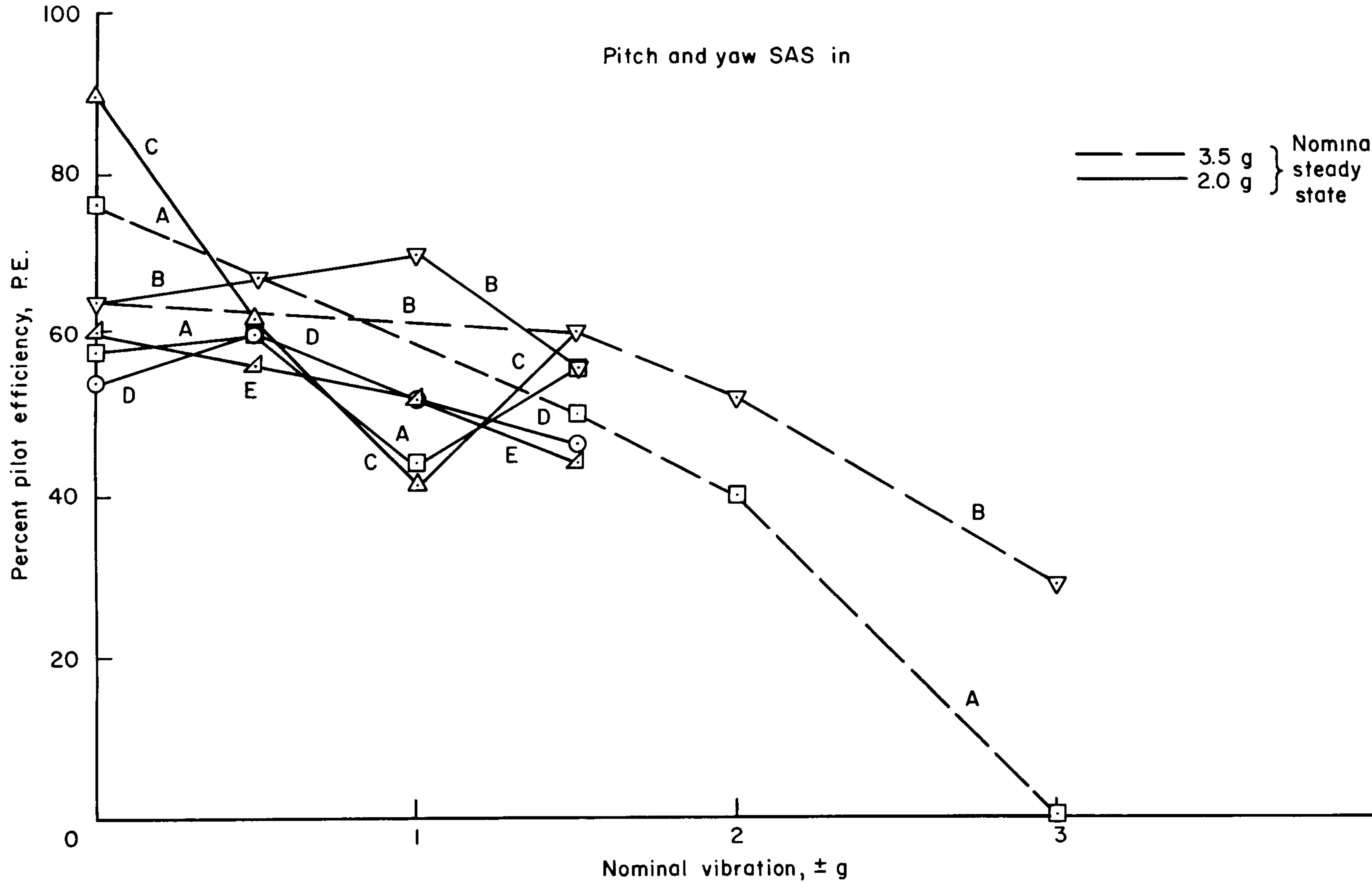
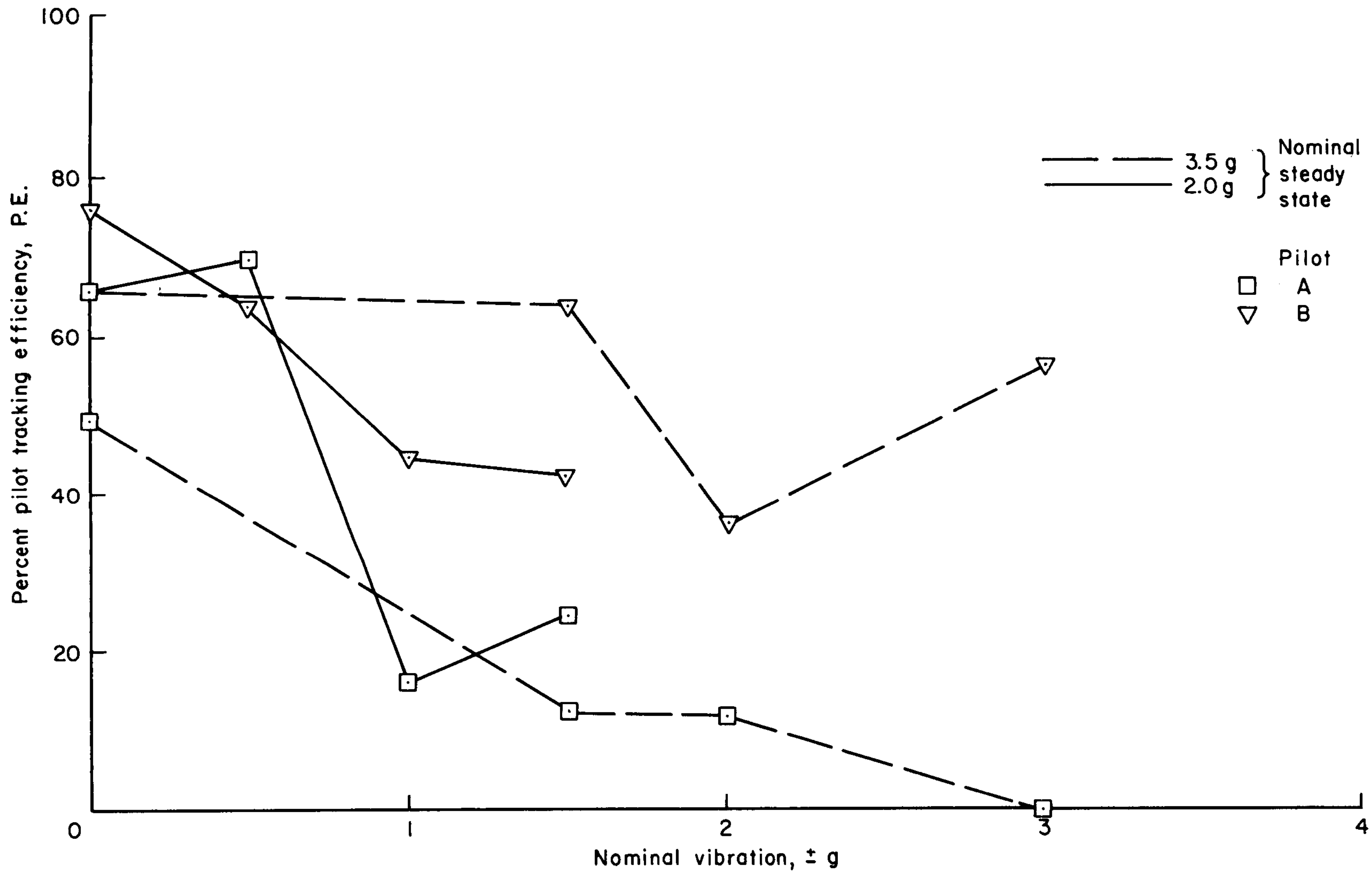
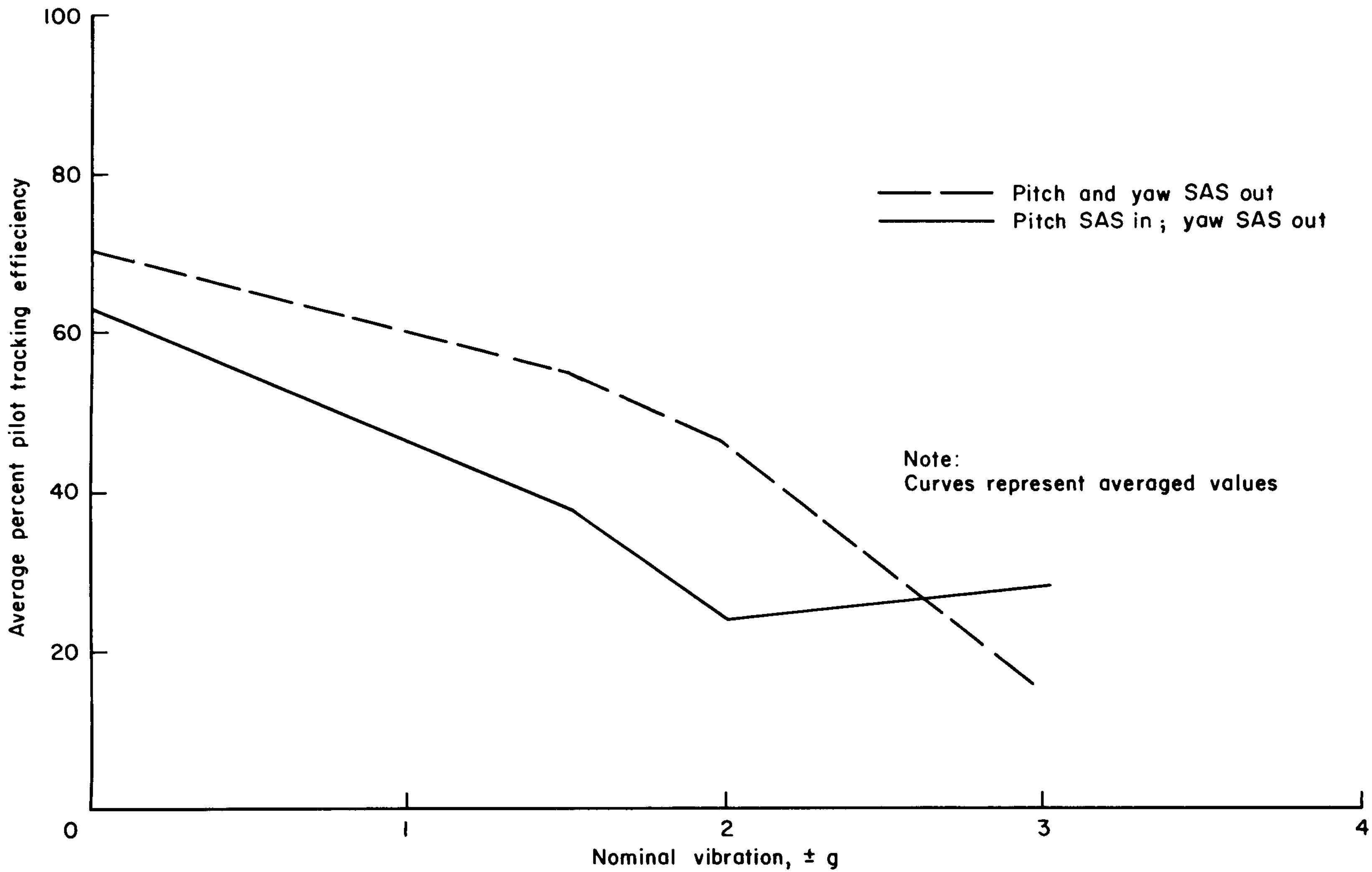


Figure 16.- Effect of combined linear and oscillatory accelerations on pilot tracking performance.



(a) Pitch SAS in; yaw SAS out.

Figure 17.- Effect of autopilot configuration on pilot performance under combined linear and oscillatory accelerations.



(b) Nominal 3.5 g steady state.

Figure 17.- Concluded.

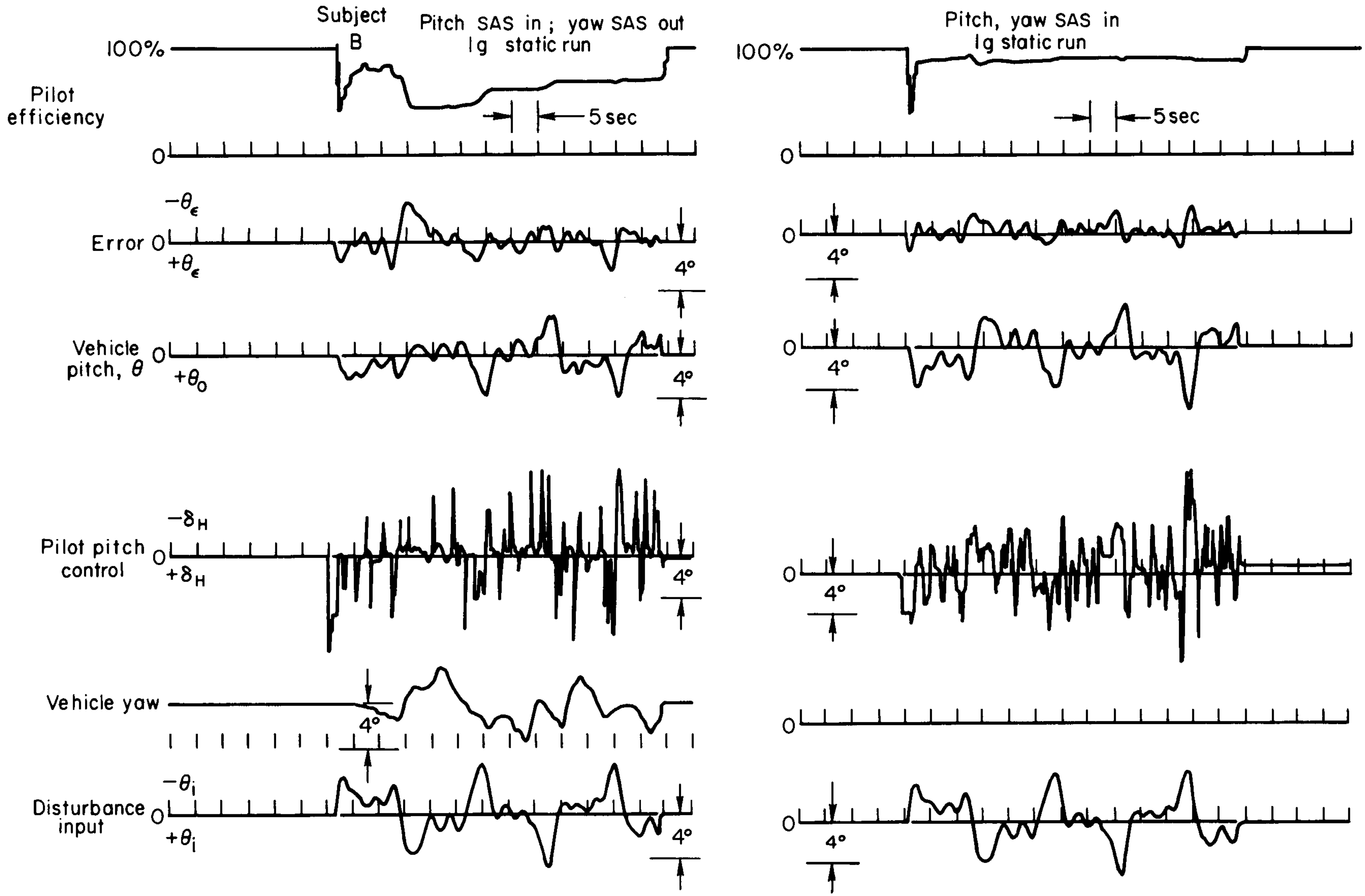
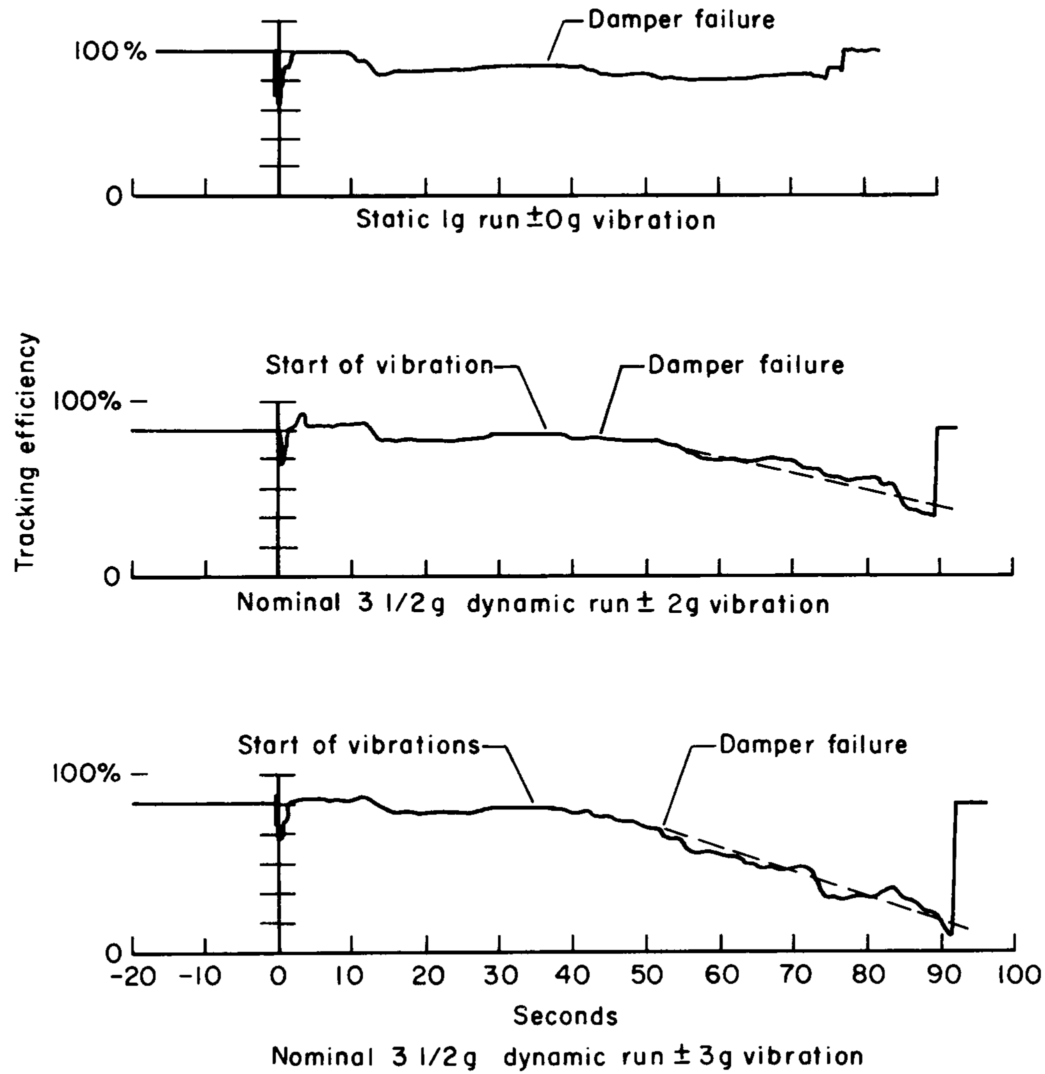
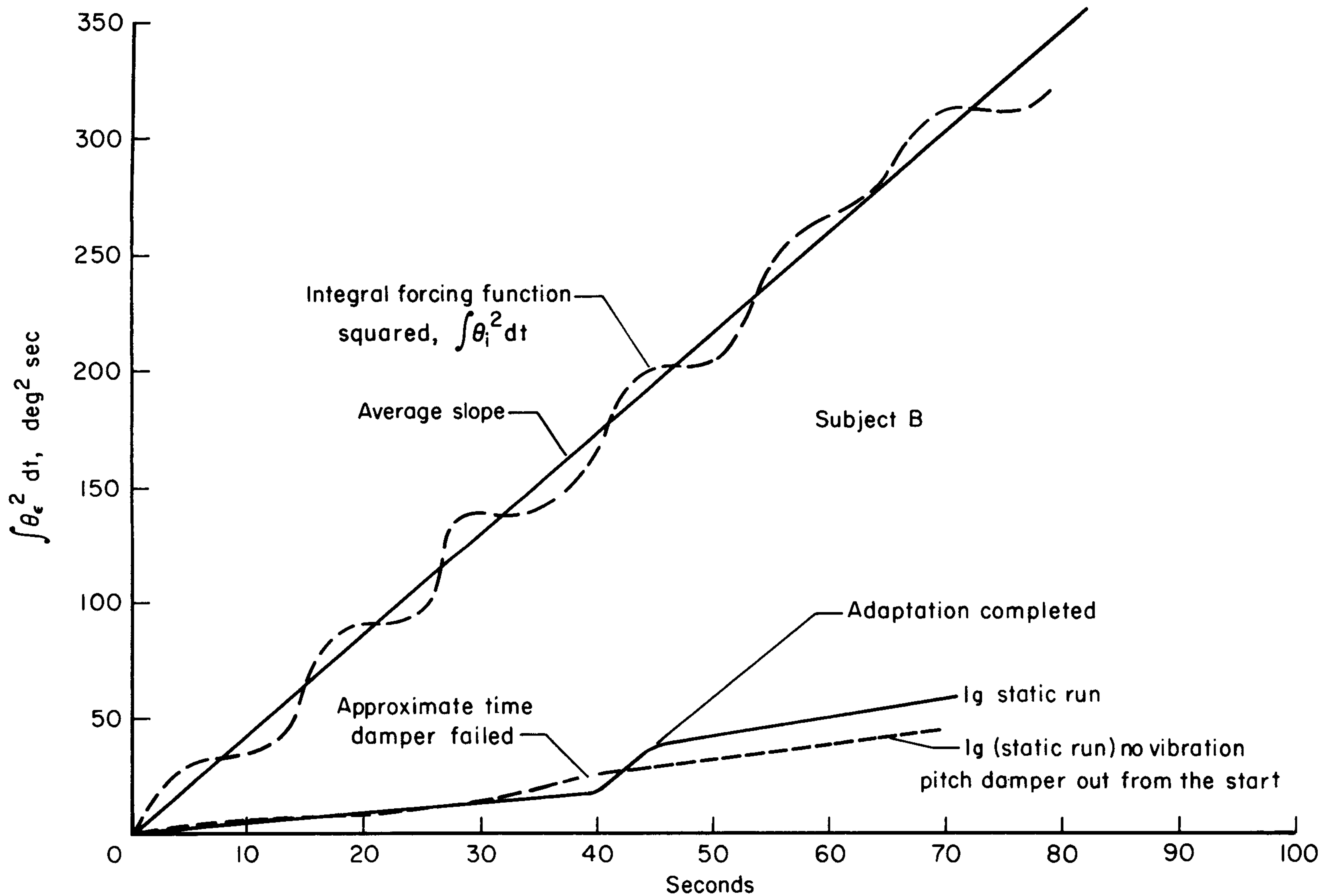


Figure 18.- Time histories illustrating effect of SAS configuration on pilot tracking performance.



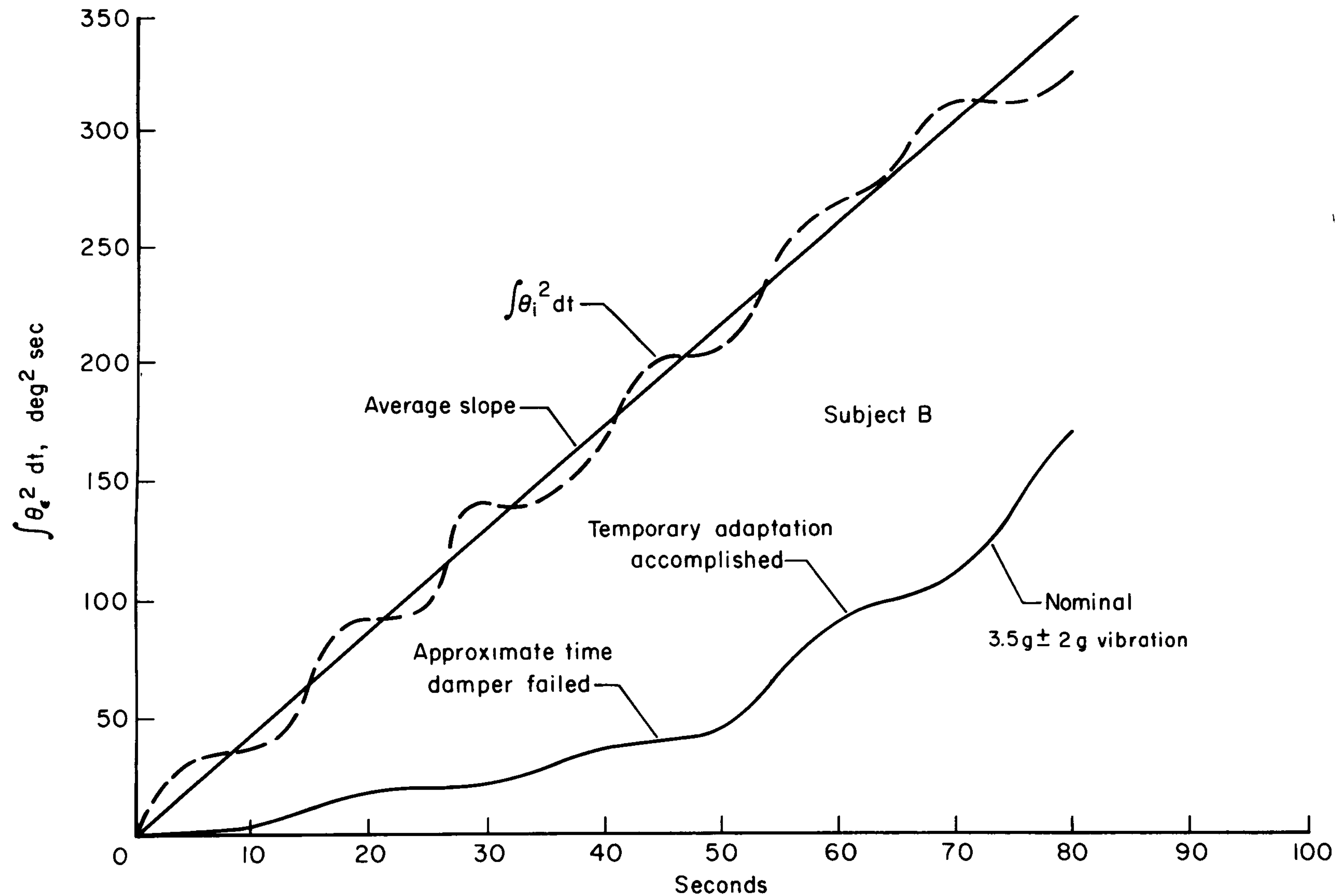
Note: Engine rate limit at 50°/sec

Figure 19.- Time histories of pilot tracking efficiency after pitch damper failure at different stress levels.



(a) 1 g static run.

Figure 20.- Effect of pitch damper failure under combined linear and oscillatory accelerations showing typical adaptation period.



(b) Nominal 3.5 g ±2.0 g vibration.

Figure 20.- Concluded.

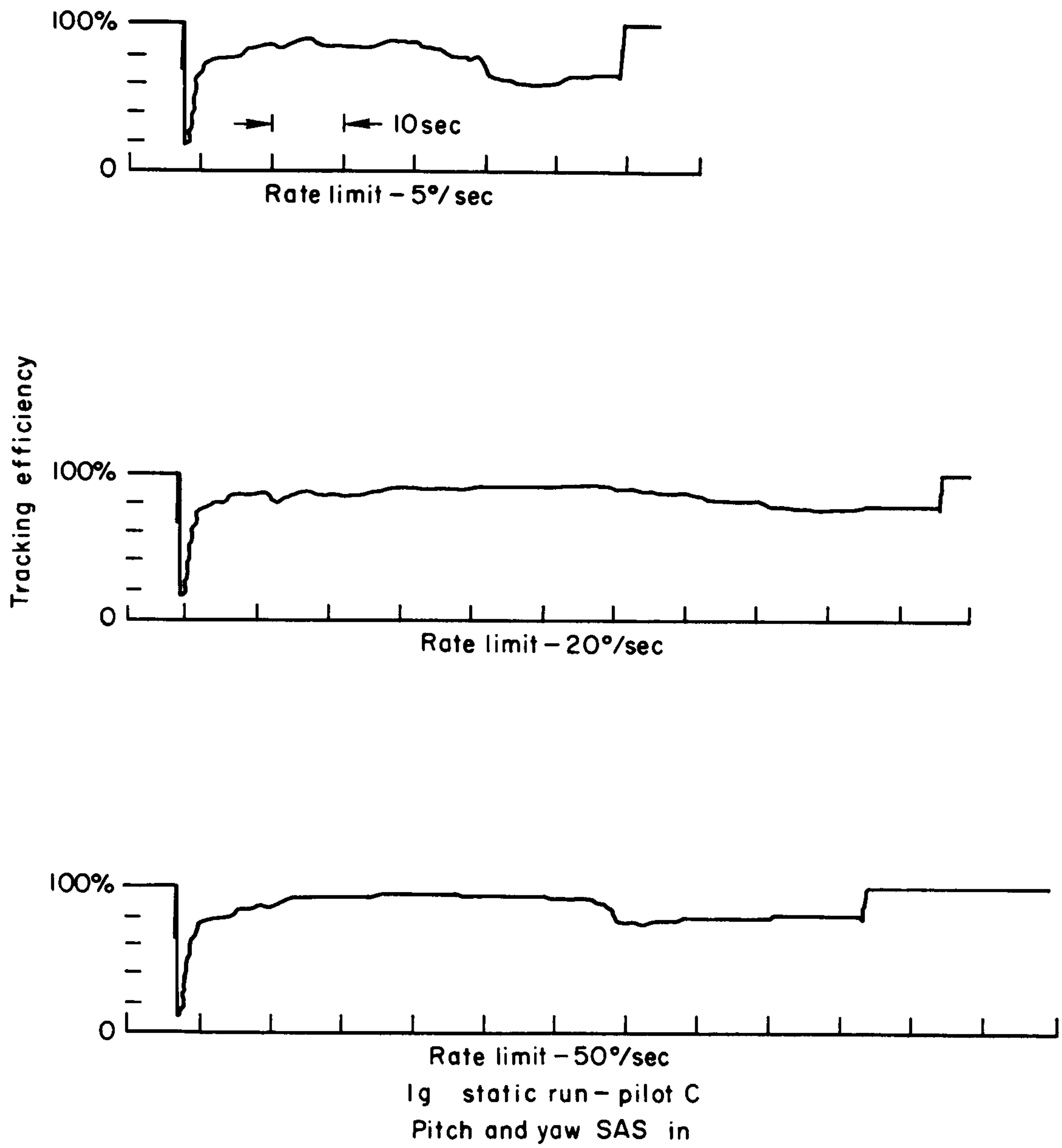


Figure 21.- Time histories showing effect of engine servo rate limiting on pilot tracking efficiencies.