NASA RESEARCH EXPERIENCE ON JET AIRCRAFT
CONTROL PROBLEMS IN SEVERE TURBULENCE

By Richard J. Wasicko

Headquarters
National Aeronautics and Space Administration
Washington, D.C., U.S.A

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SUMMARY

Several factors associated with the five jet upsets involving swept-wing jet transports which occurred in the United States are presented, and the elements of an intercenter NASA research program on the rough air control problem are reviewed. Described are some quantitative data on several factors which appear to contribute to the upsets and the piloting techniques which could cause flight path control difficulties. Aspects discussed are swept-wing jet transport handling qualities, flexible vehicle cockpit acceleration environment and its effect on pilot performance, simulator studies of aircraft control in turbulence and flight tests of upset-recovery maneuvers. It is shown that both the oscillatory and pure divergent initial phases of jet upsets similar to those experienced in airline operations could be achieved in the simulator. Flight tests of one transport revealed that supplemental recovery control in addition to the maximum elevator deflections available was required for rapid upset recovery if the stabilizer remained mistrimmed during the upset.

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Richard J. Wasicko*

1. INTRODUCTION

In 1963 and early 1964, after being in commercial air operations for four years, swept-wing jet transports in the United States experienced a series of accidents and incidents which were characterized by a period of uncontrolled flight with an attendant large altitude loss. For the majority of cases, the loss of control occurred during or soon after the penetration of a region of severe turbulence. These accidents have become known as "jet upsets," and the piloting difficulty has been termed "the rough air control problem."

The five jet upsets which occurred in the United States are usually identified by the location of the accident, these being Miami, Florida; O'Neill, Nebraska; Dulles Airport, Virginia; Houston, Texas; and New Orleans, Louisiana. A brief summary of several factors related to the five upsets is that two aircraft types were involved, and each experienced a fatal crash; three upsets occurred at night and two during the day; adverse weather existed in all five cases, although only two airplanes were in an extensive cloud formation before the occurrence; all five airplanes were attempting to climb; altitudes at which the upsets began ranged from 4,000 to approximately 38,000 feet; the altitude losses in the fatal crashes were approximately 6,000 and 19,000 feet, although successful recoveries were made in the other cases after altitude losses of about 2,600, 13,000, and 25,000 feet; and, finally, good flight recorder data were obtained in three cases, one of which was fatal. In addition to these five upsets, there are indications that at least three non-U.S. carrier fatal accidents involving similar aircraft were due to upset loss of control in turbulence.

The partial or complete loss of flight path control which occurred in the jet upsets was of considerable concern to the airlines, airplane manufacturers and government agencies involved, and several programs were initiated to examine possible contributing factors. Among the investigations were studies of attitude-instrument deficiencies, turbulence penetration speeds, instrument flight procedures in severe turbulence and acceleration stress and disorientation effects on the crew (Ref. 1-5). The problem was also studied outside the United States (Ref. 6,7).

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* National Aeronautics and Space Administration, Headquarters, Washington, D.C., U.S.A

The purpose of this paper is to briefly summarize the NASA research effort on the jet transport upset and recovery problem and to present some of the more significant results. More complete reporting on the program is contained in Refs. 8 to 12.

2. DESCRIPTION OF THE RESEARCH PROGRAM

The NASA intercenter program on the jet upset and recovery problem was initiated in December 1963 and, as briefly outlined in Figure 1, consisted of four activities. In the analysis phase, the handling qualities of three current jet transports were reviewed, and the flexible vehicle's normal and lateral acceleration response at various fuselage stations due to turbulence and control inputs were established for two aircraft. Wind tunnel tests concentrated on establishing static and dynamic stability derivatives at high Mach numbers and high angles of attack. In addition to obtaining stability and control and handling qualities data and evaluating upset recovery characteristics, the flight phase was used to measure the flexible airplane's response in turbulence and to provide large jet transport airplane control experience for NASA pilots. The simulation program studied the effect of turbulence on airplane responses and the influence of the cockpit acceleration environment on pilot performance as well as evaluating handling qualities and piloting techniques in turbulence penetrations. It also evaluated the use of a one-degree-of-freedom motion simulator as a training device.

3. RESULTS AND DISCUSSION

The research program did not reveal any singular cause for the jet transport upsets. However, quantitative data were obtained on several factors which appear to contribute to the jet upsets, and piloting techniques which could cause path control difficulties were determined. Those aspects which seem to be more directly related to the flight-experienced problem and which will be discussed in some detail are swept-wing jet transport handling qualities, the flexible vehicle cockpit acceleration environment, piloting techniques and upset-recovery maneuvers.

3.1 Handling Qualities Analysis and Flight Test Data

Based on wind tunnel and estimated stability and control data, the handling qualities of three jet transports were reviewed and compared with existing and proposed criteria and other handling qualities data, such as those in Refs. 13 to 18. Included in this review were the dynamic response characteristics for small perturbation disturbances from steady-state flight. The major observations were as follows: the longitudinal short-period appeared to have satisfactory levels of damping and natural frequency, although the frequency tended to be lower than desired during the low speed cruise and holding flight conditions; the phugoid was stable with apparent acceptable damping except for the maximum speed condition for two airplanes at which the divergent tuck mode had times-to-double amplitude from 7 to 31 seconds; the Dutch-roll damping with the yaw damper inoperative was generally low, appeared marginal when compared to several proposed criteria and exhibited a fairly large difference between airplanes; the bank angle to equivalent side velocity ratio for the Dutch-roll mode was of modest magnitude, although flight tests indicated higher values than estimated for one airplane; and the yaw response due to aileron was small.

In addition to subsonic and transonic wind tunnel tests of a representative airplane model, control effectiveness and hinge moment data were obtained for a full scale stabilizer-elevator-tab combination of one of the jet transports which experienced a fatal accident. These were used in the analysis of longitudinal control force static maneuvering stability. The results indicated a nonlinear variation of control force with normal acceleration with a slope reversal occurring at a modest negative load factor with the stabilizer at full nose-down trim and at a small negative load factor with the normal climb stabilizer trim setting. Although data at negative g's were not obtained during the flight test program of the same jet transport, the measured elevator stick force gradient with normal acceleration approached zero at very low positive load factors. Figure 2 presents the longitudinal maneuvering characteristics of this airplane at an altitude of 34,500 feet and a Mach number of 0.84. The wheel-force data are for two configurations of the elevator balance system which are described in Ref. 8.

The handling qualities analysis effort, supported by portions of the flight test data, indicated that within the normal operating boundaries there were no unusual or dangerous characteristics although the low Dutch-roll damping would increase the pilots' work load, especially in rough air flight, and hence detract from the longitudinal control task. Potentially more serious was the reduced stick force per g at low load factors, which could amplify an incipient upset.

3.2 Cockpit Acceleration Environment

A considerable portion of the analysis, flight test, and simulation effort was directed toward determining the flexible airplane response characteristics to turbulence, with emphasis on the normal accelerations at the pilots' station, and evaluating the effects of this enviornment on crew stress, tolerance, and performance. The pilots' station normal acceleration power spectra obtained from a thunderstorm penetration with an instrumented jet transport is shown in Figure 3 together with the power spectra of the acceleration at the airplane's center-of-gravity and at an aft fuselage station. These data include the flexible airplane's response to both turbulence and pilot control inputs. A peak in the power spectra of the cockpit acceleration is clearly evident at about 4.5 cps and is presumably associated with the first fuselage bending structural mode since a similar predominant vibration exists at the aft fuselage station but not at the center-of-gravity. In addition, moving simulator tests, the results of which are shown in Figure 4, indicated that in the frequency range of from 2.5 to almost 5 cps and with a conventional seat cushion the acceleration at the pilot's head was amplified by a factor of two or more with respect to the acceleration at the flight deck. With no seat cushion the acceleration amplification is slightly lower in this frequency range, and the attenuating effects of the cushion do not occur until frequencies above 5 cps are reached. Since the fuselage bending frequencies of the current jet transports are in the region where the acceleration at the pilot's head is amplified and human tolerance to vibrations is inversely related to head accelerations, it is apparent that the present seat cushions are ineffective in reducing the stress environment during flight through turbulence.

The predominant cockpit vibration at about 4.5 cps is near the frequency at which human subjective tolerance to oscillatory accelerations is most severely reduced. This is shown in Figure 5, where the range of root-mean-square accelerations at various fuselage stations of a jet transport measured during a thunderstorm penetration is compared with the data of Ref. 19. Comments from the crew on this flight generally support the conclusion based on the Ref. 19 data that the oscillatory accelerations would be considered mildly to extremely annoying. The 4.5 cps fuselage vibration is also in the frequency region where there is a significant increase in the occurrences of large instrument reading errors when relative oscillatory motion exists between a subject and an instrument dial, as shown by the data of Ref. 20 presented in Figure 6.

3.3 Simulation of Aircraft Control in Turbulence

It was considered important to produce the cockpit acceleration environment in the simulation program which assessed the relative importance of various factors on the flying task in turbulence. Consequently, the Ames Research Center's height control simulator, shown in Figure 7, was used. The simulator cab, which is mounted on a vertical track and driven by high performance electrical servo motors through a cable system, can traverse 100 feet. This device allows the partial simulation of the low frequency cockpit normal acceleration due to rigid airplane response to turbulence and control inputs and the higher frequency vibration due to flexibility. Figure 8 shows the simulator cockpit which employed basic controls and flight displays similar to those installed in jet transport airplanes. The cockpit is single place and utilized white light for instrument illumination. As can be seen in the photograph, a two-color attitude indicator was used in the simulation program.

The aerodynamic and control system characteristics which were programmed on the computer were generalized to be typical of a swept-wing jet transport at mid-cruise loading. An operating envelope extending from 25,000 to 45,000 feet in altitude and up to a Mach number of 1.0 in speed was provided, and although most of the stability and control derivatives were constant and invariant with Mach number, nonlinear representations of the lift, drag, pitching-moment, and longitudinal control gradients were used. In addition, the following characteristics were provided in a simplified, qualitative manner: a performance reduction with altitude; decreased longitudinal control power at high indicated airspeeds and Mach numbers; a reduction in longitudinal static stability at the stall; speed instability, or a tuck mode, at high Mach numbers, together with a simulated Mach trim compensator; and increased cockpit vibrations at both the stall and high Mach numbers.

There were no indications of severe control difficulties during the portion of the simulator program in which research pilots evaluated the rough air flight task with all displays operative, even under the most severe levels of turbulence. However, as indicated in the upper portion of Figure 9, a large flight-path oscillation was induced by a research pilot when he intentionally deprived himself of pitch-attitude information and over-concentrated on tight airspeed control. A portion of the pilot's comments after this simulator run is as follows: "After one or two cycles, large variations in attitude, airspeed, and rate-of-climb could be observed, but concentration was maintained in making the control inputs based on airspeed information alone. The oscillations continued to diverge, resulting in aircraft buffet during the positive g pull-out from the higher speed portions of the oscillation. The pilot was conscious of pulling and pushing with significant force to control the airplane, but this did not seem unnatural considering the variations in airspeed that were occurring." Shown in the lower part of Figure 9 is the portion of the flight recorder data just prior to an actual jet upset dive in which 25,000 feet of altitude were lost before recovery. The similar trends in the altitude and airspeed oscillations are apparent.

Simulator runs were also made with different piloting techniques when the attitude information was not used. Over-concentration on airspeed control but including altitude and rate-of-climb information in a reasonable scan pattern did not normally induce flight path control difficulties. However, the research pilot's comments on a simulator run in which an unknown out-of-trim condition was imposed immediately upon entering heavy turbulence are quite interesting. He stated, "I believe that during this run a deliberate attempt was made to over-concentrate on airspeed in order to induce some deviation in airspeed and altitude. In any case, during some of the long-period oscillations which occurred, a distinct feeling of panic occurred momentarily when a cross check of the instruments revealed that while I was holding forward pressure on the yoke to arrest a decreasing airpseed condition, the altitude could be observed rapidly increasing. This gave an immediate sense of conflict between airspeed and altitude information. This type of conflict is felt significant and could easily cause a sense of panic in any pilot who observes it. The immediate question in my mind was which information I could then rely on. Due to the rapidly rotating altitude needle and the rate-of-climb needle being pegged, it was natural to make the choice of airspeed. I believe this would be a natural choice by pilots even though it was oscillating due to the rough air, it still was moving in a steady, or more rational manner. It is well known that pilots respond to control force as a cue. Therefore, it is not difficult to realize that, to a pilot, holding strong forward pressure on the yoke was an indication that I was applying the proper correction; however, due to the nose-up mistrim condition, my correction was not enough to significantly affect airplane attitude and flight path rapidly and start the airspeed to decreasing again. This sluggish response in arresting the decelerating airspeed was in direct contrast to what occurred during the high speed portion of the oscillation. When the airspeed buildup was recognized and the stick force was relaxed, preparatory to pulling the nose-up, the out-of-trim condition automatically put in recovery control and pitch attitude probably overshot in a nose-up direction before any indication of decreasing airspeed could be noted."

It was felt that the simulation, although only involving a one-degree-of-freedom motion device, accurately reproduced the essential elements of the jet upset problem, and consequently it was used in a demonstration program for pilots from the airline industry. Each pilot spent about one hour becoming familiar with the characteristics of the simulated aircraft, including its stall response and flight behavior at speeds above a Mach number of 0.9. Then approximately one hour was devoted to simulated thunderstorm penetrations and demonstrations pertinent to rough air piloting techniques. The most critical task given each pilot was introduced during his third turbulence encounter. While requested to descend 5,000 feet and change heading simultaneously, his pitch trim compensator was rendered inoperative so that an unstable longitudinal trim change would accompany any speed increase beyond a Mach number of 0.84. Five of the fourteen pilots who were given this task experienced some form of flight path control difficulty.

Figure 10 illustrates the performance which was typical for most of the pilots. The altitude and Mach number traces show that the pilot maintained a reasonably steady rate of descent and good airspeed control. The normal acceleration environment at the pilot's station is fairly severe, with occasional load factor excursions greater than 2 g and less than zero g. The pilot in this run used relatively low control forces during the simulated turbulence penetration. An example of a simulator run in which the pilot experienced flight path control difficulties is shown in Figure 11. Although the airplane did not accelerate beyond

0.84 Mach number and into the tuck region, two momentary stalls were induced when the pilot attempted to arrest undesirably high rates of descent and stabilize at an altitude of 33,000 feet. In comparison with the results in Figure 10, fairly large control column forces were used by the pilot during the flight path oscillations.

Shown in Figure 12 are the time histories from a simulator run in which initial divergences in speed and altitude occurred due to a low frequency downward gust. The pilot first allowed the speed to increase beyond Mach number 0.84 where the tuck mode augmented the divergence, and then failed to arrest a further speed increase when applying a column pull force of only about 15 pounds. The delay in recognizing and counteracting the seriousness of the situation allowed the aircraft to accelerate into the transonic speed region where elevator control effectiveness was reduced. This simulator run produced a flight path response which could be considered the initial phase of a large altitude loss upset.

3.4 Flight Tests of Upset-Recovery Maneuvers

Since the simulation program demonstrated that it was possible to achieve both the oscillatory and pure divergent initial phases of jet upsets similar to those experienced in airline operations, one of the primary objectives of the NASA flight tests was to evaluate upset recovery techniques. Because the investigations of several turbulence-associated accidents revealed that the stabilizer was at or near the aircraft nose down limit at impact, a significant part of the flight program was devoted to investigating the longitudinal control characteristics with this trim setting and the pilots' ability to recover from an upset using elevator alone, elevator plus stabilizer retrimming, and elevator plus deployment of spoilers.

Figure 13 shows time histories of pertinent parameters during a controlled upset initiated by a stabilizer runaway to the full aircraft nose down position and a recovery using elevator and stabilizer retrim. As indicated by the normal acceleration trace, the airplane went from level flight to approximately -0.2g when the stabilizer reached its limit. The throttles were reduced to idle at overspeed warning, and recovery with elevator only was initiated one second later. At time 18 seconds the full recovery elevator deflection available was obtained and a normal acceleration of 1.3g existed. The elevator and acceleration traces between 18 and 20 seconds indicate a loss in elevator effectiveness as the Mach number increases in this time increment, since the elevator remained essentially constant while the acceleration decreased from approximately 1.3g to 1.0g. Although there is no apparent reduction in the rate of descent while the elevator only recovery was attempted, after the stabilizer was returned to its original trim position, the normal acceleration increased rapidly and a level-flight condition was soon achieved.

A similar maneuver is shown in Figure 14, but in this case the final recovery was accomplished by deflecting the spoilers with the stabilizer remaining in its full nose down position. Again it can be seen that the elevator effectiveness was reduced at the higher Mach numbers, in this case in the time period between 15 and 19.5 seconds when the load factor decreased from 1.5g to 1.1g with constant elevator deflection. Although the spoiler handle was moved to the full 60° position, only 30° of spoiler deflection were obtained because of the blowdown air loads at high dynamic pressure. However, this much spoiler, in conjunction with the elevator, was adequate to achieve complete recovery.

There were no problems in recoveries with elevator only when the stabilizer remained in the level flight trim setting during the flight upset maneuvers. It is apparent, however, that for this particular airplane supplemental recovery control in addition to the current maximum elevator deflections available is needed for rapid upset recoveries if the stabilizer remains mistrimmed during the upset.

4. CONCLUSIONS

The NASA intercenter research program showed that the following considerations could contribute to the jet transport upset and recovery problem: the low Dutch-roll damping with yaw damper inoperative could increase the pilots' work load in turbulence and detract from the longitudinal control task, which is aggravated by reduced stick force per g gradients at low and high load factors to the extent of possibly amplifying an incipient upset; the flexible airplane's response to turbulence produces increased cockpit accelerations in the 4 to 5 cps region which are further amplified at the pilots' head when a conventional seat cushion is used, thus presenting an environment detrimental to crew tolerance and instrument reading performance; inadequate use of pitch attitude displayed information and over-concentration on airspeed control can induce large flight path oscillations in severe turbulence, and a mistrim condition in conjunction with delay in rapidly counteracting airspeed buildup with the Mach trim compensator inoperative can produce the initial divergence of an upset; and finally, reduced elevator control power at higher Mach numbers can retard elevator-only upset recoveries with a critically mistrimmed stabilizer.

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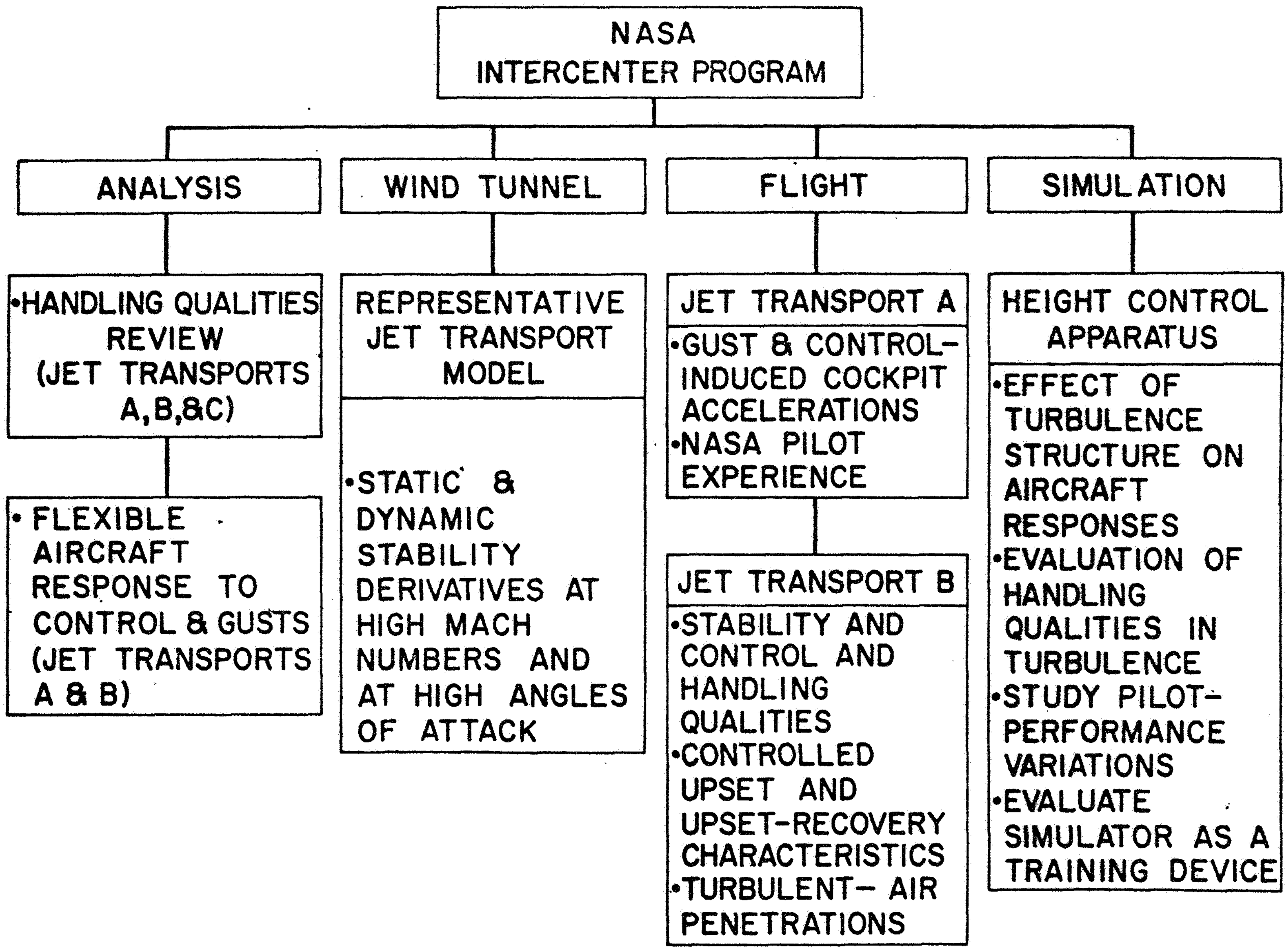

Fig. 1 NASA research programs on the jet transport rough air control problem

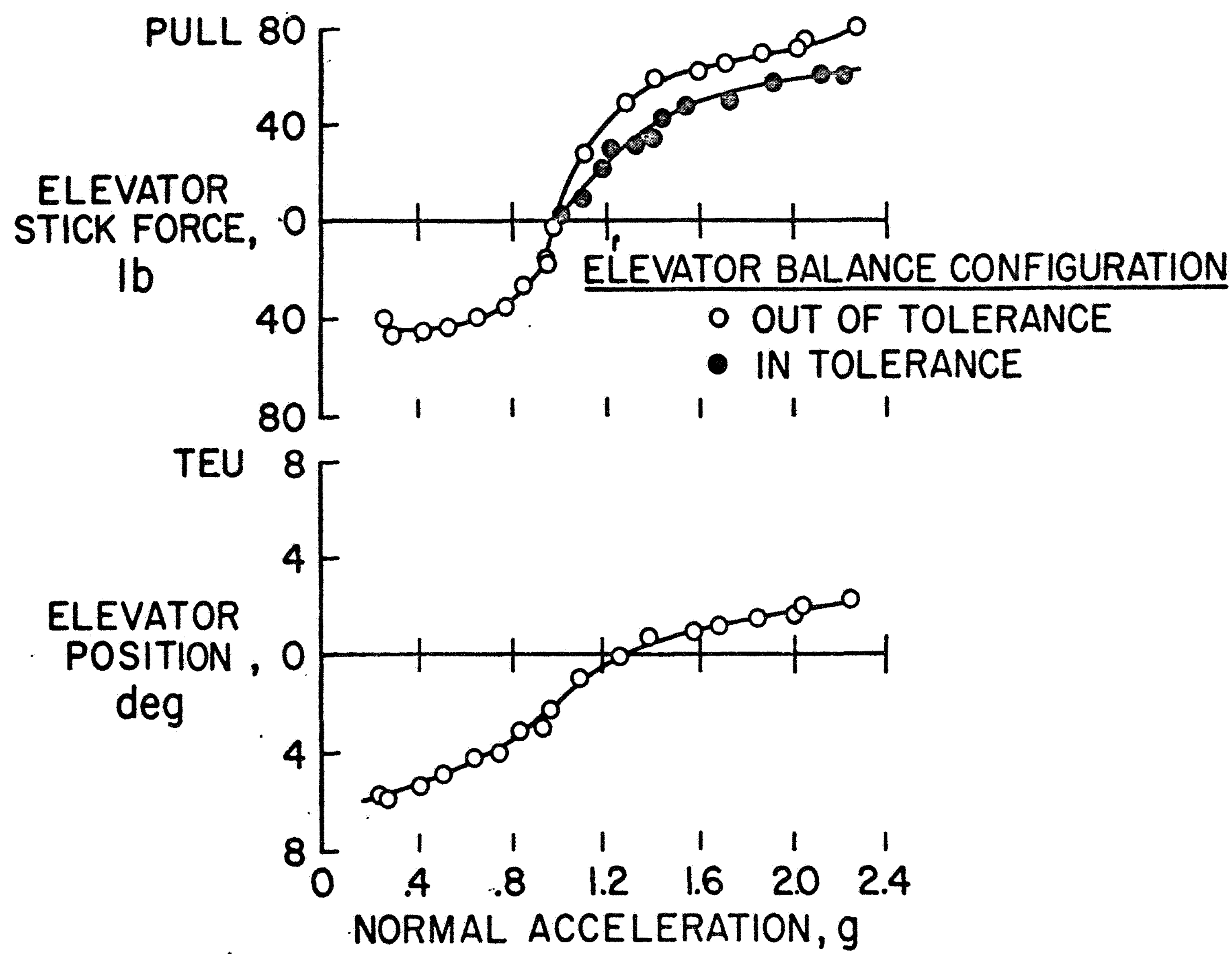

Fig. 2 Longitudinal control maneuvering characteristics

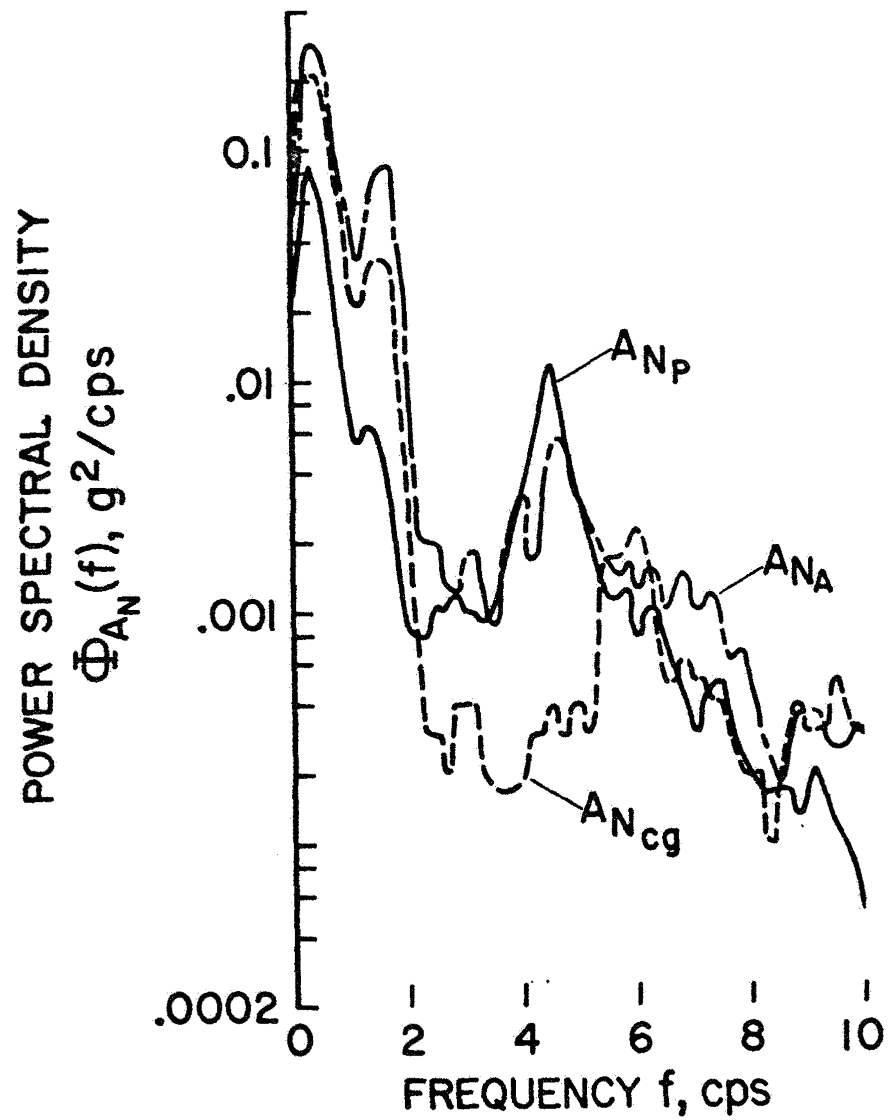

Fig. 3 Normal acceleration power spectra

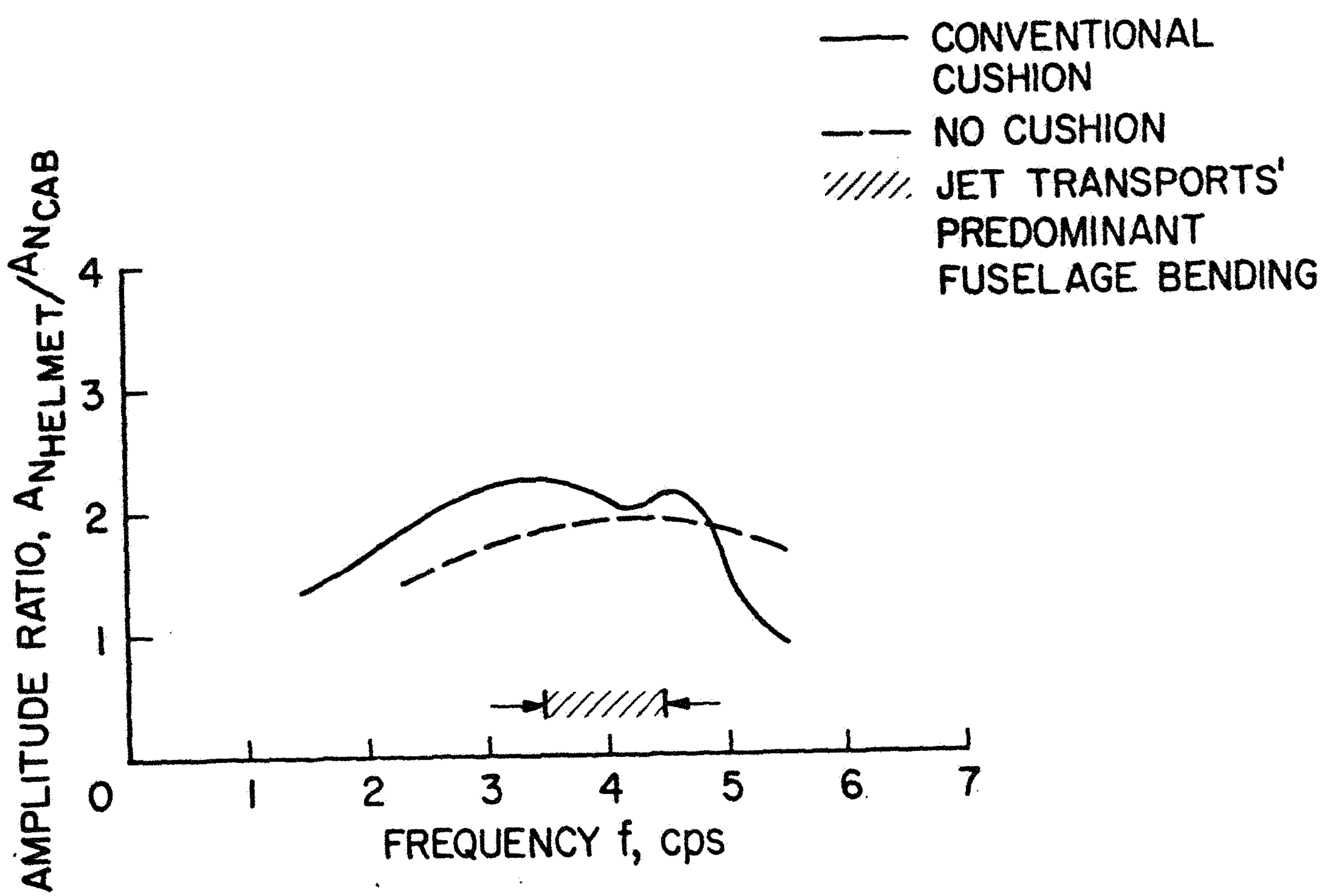

Fig. 4 Effects of seat cushion on acceleration amplification at pilot's head

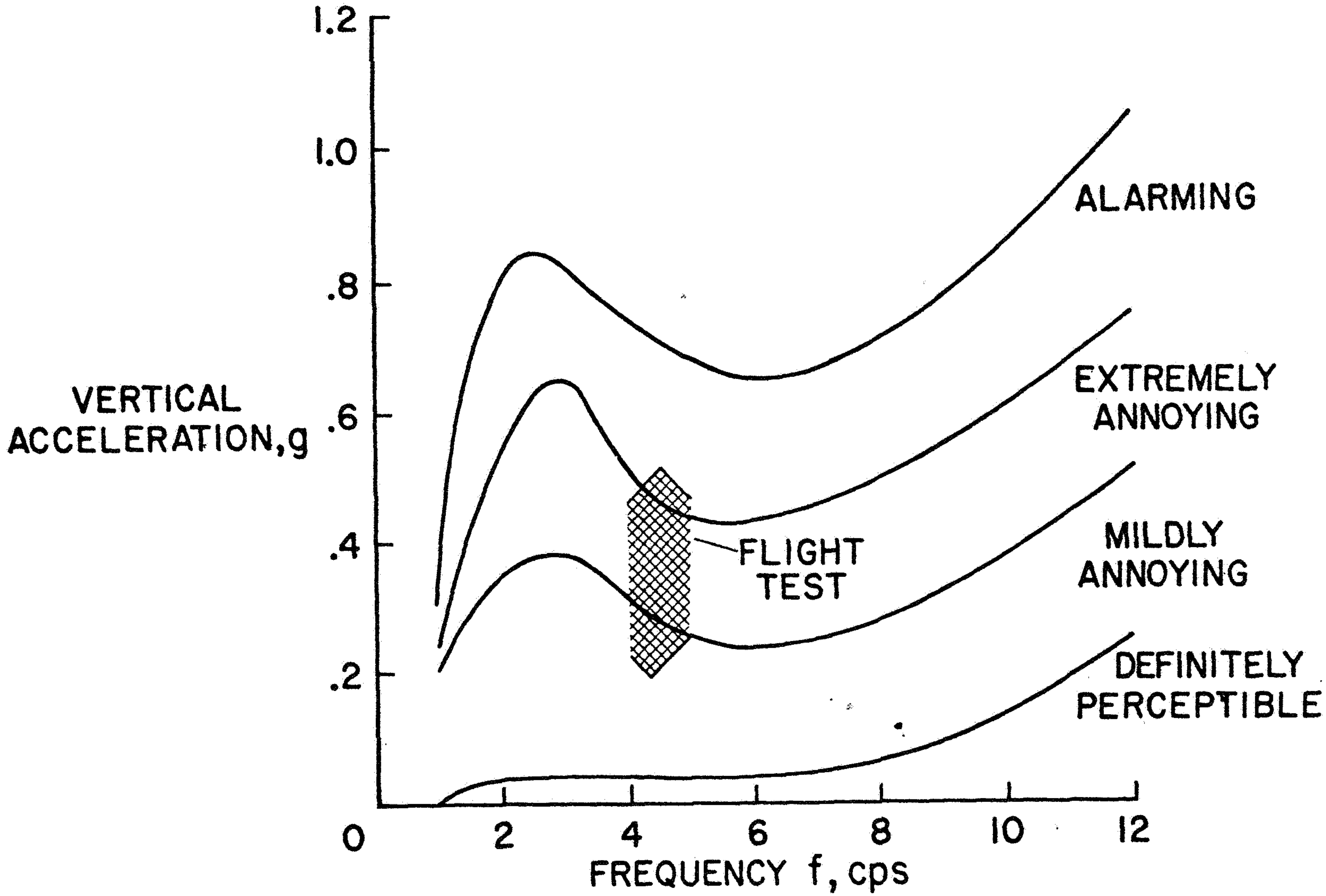

Fig. 5 Human subjective response to vibratory accelerations

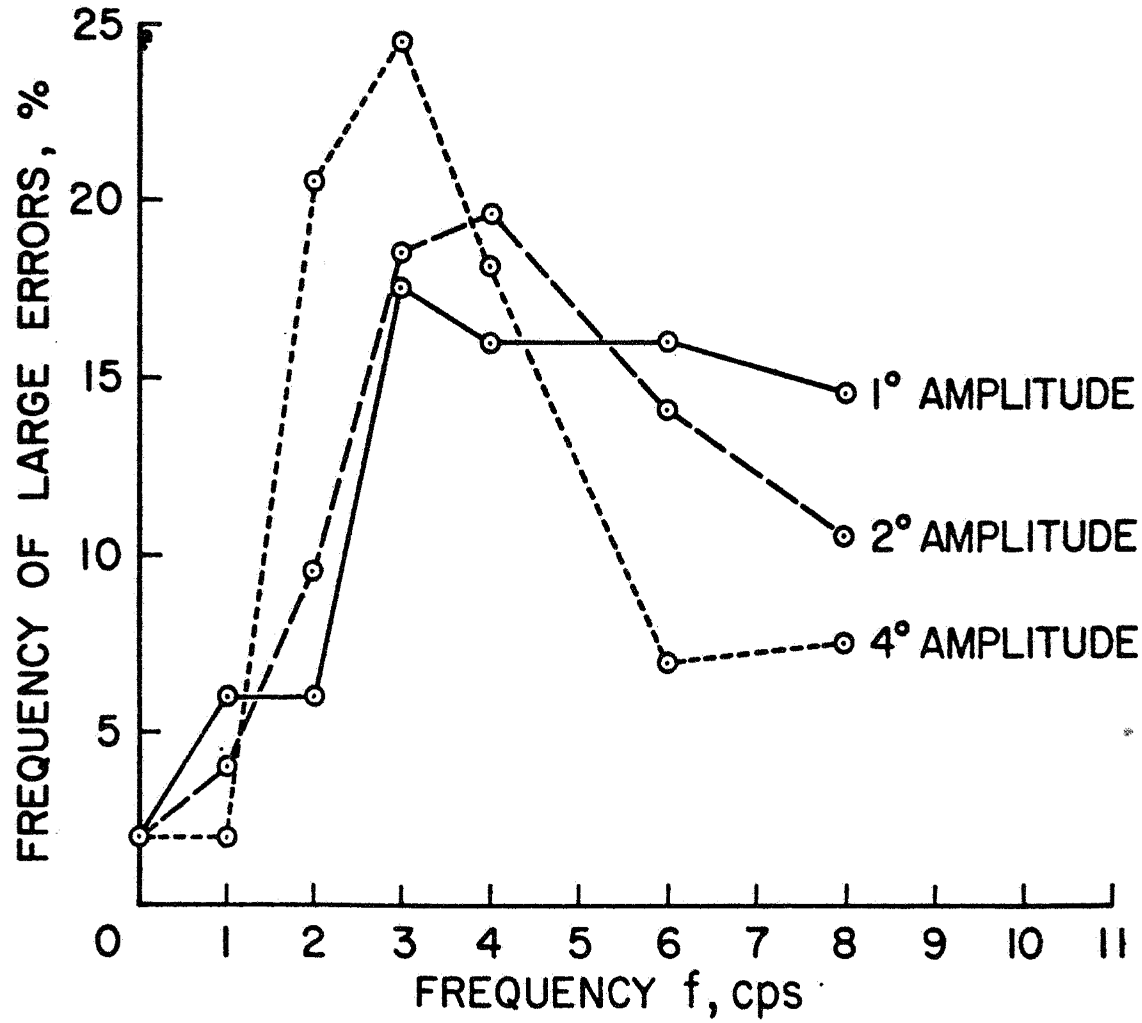

Fig. 6 Effect of vibration on instrument reading errors

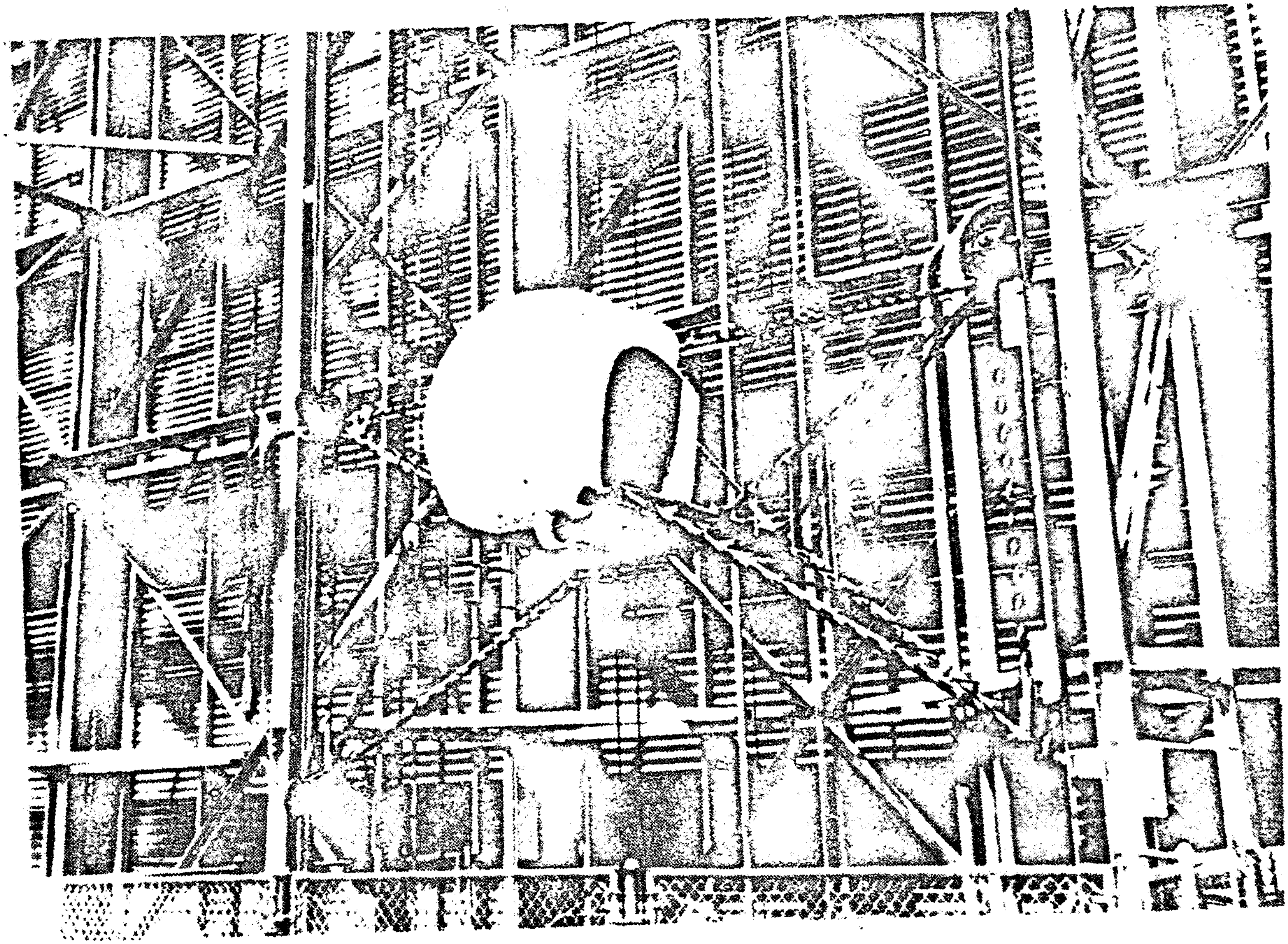

Fig. 7 View of piloted simulator cab

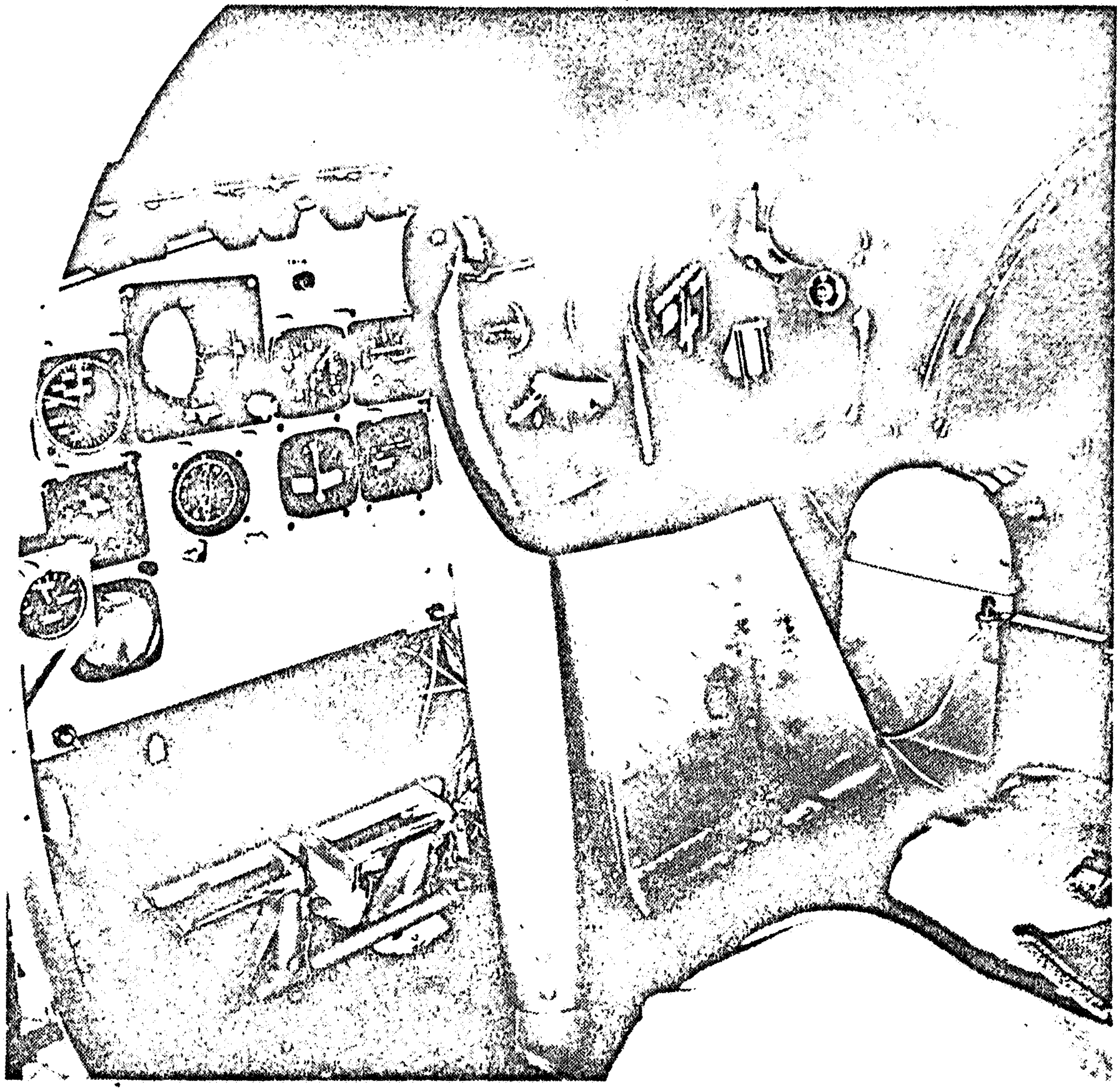

Fig. 8 View of cockpit interior

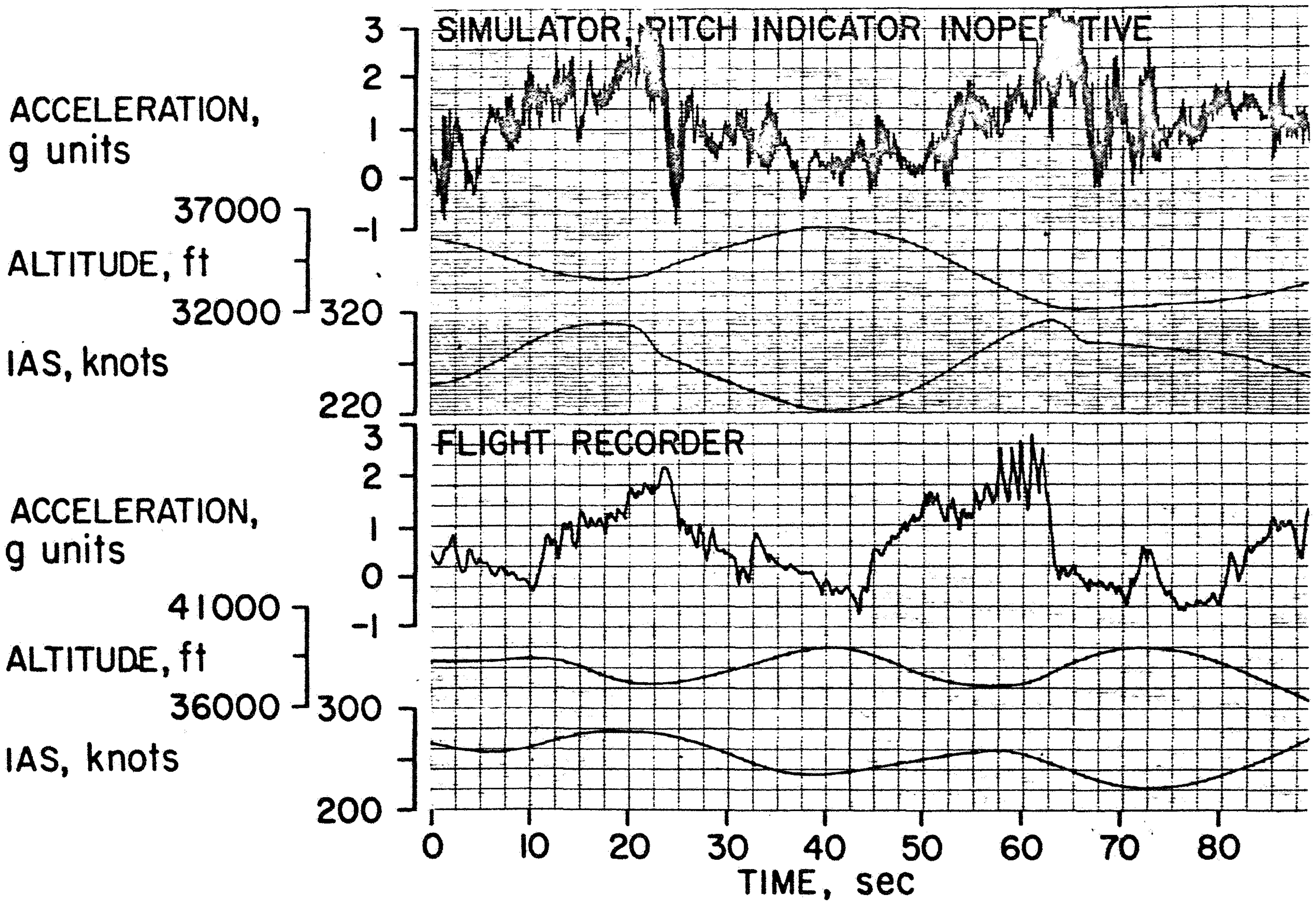

Fig. 9 Flight path oscillation in the simulator and in flight

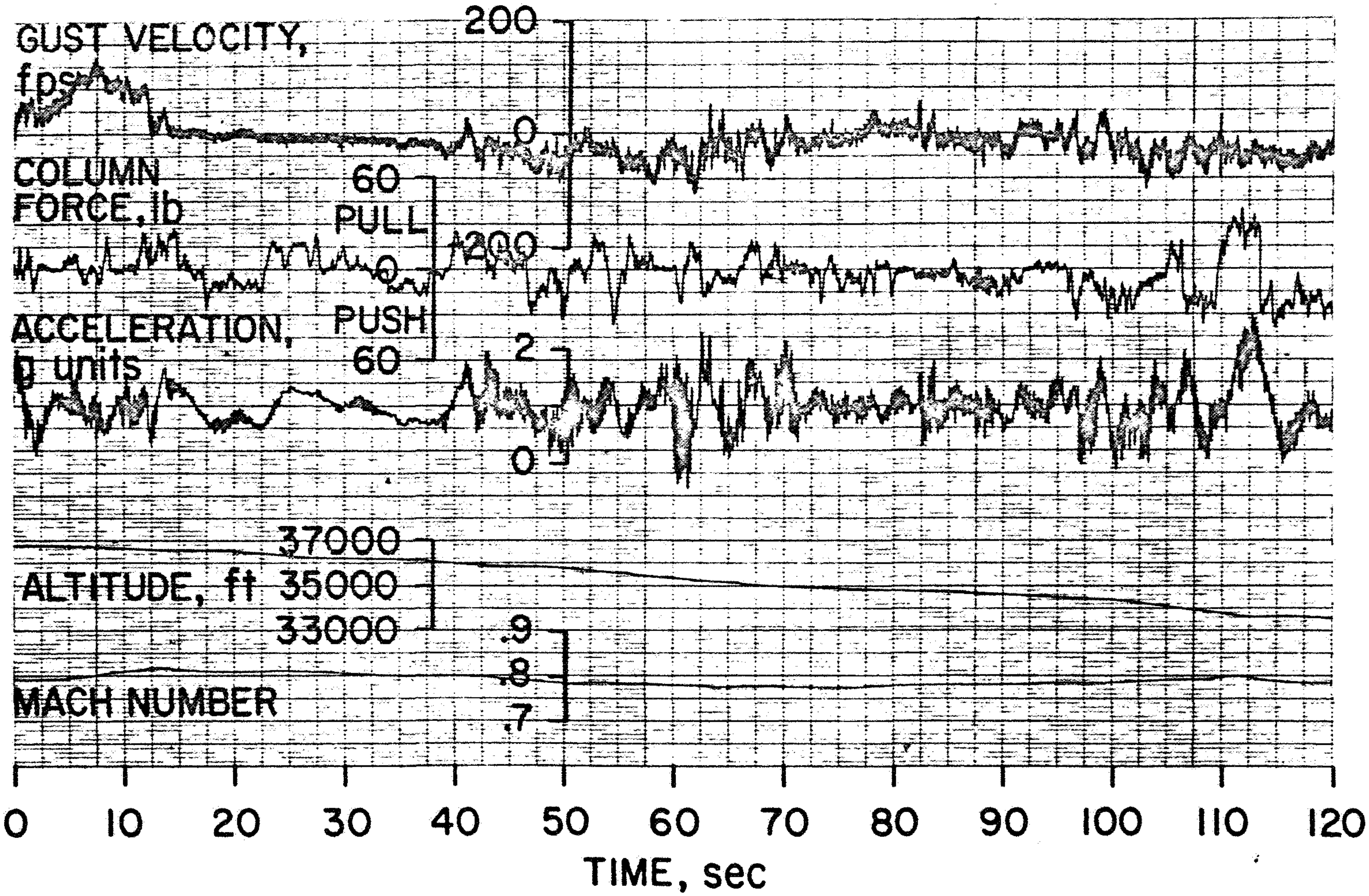

Fig. 10 Precise flight path control during simulated severe turbulence penetration

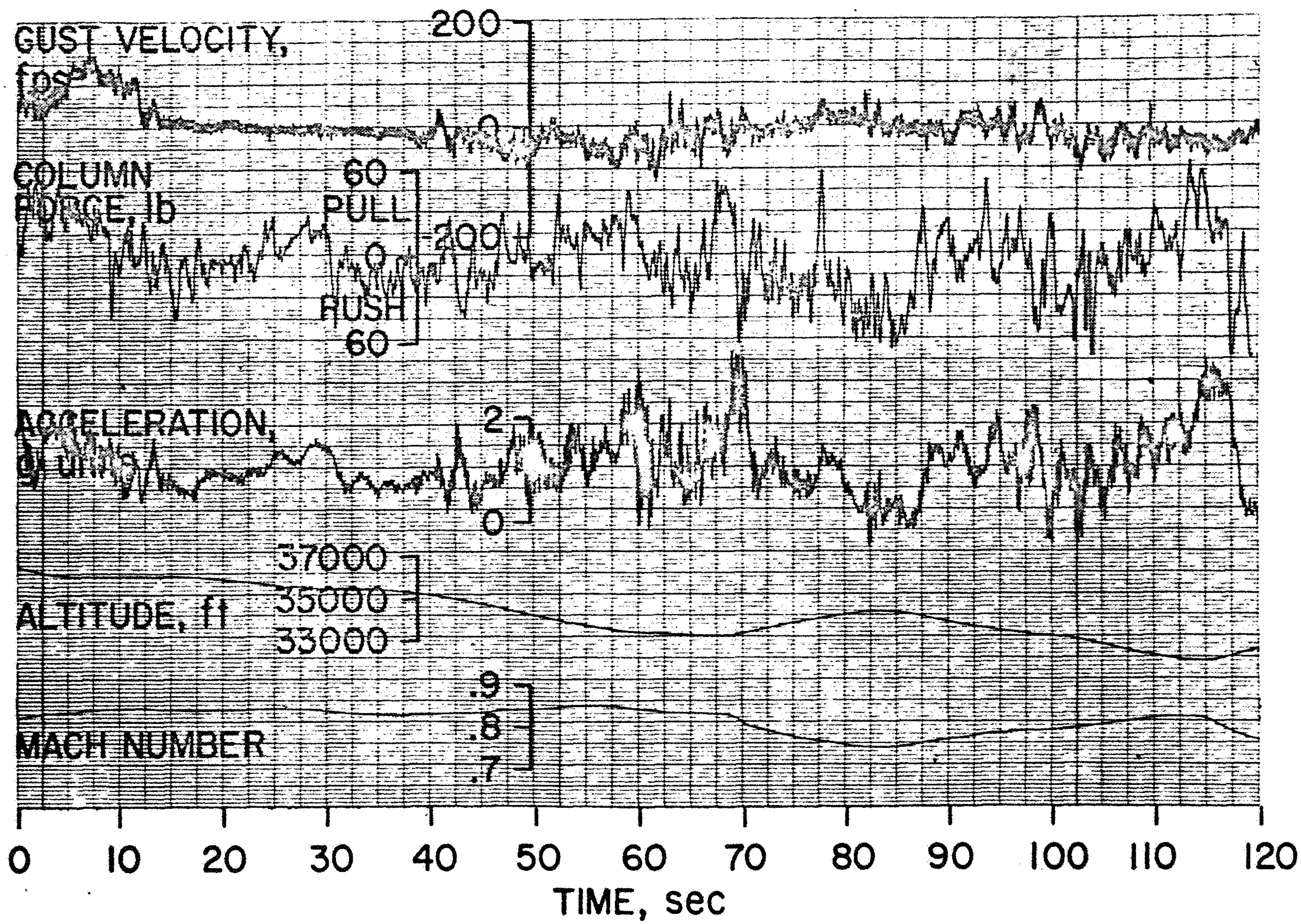

Fig. 11 Marginal flight path control during simulated severe turbulence penetration

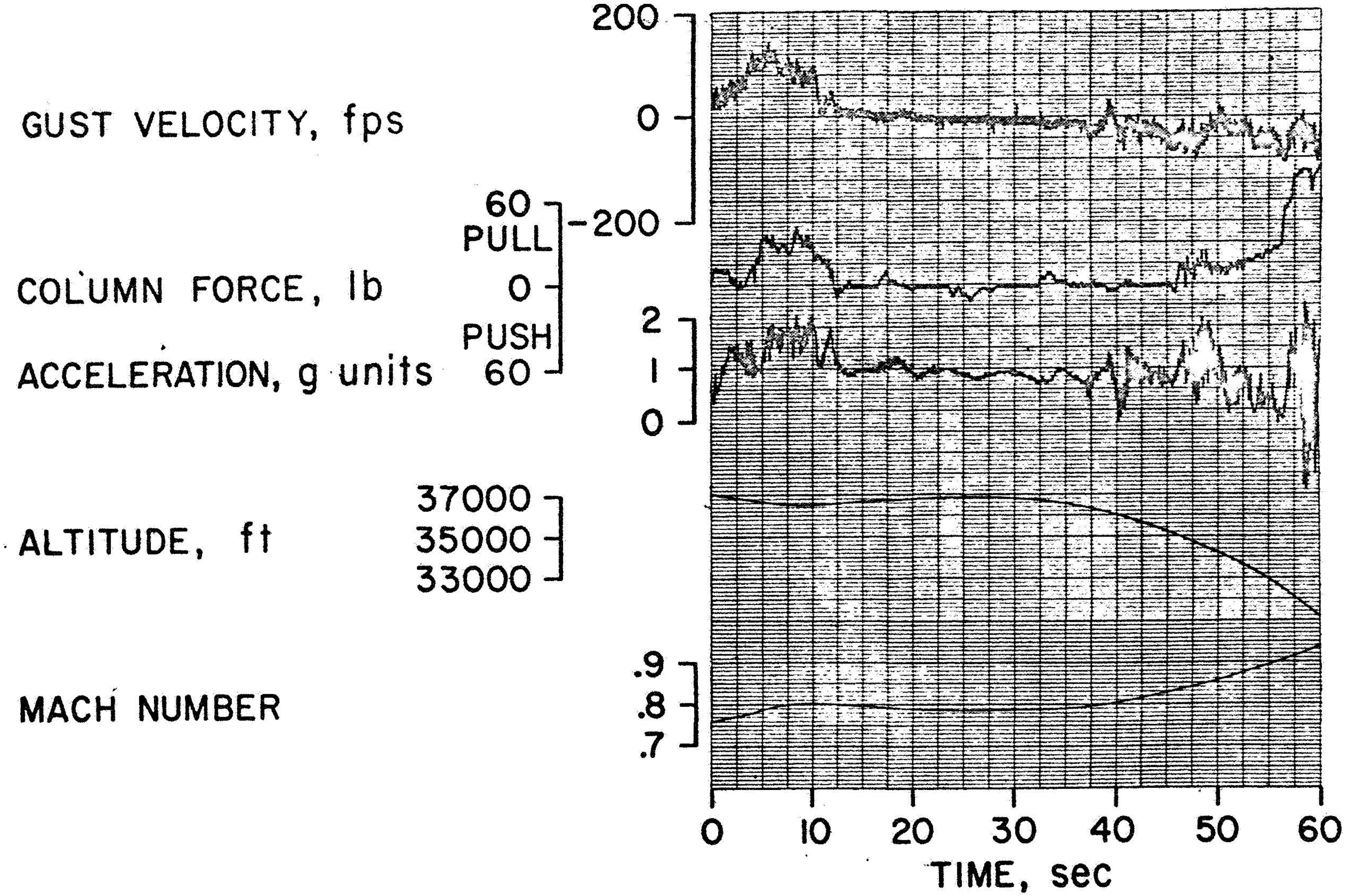

Fig. 12 Flight path divergence obtained in the simulator

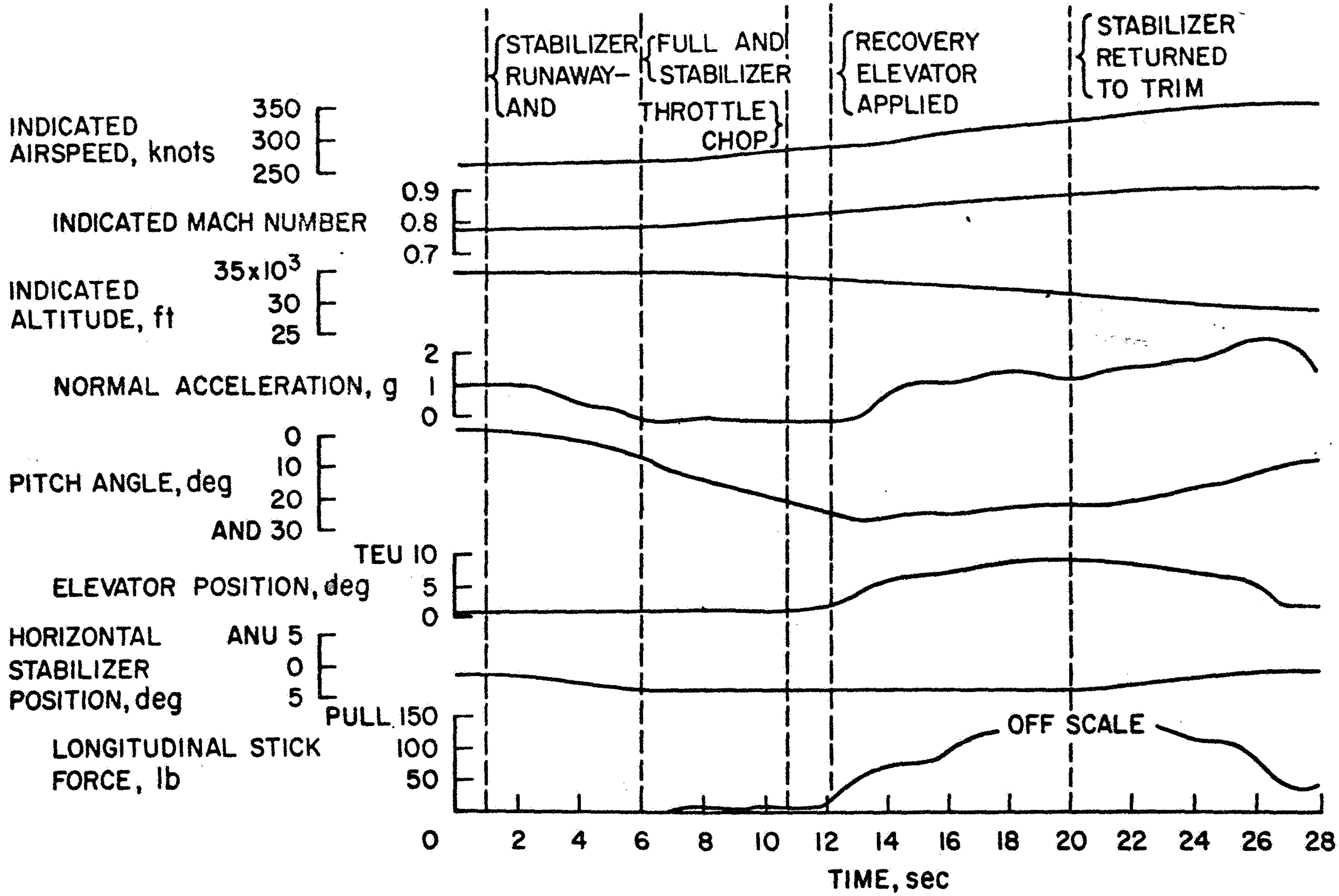

Fig. 13 Controlled upset maneuver - elevator/stabilizer recovery

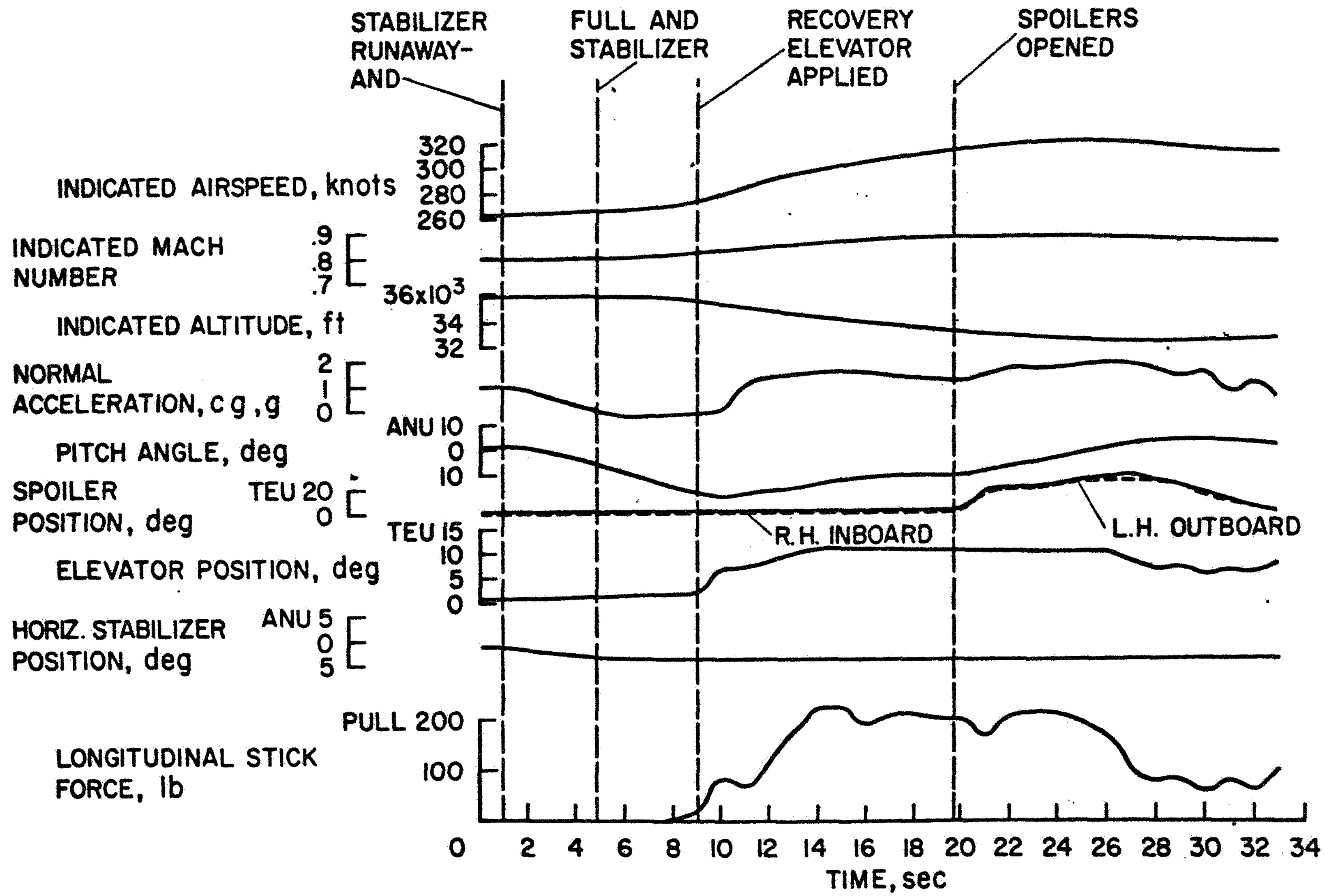

Fig. 14 Controlled upset maneuver - elevator/spoiler recovery