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Summary of NASA Research on Jet Transport Control Problems in Severe Turbulence

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Research results from analytical, piloted-simulator, and flight studies have made it possible to evaluate the relative significance of cockpit accelerations, stability and control characteristics, and handling qualities in the upset and recovery problems of swept-wing jet transports encountering severe turbulence. Results of simulator tests, conducted on a device capable of reproducing cockpit-acceleration response to thunderstorm turbulence, indicated that cockpit accelerations (including vibration caused by a predominant fuselage bending mode) were distracting to the pilots and impaired their normal instrument-scan pattern. These acceleration effects appeared to be primary contributing factors to several incidents involving marginal and complete loss of control observed during pilot performance of a complex task in the simulator. Results and comments from a number of airline pilots exposed to the simulation demonstrated the training potential of this type of simulator for familiarizing the pilot with the disconcerting accelerations of the aircraft and with handling characteristics beyond the normal operating range. Flight tests, conducted in cooperation with the Federal Aviation Agency (FAA), indicated that, in simulated upsets, elevator control alone was insufficient for recovery, even at moderate overspeeds. Spoilers and stabilizer proved useful control aids for recovery; however, the use of an accelerometer to monitor acceleration during recovery was considered desirable.

Nomenclature

A_N = normal acceleration, g
A_Y = transverse acceleration, g
f = frequency, cps
g = acceleration of gravity, ft/sec²
h = pressure altitude, ft
V_i = indicated airspeed, knots
Φ_{A_N} = normal acceleration power spectral density, g^2/cps
$_Y$ = transverse acceleration power spectral density, g^2/cps

Subscripts

A = aft fuselage
c.g. = center of gravity
P = pilot station

Introduction

DURING the past several years, swept-wing, jet transport aircraft have been involved in a number of serious incidents resulting from encounters with heavy turbulence. These experiences fall into two categories: those resulting from encounters with clear-air turbulence that caused structural damage and personnel injury, and those from encounters with storm turbulence, during instrument flight, which resulted in partial or complete loss of control of the aircraft. The former problem clearly indicates the need for improved techniques for detecting clear-air turbulences; however, the latter problem is less well defined and has resulted in increasing concern to the air-carrier industry. Consequently, several programs were initiated by the airlines, the manufacturers, and government agencies, including the FAA and the NASA, to examine possible factors that might contribute to piloting problems in severe turbulence. Among those investigated are: 1) attitude-instrument deficiencies, 2) instrument flight procedures in severe turbulence, 3) acceleration stress effects on crew, 4) longitudinal control characteristics, and 5) handling qualities. In Refs. 1 and 2, attitude instrument characteristics and suggested instrument-flight procedures for storm turbulence penetration are discussed in some detail. Reference 1 also provides some relevant information on longitudinal control and handling qualities characteristics, particularly in the overspeed region.

The purpose of the present paper is to summarize NASA research on the jet transport upset and upset-recovery problem from analysis and from piloted-simulator and flight studies. The latter program was conducted with the cooperation of the FAA. The discussion will be confined to three main areas: 1) a review of potential problem areas (e.g., preceding items 3–5) and a preliminary assessment of

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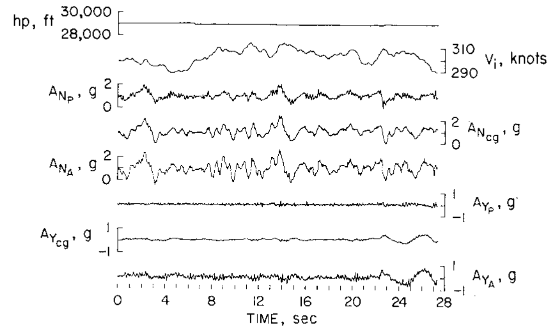
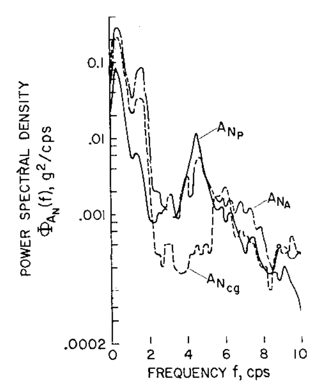


Fig. 1 Time history of thunderstorm penetration; $V_i \approx 300$ knots, $h_p \approx 29{,}000$ ft (jet transport A).

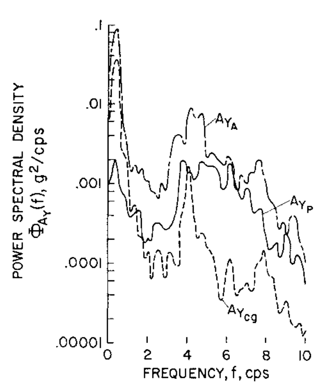
their relative importance; 2) a summary of piloted-simulator research results for a representative jet transport, including aircraft response to large-scale turbulence, handling qualities in turbulence, and cockpit-acceleration effects and pilot performance; and 3) a presentation of some flight-test results on the upset-recovery problem and on possible recovery control procedures. A more complete reporting of studies related to items 2 and 3 is provided in Ref. 3.

Review of Potential Problem Areas

During NASA's initial review of the transport rough-air problem, three problem areas considered of sufficient importance to review here were isolated. These are 1) flexible aircraft response characteristics and the associated pilot-station acceleration-stress effects on crew tolerance and performance, 2) maneuvering control characteristics, and 3) handling qualities. In all three of these areas, current jet transports exhibit less desirable characteristics, which impose an increased work load on the pilot compared to that for the preceding generation of propeller-driven transports.



a) **Normal accelerations**



b) **Transverse accelerations**

Fig. 2 Acceleration spectra.

Flexible Airplane Response Characteristics

Acceleration responses

The response characteristics of jet transport A obtained during a thunderstorm penetration are provided in Figs. 1 and 2. Figure 1 is a time history of a portion of the penetration run. Noteworthy in this figure are the relatively small airspeed deviations (290 ± 10 knots), altitude deviations less than 100 ft, and peak accelerations at various fuselage stations as indicated in Table 1. Also apparent in Fig. 1 is a predominant structural vibration of about 4 or 5 cps in the normal- and transverse-acceleration record for the pilot station and in the transve se-acceleration record for the tail.

In order to show these predominant frequencies more clearly, power-spectral densities, associated with the acceleration responses in Fig. 1, were obtained and are presented in Fig. 2. Normal-acceleration power spectra (Fig. 2a) indicate clearly the peak in cockpit acceleration at about 4.5 cps (presumably the first fuselage bending mode). The other peaks shown are the short-period rigid-body mode ($\approx$0.35 cps) and symmetrical first wing bending ($\approx$1.5 cps). The lateral acceleration spectra (Fig. 2b) clearly show the rigid-body Dutch-roll mode ($\approx$0.3 cps) and less well-defined response peaks between 4 and 6 cps caused by fuselage side bending. These acceleration spectra depend, of course, on the turbulence structure (level and scale), on pilot control inputs, and on the flexible aircraft transfer functions to gust and control. (For additional information on turbulence structure and on flexible aircraft response to control and gust inputs, see Refs. 4–18.)

Pilot station acceleration effects

The question arises whether the measured responses at the cockpit have a significant effect on crew tolerance and proficiency. Results of previous research [19] indicate that crew tolerance and effectiveness are influenced by the level and duration of the root-mean-square accelerations experienced. Figure 3 provides the root-mean-square acceleration as a function of fuselage station for the thunderstorm penetration with transport A (Fig. 1). At the pilot station, the accelerations are 0.24 g rms normal acceleration and 0.09 g rms transverse acceleration. For jet transport B, analysis of data provided by the manufacturer from a traverse of turbulence associated with a mountain rotor wave indicated a normal acceleration of 0.39 g rms at the cockpit. On the basis of a comparison of the present results with those in Ref. 19, little effect on crew proficiency would be expected for the level of accelerations experienced with transport A, and some deterioration of crew proficiency (increased difficulty in reading instruments, etc.) might be expected for the acceleration level experienced in transport B.

With regard to the effects of the predominant normal cockpit vibrations at about 4.5 cps indicated in Figs. 1 and 2, results[20–24] indicate a significant decrease in human tolerance and performance for vibrations in the range of 3 to 7 cps. This decreased tolerance, apparently caused by upper body and visceral resonance effects, is illustrated clearly in Ref. 20 (see Fig. 4). Comparison of the vibratory-acceleration component for transport A (Fig. 1) and for transport B (data not shown) with the results in Fig. 4 indicates the oscillatory ac-

Table 1 Acceleration responses (transport A)

Acceleration	Fuselage station	Peak values, g
Normal	Pilot station	+2.0, −0.1
	c.g.	+2.4, −0.1
	Tail	+2.6, −0.3
Lateral	Pilot station	+0.4, −0.3
	c.g.	±0.4 . . .
	Tail	±0.8 . . .

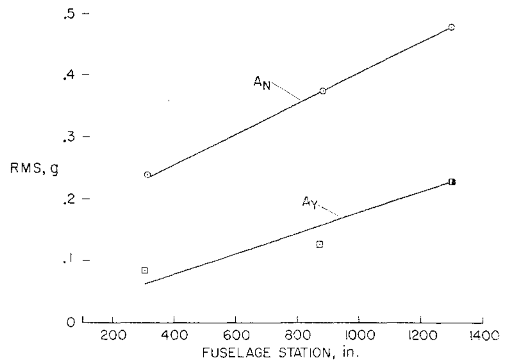


Fig. 3 Variation of root-mean-square accelerations along fuselage (jet transport A).

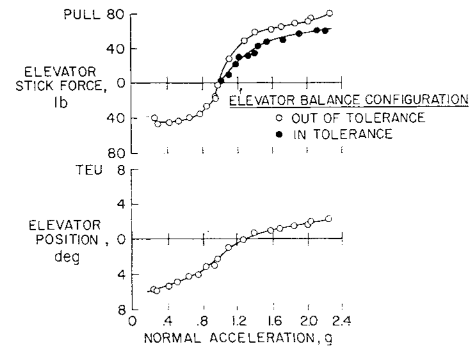


Fig. 5 Longitudinal control maneuvering characteristics (jet transport B).

celerations alone would be considered mildly to extremely annoying by the crew. (Crew comments generally confirmed this observation.)

Effects of vibration on human physiological responses and performance have been reported.[21–24] Relative vibration between subject and an instrument dial resulted in a significant increase in the frequency of large reading errors at frequencies between 3 and 5 cps.[23] It was noted[23] that the deterioration of performance caused by vibration of the display (subject fixed) also was observed in other tests where the subject was vibrated (with the display fixed).

Maneuvering Control and Handling Quality Aspects

Two other potential problem areas that might contribute to piloting problems in rough air are the longitudinal maneuvering control characteristics, that is, wheel force and elevator variations with acceleration, and the handling quality characteristics, specifically Dutch-roll dynamics, of current swept-wing transports. The swept-wing design and increased flight envelope of current machines generally has resulted in undesirable nonlinear characteristics of the longitudinal control system and in decreased damping about all three axes relative to characteristics of the preceding generation of transport aircraft. Results in Figs. 5 and 6, obtained during NASA flight tests of transport B, are considered typical for all current swept-wing transports.

Maneuvering control

In Fig. 5, wheel force and elevator angle variations with acceleration are provided. These results show clearly the undesirable nonlinear stick-force variations with acceleration. The two sets of wheel-force data are for two elevator-balance configurations as indicated. Near trim (1 g) the wheel-force gradient is about 150 lb/g; whereas near 2 g and zero g, the gradient decreases to about 30 lb/g and 10 lb/g, respectively. This nonlinear stick force makes inadvertent accelerated stalls more likely, undoubtedly increases pilot work load, and may contribute to piloting problems in severe turbulence.

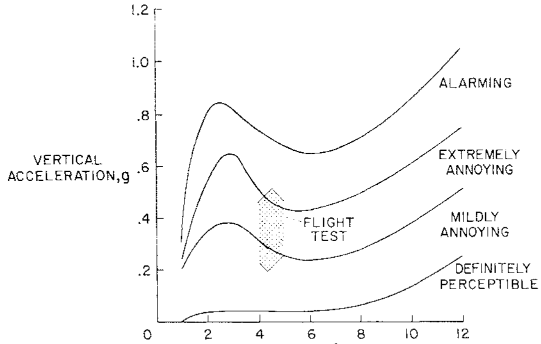


Fig. 4 Human subjective response to vibratory accelerations.

Handling quality aspects

In the analysis phase of the NASA program, the handling qualities of three current jet transports were reviewed. The analysis was based on wind-tunnel and estimated data provided by the manufacturers. (These data, incidentally, also are used in operational flight trainers for training airline pilots.) The analysis resulted in the following observations: 1) Longitudinal short-period and phugoid handling characteristics are considered satisfactory on the basis of a comparison of estimated characteristics with proposed military and civil transport guidelines[25, 26]; 2) The lateral-directional characteristics (yaw damper inoperative) are generally marginal, based on proposed guidelines[26]; and 3) Comparison of estimated handling qualities with flight-derived measurements from unpublished data for three current transports indicated, in general, lower damping levels in flight particularly for the Dutch-roll mode.

As part of the basic handling-qualities evaluation during the flight program, Dutch-roll dynamic characteristics were measured for transport B for yaw damper on and inoperative, and some of the results are shown in Fig. 6. The low damping with yaw damper inoperative is illustrated clearly by these results. Based on these data and the experience acquired during the turbulence-penetration flights with this aircraft, it was apparent that the low levels of damping, particularly with the damper off, increase pilot work load significantly in rough-air flight.

Summary of Piloted-Simulator Research

In this part of the paper, the primary results of the piloted-simulator investigation are reviewed. The present discussion will be confined to a brief description of the airplane simulation, and the results of evaluations of potential problem areas discussed earlier, for example, handling qualities in turbulence, cockpit-acceleration effects, and pilot performance variations.

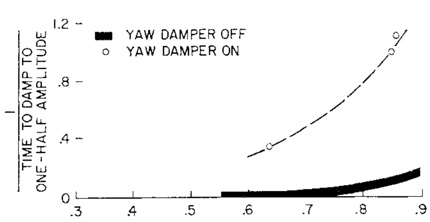


Fig. 6 Dutch-roll damping characteristics (jet transport B).

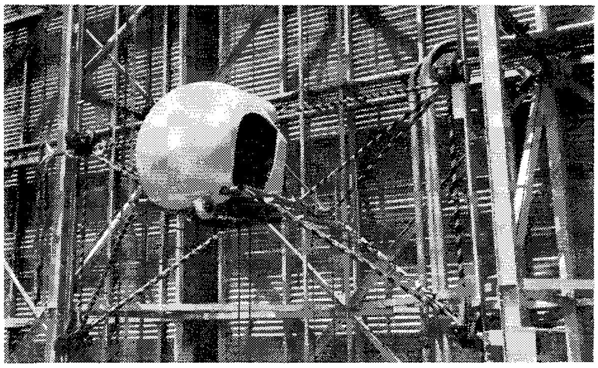


Fig. 7. View of piloted simulator used.

Airplane Simulation

Simulator description

Since many of the first-hand accounts of incidents in heavy turbulence and results in the first part of the paper stressed the distracting aspects of cockpit accelerations and vibrations, the simulation used in the Ames program was designed to utilize a device known as the Height Control Simulator. The simulator cab, illustrated in Fig. 7, is mounted on a vertical track that provides 100 ft of travel. High-performance electrical servomotors drive the cab through a cable system. The simulated cockpit employed basic controls and instruments similar to those installed in jet transport aircraft.

Simulation of structural vibration

The upper portion of Fig. 8, which is a sample of the flight-recorded airplane accelerations, clearly indicates the 4-cps cockpit vibration that appears to be excited constantly by the turbulence. The lower portion of Fig. 8 presents for comparison the c.g. and cockpit accelerations computed in the simulation program as the response to simulated turbulence inputs. The computed cockpit accelerations were reproduced accurately in the simulator cab over a frequency range of 0.3 to 6.0 cps.

Tests

The observations discussed in this paper are based on several periods of operation of the simulator by a total of 26 NASA, FAA, and industry pilots. Research pilots made repeated runs in the simulated heavy turbulence in order to assess the relative significance of the various factors that bear on the task of flying in turbulence. At the conclusion of the program, the simulation was used in a demonstration program for some 16 pilots from the air-carrier industry.

Primary Results

Handling qualities in turbulence

Assessments of handling qualities of the simulated aircraft in heavy turbulence indicated that there were no marked deficiencies within the normal operating boundaries and with the yaw damper and pitch trim compensator operating. Dutch roll was a constant annoyance, but good lateral control mitigated its significance. Control characteristics were considered satisfactory to speeds as low as 230 knots at the aircraft loading conditions assumed for the tests. The changes in trim and control power above $M = 0.85$ were considered unsatisfactory particularly in heavy turbulence. The line pilot has a minimum of training exposure to these characteristics and may have difficulty recognizing the changes quickly in turbulence.

Cockpit accelerations

The cockpit-acceleration environment in the heaviest turbulence was considered to be detrimental to instrument flight proficiency. The pilot agreed that the instruments generally remained readable, but only with increased effort, and that this requirement for increased concentration tended to disturb the normal scan pattern, which is the key to proficient instrument flight. It was interesting to note that the level of physical discomfort and concern tended to decrease with repeated exposures to the highest turbulence levels. These facts in themselves point to the benefits that might be derived by providing cockpit accelerations in training simulators.

Several subjects were exposed to the simulation of heavy turbulence with the structural frequency removed, that is, with no 4 cps resonance. The resulting cockpit-acceleration environment was considered much more tolerable even though the root-mean-square level of accelerations was not decreased significantly. This observation, together with a desire to substantiate available physiological data, inspired tests to determine pilot tolerance to vertical vibrations as a function of frequency. In Fig. 9, acceleration measurements at a subject's head are compared with cockpit accelerations for frequencies up to 6 cps. Results are provided for a conventional pilot seat cushion used in 707-type aircraft and for an airseat developed by the Martin Company for human vibration and impact protection.[27] With the subject seated on a conventional seat cushion, there is an amplification factor of more than 2 at frequencies between 3 and $4\frac{1}{2}$ cycles. With no cushion at all the amplifications are slightly lower at these frequencies, but the attenuating effects of the cushion do become apparent above $4\frac{1}{2}$ cycles. Subjective tolerance to vibrations decreases with the increase in head accelerations. As indicated on the figure, the fuselage bending frequencies of the current aircraft lie in this most sensitive range, and the present seat cushions are ineffective in reducing the stress on the pilot. Results for the airseat (Fig. 9) show an acceleration amplification between 2 and 3 cycles and an attenuation above about 3.5 cycles, as compared to the results for no cushion. Although these results show some improvement in vibration isolation for the airseat relative to conventional cushions in the range of predominant fuselage bending frequencies, additional research is considered necessary to determine whether this improvement would be operationally significant.

Pilot performance variations

During this portion of the program in which research pilots were evaluating the rough-air flight task, there were no indications in their performances of severe control difficulties; that is, there were no incidents or upsets, even under the most severe conditions of turbulence and task. However, it must be remembered that their familiarity with the objectives of the

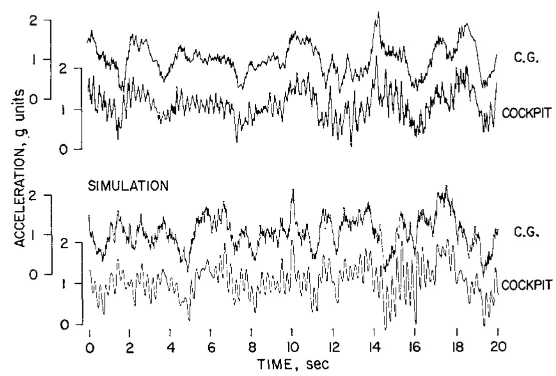


Fig. 8 Comparison of flight-measured and computed gust-induced accelerations.

test and their background of test flying eliminated any element of surprise or distraction from the environment. The performances of the industry pilots were more interesting and varied. The primary objectives were to demonstrate the simulated rough-air environment, to exchange ideas and opinions on operating in turbulence, and to assess the value of this type of simulator in airline training.

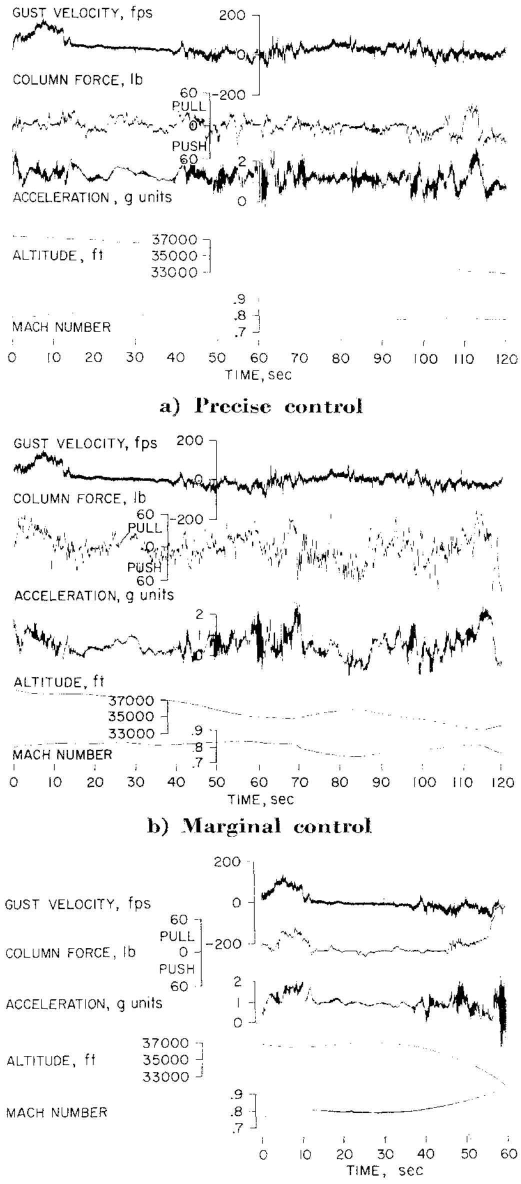
Each subject averaged about 2 hours in the simulator. Most of the first hour was devoted to familiarization and demonstration of the characteristics of the simulated aircraft, including stalls and flight beyond a Mach number of 0.9. The rest of the time was devoted to simulated thunderstorm penetrations and demonstrations pertinent to rough-air flight techniques.

The most critical task posed for each subject was introduced during his third turbulence encounter. He was requested to descend 5000 ft and simultaneously change heading. Unknown to the subject, his pitch trim compensator was rendered inoperative so that an unstable longitudinal trim change would accompany any acceleration past a Mach number of 0.84. During this task, 5 of 14 subjects experienced some form of control difficulty. Figures 10a–10c are examples of performance recorded in this task.

The performance illustrated in Fig. 10a is typical of that of the majority of the subjects. With relatively low control forces, the pilot maintained a reasonably steady rate of descent and good control of his speed.

In comparison, the pilot whose performance is illustrated in Fig. 10b demonstrated difficulties in his control of the descending flight path. Although he did prevent the airplane from accelerating beyond 0.84 and into the tuck region, his attempts to stabilize at 33,000 ft resulted in large flight-path excursions. Two momentary stalls were induced in attempts to arrest undesired rates of descent. Compare the control activity in this case with that of Fig. 10a.

In Fig. 10c is shown what might be considered an upset. An initial speed divergence was compounded by the tuck, and the pilot's delay in recognizing the gravity of the situation was apparently long enough for the aircraft to accelerate until longitudinal control was relatively ineffective. Figure 11 illustrates the performance, in the simulator, of a research pilot who intentionally deprived himself of pitch-attitude information and placed exaggerated emphasis on control of airspeed. This resulted in a flight-path oscillation with a period of about 30 sec. Several stalls were induced at the highest speeds, as an effort was being made to reduce airspeed and rate of descent. This behavior may be compared with that illustrated in the lower portion of the figure, which is a transcription of a portion of a flight-recorder record of one of the more serious flight incidents. It is interesting that the simulator performance of Fig. 11 demonstrates very similar flight-path variations. These similarities do not merit extensive and detailed interpretation, but they do suggest that pilot techniques and cockpit environment are as significant to the problem of flying jet transports in turbulence as are the mechanics of large-scale turbulence or the aerodynamic characteristics of the aircraft.



a) Precise control

b) Marginal control

c) Example upset

Fig. 10 Examples of pilot performance of complex task in severe turbulence.

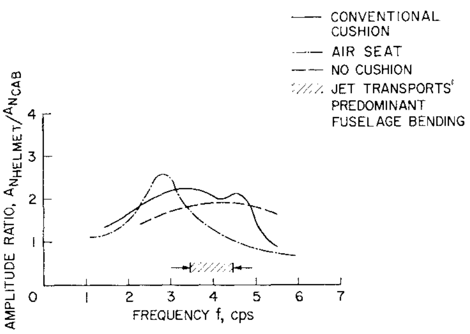


Fig. 9 Effects of seat cushion on vibratory amplification at pilot's head.

Review of Flight-Test Results

The primary objectives of the flight-test phase of the NASA program were 1) to evaluate pertinent longitudinal control-system characteristics of a representative jet transport, 2) to evaluate airplane characteristics during controlled upset and recovery maneuvers, and 3) to assess airplane behavior in turbulent air. In this final section, results obtained from phases 1 and 2 of the flight investigation which bear on the upset-recovery problem and on possible upset-recovery control techniques are stressed.

Upset-Recovery Problem

Since most of the serious incidents encountered by jet transports have culminated in steep dives during which high subsonic Mach numbers were attained, some discussion of the effects of Mach number on longitudinal control-system characteristics is believed warranted. Figures 12 and 13 present

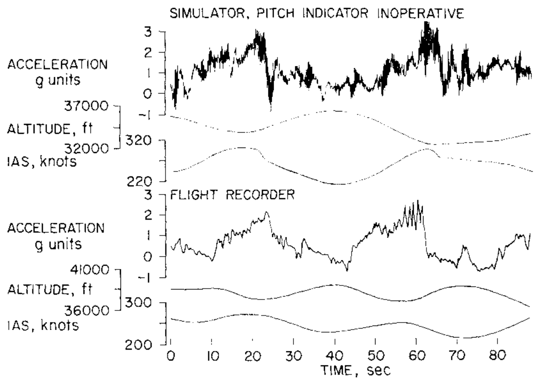


Fig. 11 Flight-path oscillation in turbulence in the simulator and in flight.

some of the pertinent flight results in this area from the NASA program.

Elevator/stabilizer trade characteristics

In some incidents large out-of-trim (airplane nose down) stabilizer deflections were applied. To illustrate the effects of a mistrimmed stabilizer, Fig. 12 presents a summary of elevator/stabilizer trade characteristics for 1 g flight at altitudes of 15,000 and 35,000 ft. At both altitudes tested, it may be seen that approximately 2° to $2\frac{1}{2}$° of elevator are required for every degree of mistrimmed stabilizer over the speed range tested. Considering the related stick force characteristics at the test altitude of 35,000 ft, it may be seen that for 1° of mistrimmed stabilizer, the forces required to maintain level flight vary, over the speed range, from 15 to 35 lb/deg. At an altitude of 15,000 ft, the force approaches 70 lb/deg at the highest speed tested. The implication here, of course, is that the pilot has to overcome these high forces to maintain 1 g level flight, and, therefore, his maneuvering or recovery capability is considerably impaired.

Effects of Mach number on elevator effectiveness

In addition to the serious effect of a critically mistrimmed stabilizer on upset-recovery capability, the usual adverse effects of Mach number on elevator effectiveness pose another problem. Flight-test results at an altitude of 35,000 ft indicated that elevator effectiveness deteriorates rapidly at Mach numbers above 0.85. Accelerations developed per degree elevator (in the range 1.0–1.5 g) decreased from about 0.25 to 0.13 g/deg as Mach number was increased from 0.85 to 0.87.

Effects of Mach number on maximum elevator available

A final point of interest related to the upset-recovery problem is the maximum available elevator for recovery with the stabilizer critically mistrimmed fully in the aircraft nose down position. Figure 13 presents a comparison of the manufacturers' predictions with the maximum elevator attained during the flight test over the Mach number range from 0.62 to 0.89 at an altitude of 35,000 ft. The manufacturers' estimate represents the maximum elevator that should be attained with a maximum deflection of the elevator tab and a wheel pull force between 150 and 300 lb. The flight-test data represented by the open and solid symbols show the actual elevator deflection obtained with the stabilizer trimmed in the full airplane nose down position of 3.5 units and with the pilot applying between 350 and 175 lb pull force as the airplane decelerated from $M = 0.89$ to 0.62. The higher forces are associated with the $M = 0.89$ data represented by the solid symbols, and in this case, both pilots were applying their maximum pull force capability on the wheel.

The open and solid symbols represent the results for two elevator-balance configurations (one out-of-tolerance and one within manufacturers' tolerance). Initially, it may be seen that the out-of-tolerance configuration costs about 2.0° to 2.5° in elevator deflection over the speed range. Further, for the within-tolerance configuration (solid symbols), it may be seen that for the specified trim conditions at $M = 0.89$, there is approximately 8.5° of elevator available for trim and maneuvering. As the speed is reduced to $M = 0.71$, the elevator available increases to approximately 10.5°.

The apparent deviation between the manufacturers' prediction and the maximum elevator attained during the flight tests represents a considerable reduction in longitudinal recovery control available for the airplane used in this test. Since the maximum recovery capability of the airplane depends upon the effects discussed previously and the actual elevator available (Fig. 13), a limitation in the elevator available is of primary concern. The significance of all these factors will be illustrated further in the discussion of the controlled upset maneuvers in the next section.

Upset-Recovery Control Techniques

Hopefully, with a clear indication of the upset-recovery problem in hand, some consideration will be given to possible recovery-control aids. Two techniques were used which involved supplemental stabilizer control in addition to maximum available elevator and supplementary spoiler control. These procedures were investigated during controlled upset maneuvers.

Elevator/stabilizer recovery

Figure 14 presents a stabilizer runaway at 35,000 ft and an initial Mach number of 0.78. At 1 sec, the stabilizer was activated in the full nose-down direction, and at 6 sec the stabilizer was deflected 3.5 units airplane nose down. In this period of 5 sec, the airplane deviated from level flight to $\approx -0.2\ g$. At 10.7 sec the throttle was reduced to idle, and at 12 sec the pilot initiated recovery through the elevator. At 18 sec full available elevator had been applied, and a maximum of 1.3 g was attained. At 20 sec the stabilizer was activated towards the trim position, and, as the g increased,

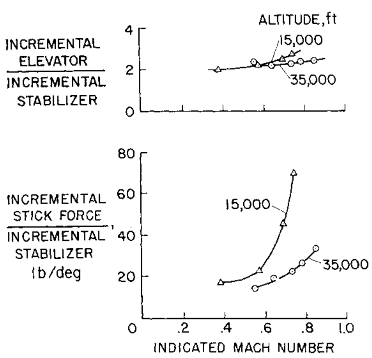


Fig. 12 Longitudinal trim (elevator/stabilizer trade) (jet transport B).

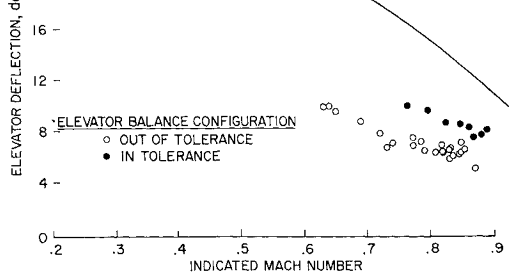


Fig. 13 Effects of Mach number on maximum elevator available (jet transport B).

elevator input was reduced until time 26 sec when full recovery had been effected and the airplane had reached a load factor of 2.3 *g*. By observing elevator and *g* traces between 18 and 20 sec, it may be seen that there is a loss in elevator effectiveness. The elevator remains essentially constant in this region, whereas the *g* decreases from ≈1.3 to 1.0 *g*. Also, at 18 sec it is not apparent that the airplane's rate of descent has been reduced. However, after the stabilizer is returned to the trim position, the load factor increases, the rate of descent is checked, and the airplane returns to a level flight condition.

Elevator/spoiler recovery

Figure 15 presents a similar stabilizer runaway where the initial recovery is effected through the elevator control, and the final recovery is accomplished by deflection of the spoiler system instead of by retrimming the stabilizer. The general operational procedures used in performing the upset were the same as those employed in the previous maneuver. An apparent loss of elevator effectiveness is observed again between 15 and 19.5 sec. In this region the elevator remains fixed at ≈11°, whereas the acceleration decreases from 1.5 to 1.1 *g*. Also, the airspeed and altitude traces indicate that the rate of descent had not been checked until after the spoilers had reached their maximum deflection of ≈25°. In this maneuver, the spoiler handle was moved to the full spoiler position of 60°. Although only 25° of spoiler was obtained because of the blow-down effect at high speed, this much spoiler, combined with maximum available elevator, resulted in complete recovery of the airplane to a level flight condition, whereas the stabilizer remained at full airplane nose-down trim setting.

In similar maneuvers performed with the stabilizer in trim, there was no problem in recovery with the elevator alone. However, in the upsets with the mistrimmed stabilizer, it is obvious that supplemental recovery control is required if additional elevator authority cannot be provided.

It also has been observed that an indicating accelerometer proved very useful in monitoring the recovery, since pilot work load (large wheel forces, etc.) tended to mask actual accelerations applied during the recovery maneuver.

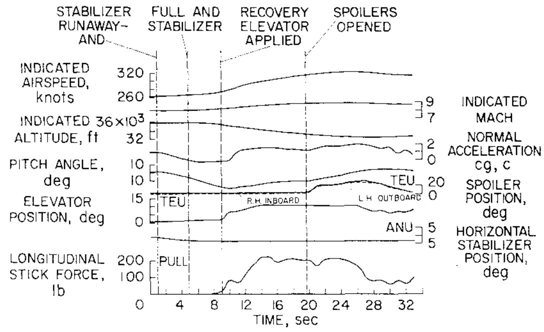


Fig. 15 Upset recovery with elevator-spoiler combination (jet transport B).

damper inoperative) increase pilot work load and possibly amplify incipient airplane upsets.

2) The experiences with the simulation, together with opinions offered by the visiting airline pilots, suggest that the capabilities of current training simulation be extended to include the most significant cockpit environmental effects and the aircraft response induced by heavy turbulence. In addition, the training simulator should have the capability of representing accurately the airplane's stability and control characteristics at and beyond the normal operating boundaries.

3) Piloted simulator results demonstrated that the cockpit environment in heavy turbulence can inhibit seriously the ability of the pilots to perform tasks demanding the integration of information from a number of instruments. Consequently, it is recommended that: a) the pilot make every effort to minimize deliberate flight-path changes in heavy turbulence, keeping his task as simple as possible; b) the pilot avoid imposing large angular rates on the aircraft, i.e., he should try to limit his control function to that of a low-gain attitude stabilizer; c) consideration be given to modifying overspeed warning systems to include rate-of-speed build-up (by including pitch-attitude information in the warning system); d) consideration be given to the possibility of isolating the pilot from the most distracting vibrational frequencies through modification of the seating and restraint systems; and e) increased attention be directed toward the development of attitude presentations that can be interpreted with something approaching the ease with which the outside world is used in Visual Flying Rules (VFR) flight.

4) Flight-test results indicated that: a) the upset-recovery problem primarily is because of a limitation of maximum available elevator, particularly for a critically mistrimmed stabilizer; and b) recovery control can be augmented by use of supplementary stabilizer and spoiler control. However, the large control forces exerted by the pilot during recovery tend to mask the recovery accelerations. Consequently, a suitable indicating accelerometer is considered essential for monitoring the recovery from an upset when augmented control, that is, stabilizer or spoilers, is used.

Conclusions and Recommendations

NASA research results from analysis and piloted simulator and flight-test programs on the piloting problems of current swept-wing jet transports in severe turbulence indicated the following:

1) Review of potential problem areas that may contribute to airplane upset, for example, pilot-station accelerations, longitudinal maneuvering control characteristics, and handling qualities, suggested that a) cockpit accelerations, including a predominant structural mode of 4 to 5 cps, can adversely affect crew performance in heavy turbulence; and b) nonlinear maneuvering control characteristics and poor lateral-directional damping characteristics (particularly with yaw

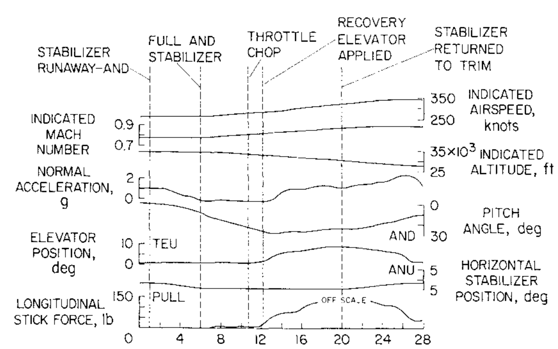


Fig. 14 Upset recovery with elevator-stabilizer combination(jet transport B).

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