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ANALYTICAL STUDY OF EFFECTS OF AUTOPILOT OPERATION ON MOTIONS OF A SUBSONIC JET-TRANSPORT AIRPLANE IN SEVERE TURBULENCE

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16. Abstract

An analytical study has been conducted to determine the capability of a conventional autopilot system to control a subsonic jet-transport airplane in severe turbulence. Various configurations of a simplified three-axis attitude-hold autopilot were evaluated to determine an optimum configuration for prevention of lateral upsets caused by reversal of dihedral effect.

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SUMMARY

Since earlier analytical studies have indicated that subsonic jet-transport airplanes operating in severe turbulence are susceptible to gross lateral upsets caused by reversal of effective dihedral at Mach numbers slightly above the nominal cruise Mach number, an analytical study has been made to determine whether autopilot operation in severe turbulence could prevent such gross lateral upsets. Various combinations of channels of a simplified autopilot system representing a three-axis attitude-hold autopilot were evaluated to determine the optimum autopilot configuration for prevention of such lateral upsets. The effect of aircraft size was also investigated; the main body of the study was conducted for a configuration operating at a weight of 175 000 pounds (778 400 newtons), and a few additional calculations were made for the same aerodynamic configuration scaled up to a weight of 584 000 pounds (2 597 632 newtons).

The results indicated that the simplified autopilot system would be capable of preventing gross upsets due to reversal of dihedral effect. Calculations indicated that the autopilot command gains could be reduced by about 95 percent and still prevent the upset condition. Furthermore, an optimum autopilot configuration for prevention of the aforementioned lateral upsets was found to be a combination of roll and yaw channels with or without a heading-hold mode on the roll channel. The calculations for the scaled-up configuration showed that it was also susceptible to such lateral upsets and that the use of the simplified autopilot prevented such lateral upsets.

INTRODUCTION

During recent years the problem of subsonic jet-transport upsets in atmospheric turbulence has generated considerable research effort in the form of flight tests (ref. 1), ground-based simulations (refs. 2 and 3), and analytical studies (ref. 4). One of the analytical studies (ref. 4) was conducted specifically to determine whether the inherent uncontrolled (open-loop) stability and response characteristics of subsonic jet-transport airplanes could result in a gross upset when the airplane was flying in severe turbulence and, if so, to determine the techniques that might aid in the prevention of possible upsets from this cause. Results of that study indicated that uncontrolled swept-wing transports in severe turbulence would be susceptible to gross upsets because of an inherent lateral-directional instability at Mach numbers slightly above the efficiency cruise Mach number (if for any reason, including turbulence, the Mach number should increase to such a value). The instability consisted of an unstable spiral dive and was related to reversal of dihedral effect at Mach numbers slightly higher than the efficiency cruise Mach number. Furthermore, the study considered changes in basic stability characteristics of the airplane and pointed out loose-attitude and proportional control techniques which might aid in avoiding such upsets. Current flight procedures for operation in turbulence are concerned mainly with preventing large excursions in airplane attitude to avoid divergent conditions where recovery would necessitate rather high loadings on the airframe. Some currently recommended control procedures for operation of subsonic jet-transport airplanes in turbulence, as found in reference 5, indicate that the autopilot should be on, without the altitude-hold mode, for operation in turbulence. Furthermore, reference 5 recommends that the yaw damper always be on and that the flight director be operative in the pitch and heading modes if the autopilot is off.

The primary concern of the present investigation was to evaluate the effects of autopilot operation on the flight motions of the same airplane flying through the same turbulence samples that were used in reference 4. In particular, emphasis was placed on the ability of the autopilot to prevent gross upsets due to the lateral-directional instability. (No longitudinal upsets were encountered for the flight conditions investigated.) The study was composed primarily of calculations of airplane motions in severe turbulence for various configurations of a simplified attitude-hold automatic control system. Aerodynamic data, describing the airplane as a rigid body with six degrees of freedom, were based on wind-tunnel tests of a model which was representative in general configuration of swept-wing subsonic jet transports. The complete analytical model of the airplane and control system, including nonlinearities of the aerodynamic characteristics, atmospheric properties, and control-system gains, was solved by numerical integration procedures on a high-speed digital computer.

SYMBOLS

All flight motions presented herein are given with respect to a body-fixed axis system shown in figure 1. The units for the physical quantities used herein are presented in both the U.S. Customary Units and the International System of Units.

a_n normal acceleration, g units

Δa_n	increment of normal acceleration from 1g flight, g units
a_Y	lateral acceleration, g units
$C_{1/2}$	cycles required to damp to one-half amplitude
C_l	rolling-moment coefficient
$C_{l_\beta} = \frac{\partial C_l}{\partial \beta}$	
F_P	automatic control system (ACS) pitch-channel gain factor
F_R	ACS roll-channel gain factor
F_Y	ACS yaw-channel gain factor
g	acceleration due to gravity, ft/sec^2 (m/sec^2)
h	altitude, ft (km)
M	Mach number
P	period, sec
p,q,r	rolling, pitching, and yawing angular velocities, respectively, rad/sec
t_R	roll time constant, sec
$t_{1/2}$	time to damp to one-half amplitude, sec
u,v,w	components of airplane velocity with respect to inertial space projected along X, Y, and Z body axes, respectively, ft/sec (m/sec)
V	resultant true airspeed of airplane, ft/sec (m/sec)
v'_g,w'_g	velocity components of turbulence referenced to Y and Z earth axes, respectively, ft/sec (m/sec)

X,Y,Z	longitudinal, lateral, and vertical axes, respectively
α	angle of attack, deg
β	angle of sideslip, deg
δ_a	aileron deflection, positive for right roll command, deg
δ_e	elevator deflection, positive when trailing edge is down, deg
δ_r	rudder deflection, positive when trailing edge is left, deg
ζ	damping ratio
θ	angle of pitch, deg
ϵ_θ	pitch attitude error $\left(\theta - \theta_{trim}\right)$, deg
ϵ_ψ	airplane heading error, deg
ϕ	angle of bank, deg
ψ	angle of yaw, deg
ω_n	undamped natural frequency, rad/sec

A bar over a symbol indicates root-mean-square (rms) value of that symbol.

DESCRIPTION OF AIRPLANE

The airplane configuration used in this study was that used in an earlier analytical study (ref. 4) and is considered to be representative of current subsonic jet-transport airplanes. The airplane was assumed to be flying at a weight of 175 000 pounds (778 400 newtons). A second version of the airplane studied had nondimensional aerodynamic characteristics identical to those of this airplane but had values of mass and dimensional characteristics scaled up to represent a larger airplane flying at a weight of 584 000 pounds (2 597 632 newtons). The dynamic stability characteristics of both airplanes are presented in table I, and the static and dynamic aerodynamic characteristics used as input data to the calculations may be found in reference 4.

DESCRIPTION OF AUTOMATIC CONTROL SYSTEM

The autopilot simulated in this study was a simplified three-axis, attitude-hold automatic control system (ACS) intended to be representative of systems currently in use on swept-wing subsonic jet transports. A block diagram showing the ACS configuration is presented in figure 2. As shown in figure 2, each ACS channel is composed of (1) a command circuit, (2) a command loop gain control, (3) a servomechanism, and (4) a rate and position limit control. The pitch command circuit monitored the pitch attitude error ϵ_θ and the pitch rate q. A static gain of 2.36 was applied to ϵ_θ whereas the pitch-rate signal was operated on by a static gain of 3.2, by a gain factor F_P which decreased with indicated airspeed, and by a second-order bandpass filter having break frequencies at 1.0 and 18.5 rad/sec. These two modified signals were summed by the pitch command circuit to obtain the elevator command signal. The roll command circuit monitored roll angle ϕ, roll rate p, and heading error ϵ_ψ. Static gains of 0.953 and 0.44 were applied to the ϕ and p signals, respectively, whereas the ϵ_ψ signal was operated on by a static gain of 0.485, by a gain factor F_R which increased with indicated airspeed, and by a first-order lag circuit having a time constant of 1 second. The three modified signals were summed by the roll command circuit to obtain the aileron command signal. The yaw command circuit monitored yaw rate r. This rate signal was subjected to a static gain of 4.03, to a gain factor F_Y which decreased with indicated airspeed, and to a second-order bandpass filter having break frequencies at 0.6 and 2.5 rad/sec. The resultant modified signal was the rudder command signal. The gain factors for the pitch, roll, and yaw channels are shown in figure 3 as functions of indicated airspeed.

For purposes of this study, a command loop gain factor (command loop gain control, fig. 2) was applied to command signals in each channel immediately before the signal was fed to the servo (represented as second order for each channel) to provide control over the channel loop gain on the command circuit. A value of unity for this factor sets the automatic control system for normal operation in still air, and a value of zero in a given channel eliminates any control from that channel. The natural frequencies and damping ratios for the servo for each channel are listed in table II. The ailerons, rudder, and elevator were subjected to rate and position limits. These limits for each channel are presented in table III and are discussed under "Procedures and Calculations."

PROCEDURES AND CALCULATIONS

Time histories of the airplane flight motions and control-system activity in severe turbulence were calculated by numerical integration procedures with a high-speed digital computer using the airplane equations of motion presented in reference 4 combined with equations describing the automatic control system (ACS) as shown in figure 2. Nonlinear, six-degree-of-freedom equations of motion, referenced to a body-axis system, were used to calculate the airplane motions. The ACS model used was a simplified representation which allowed reasonably accurate simulation of ACS lags, frequency response, and control activity.

All computed flights had initial conditions corresponding to the efficiency cruise conditions for the subsonic jet-transport airplane, that is, an altitude of 40 000 feet (12.19 km) and true airspeed of 470 knots ($M \approx 0.82$), which were also the initial cruise conditions for the scaled-up transport. Mach trim compensator effects were included in the calculations to trim the airplane at the desired Mach number.

The turbulence sample consisted of tape-recorded time histories of the vertical component w_g' and lateral component v_g' of the turbulence. Longitudinal-gust time histories were not available for the turbulence sample employed. Figure 4 shows the turbulence sample used for calculations in this study. The velocities in this figure are referenced to an earth-axis system. (See fig. 1 for relation to body axes.) These gusts were applied at the airplane center of gravity, since the airplane was represented as a point mass. The effects of the turbulence were felt by the airplane as changes in angle of attack α, angle of sideslip β, and true airspeed V. Flights were computed to determine the effects of operating the three ACS channels both singly and in various combinations, and calculations were made to determine the effect of varying the ACS command loop gains. In connection with the ACS configuration studies, step gust disturbances were used in certain cases to give a better understanding of the ACS effects than could be obtained with the random turbulence sample.

The ACS control authorities (table III) were computed in the following manner. The elevator authority of $\pm 5^{\circ}$ was estimated to limit the maximum increment (due to elevator deflection) in airplane normal acceleration to less than 1g from the efficiency cruise condition. The aileron authority was assumed to be about 60 percent of maximum travel available, and the rudder authority was assumed to be 30 percent of maximum travel available.

As a direct extension of the earlier analytical work (ref. 4), an uncontrolled scaled-up version of the basic airplane (the so-called "jumbo" airplane) was studied to determine the effects of size on the response to turbulence.

RESULTS AND DISCUSSION

The results of the present study are presented in the form of calculated time histories of the airplane flight motions and control-surface deflections. Flights are described by time histories of pitch angle θ, bank angle ϕ, yaw angle ψ, normal acceleration a_n, lateral acceleration a_y, Mach number M, altitude h, angle of attack α, angle of sideslip β, and control-surface position.

Response of Uncontrolled Basic Airplane to Turbulence

The results of calculations made to describe the flight of the uncontrolled basic transport (that is, the smaller transport studied herein) in the severe turbulence sample are presented as time histories in figure 5, taken from reference 4. As can be seen in the figure, the uncontrolled airplane was grossly upset (right wing down) by the end of the 100-second time period – experiencing a large loss of altitude accompanied by a considerable increase in Mach number until the computing program "pegged" the Mach number at 0.95 (available data limited to $M \leqq 0.95$). The upset was brought about by a large lateral gust at about 37 seconds, which caused large rolling motions, followed by dropping of the nose, an increase in Mach number, and finally a divergent spiral dive. The technical term "spiral dive" may give an erroneous impression, however, since the airplane turned only about 150° (low turn rate resulting from high speed) during a period of about 50 seconds but during which time it lost about 15 000 feet (4.6 km) of altitude.

The specific cause for this event, as pointed out in reference 4, was the reversal of effective dihedral C_{l_β} with Mach number, as shown in figure 6. The point on the curve just past the sharp upward break ($M \approx 0.82$) denotes the initial cruise condition of the airplane. This cruise condition places the airplane in a Mach number sensitive region where only a slight increase in Mach number would be required to cause the value of C_{l_β} to change from a stable (negative) value to an unstable (positive) value. This phenomenon is believed to be the cause of the computed upset – that is, spiral instability at a Mach number slightly above the cruise Mach number where, when a wing drops, it will not naturally return to level but will diverge unless raised artificially. This problem was thoroughly discussed in reference 4 and will not be further discussed herein.

Response of Controlled Basic Airplane to Turbulence

Controlled flight by the use of a simplified autopilot was the purpose of the present study. The ACS described in figure 2 was incorporated with the airplane characteristics described heretofore, and the combination was analytically "flown" through the sample of severe turbulence to appraise the control system in its normal mode of operation, that is, all channels on and all gains normal for cruise in still air. Figure 7 presents computed time histories of this controlled flight. As can be seen, the airplane was not grossly upset. The rolling activity between 20 and 40 seconds is the controlled response of the airplane to the large gusts (fig. 4) which initiated the upset of the uncontrolled airplane. In suppressing the roll response, the ACS drove the ailerons to full authority once (near 37 sec). However, no other controls required their full authority. The primary result to be noted in figure 7 is that the autopilot was able to control the airplane and prevent the gross upset shown in figure 5.

Effect of ACS Gain Reduction

In an attempt to determine the minimum level of control activity required to prevent the upset, flights were computed for ACS command loop gain factors between 0 (no control) and 1 (normal). For each case, all channel command loop gains were reduced by the same percent. The resulting flights were summarized by taking the root-mean-square (rms) values of certain flight parameters for each 100-second flight through the turbulence sample. Figure 8 shows the results of this gain survey in the form of a plot of the rms values of the parameters for 100-second flights as a function of the command loop gain factor (for all channels). For gain factors at or below a value of 0.5, no control authority limits were encountered by the ACS. The significant point to be noted is the relative insensitivity of these flight parameters to the variation in the ACS gain. For a low value of 5 percent of the normal ACS gains (gain factor of 0.05), the airplane was still controlled (for example, ϕ never exceeded $\pm 40^{\circ}$ and changes in M and h were insignificant) in the 100-second flight in turbulence. Also, accompanying this gain reduction was a considerable reduction in control activity, particularly for δ_a, as is seen in the curves for $\bar{\delta}_a$, $\bar{\delta}_e$, and $\bar{\delta}_r$.

Effect of ACS Mode of Operation

Another approach to evaluating the ACS operation in turbulence was to observe the effects of operating with various combinations of channels on, that is, in various modes of operation. The results indicated that the ACS pitch channel had no significant effect on this particular upset problem. That is, the ACS with only the pitch channel active (normal gains) did not prevent the lateral upset, and the only effect of this channel being active in conjunction with the roll and yaw channels (at normal gains) was a small reduction in airplane pitching motions (θ variations) and an insignificant reduction in normal accelerations (Δa_n). This result is primarily due to the lateral nature of the computed upset. In addition, it was found that the ACS operating with only the roll channel (at normal gains) could prevent the lateral upset; this result is in agreement with the conclusions of reference 4. Furthermore, little or no change in flight motions in turbulence was noted when the heading-hold feature was deleted from the ACS roll channel. Operation of the yaw damper (yaw channel) had favorable effects on the flight motions and control activity. The following results show the effects on the airplane flight motions of various ACS modes of operation.

Effect of heading-hold feature.- As was just mentioned, the heading-hold feature in the ACS roll channel seemed to have little or no effect on the airplane flight motions in the turbulence sample. To make the effects more evident, flights were computed wherein the airplane was flown through a 100-ft/sec (30.5-m/sec) step lateral gust for a period of 50 seconds. For this particular study, two flights were made: one with all ACS channels on and a second with all channels on except that the heading-hold mode was eliminated. Figure 9 shows the effect of the heading-hold feature on the flight motions in a lateral gust. A direct comparison of the bank-angle ϕ and yaw-angle ψ time histories in figures 9(a) and 9(b) shows that the heading-hold feature caused the airplane to roll in a manner to correct the heading error (change in ψ) caused by the lateral gust.

The same two autopilot configurations were also flown through the severe turbulence sample, and figures 10(a) and 10(b) show the results in terms of bank angle ϕ, yaw angle ψ, aileron deflection δ_a, and rudder deflection δ_r. The effect of heading hold is not evident in these figures. It was reasoned that since the gusts of the turbulence sample used in this study were of short duration in any one direction, the airplane never produced any large response in yaw while its wings were kept level; therefore, the heading-hold feature of the ACS never generated any significant roll commands. Thus, the heading-hold mode of the ACS roll channel did not seem to be necessary for maintaining the airplane heading in turbulence composed of short-duration gusts. Thus, if the airplane wings were kept level (which was the function of the ACS roll channel without the heading-hold feature) in the severe turbulence, little or no heading error accumulated.

Effect of yaw damper.- Although operation of the ACS with only the roll channel did avoid the upset in turbulence, the addition of the yaw channel was beneficial in reducing the magnitude of the rolling motions (associated with Dutch roll mode) and lateral control activity. To determine the effects of the yaw damper more clearly, the step-gust approach was again employed. Two flights were computed without the heading-hold feature: one with only the ACS roll channel operative, and a second with the roll and yaw channels operative. The calculated motions for these two flights are shown in figures 11(a) and 11(b). By comparing the roll time histories, the reduction in the magnitude and duration of the rolling motions with the addition of the yaw damper is obvious. (This reduction was also noted in ref. 4.) However, one other advantage of the addition of the yaw damper, not obvious from flight motions in turbulence, is the reduction of the magnitude and duration of the control activity of the ailerons. The reduction in the magnitude of control activity was also evident for flights in turbulence. Another advantage of having the yaw channel operational with the roll channel was that the magnitude of the lateral accelerations was considerably reduced. (The rms value of a_y in turbulence was reduced by a factor of about 2.) Thus, the operation of the yaw damper in conjunction with the roll channel (without the heading-hold feature) noticeably reduced the magnitude and duration of the rolling activity, lateral accelerations, and control activity.

Results of control by yaw damper alone.- Since results of the study in reference 4 indicated that a sufficiently effective yaw damper could control the airplane in turbulence and avoid the upset under study, an attempt was made in the present study to control the airplane with only the yaw channel by raising the channel gain. Studies of the computed individual time histories showed that as the factor approached 0 or exceeded 4, the airplane steadily approached the lateral upset conditions, that is, ϕ, ψ, and M were consistently increasing with time and h was decreasing. However, for the midrange gains, the airplane (although loosely controlled) did not show any consistent trend toward entry into the spiral dive (for example, ϕ and M were oscillatory about trim, and there was no significant change in h). Also, for gain factors above 4, the rudder frequently encountered its authority limits for rate and position.

The results of this series of "flights" are shown in figure 12 as the computed variation of the rms value of the flight parameters (for 100-second flights in turbulence) with increasing command loop gain factor on the yaw channel. The four parameters $\bar{\phi}$, $\bar{\epsilon}_{\psi}$, $\bar{\epsilon}_{\theta}$, and $\bar{a}_y$ exhibited relatively higher values toward the low and high values of gain factor. At the lower gain factors the yaw-damper control was too light, whereas at the higher values of gain factor, the yaw-damper control capability was severely decreased because of excessive roll due to rudder deflection (a result of larger rudder deflections at high gain). Although these results indicated that the yaw damper alone with gains near 4 might be able to prevent the lateral upset discussed herein, the fact that current maximum values for the yaw-channel gain factor on a system such as represented herein are about 2.0 or below indicates that attempting control by using the yaw damper alone would probably not be feasible.

Optimum configuration.- These control-system studies indicated that an optimum configuration for the ACS for prevention of the lateral upset due to reversal of dihedral effect in severe turbulence would have the roll and yaw channels on, with or without the heading-hold mode and with the system gains considerably reduced. Having the ACS pitch channel active reduced the magnitude of the pitching motions; however, it did not effect any significant reduction in normal accelerations, nor did it significantly affect the lateral upset problem. For low-speed flight conditions where the stall could be a problem or for turbulence having vertical gusts of relatively long duration in any one direction, the chance of a longitudinal upset would probably necessitate having the ACS pitch channel active, but such flight conditions were not investigated in this study.

Effect of Mass and Dimensional Characteristics

As an extension of the earlier work (ref. 4), an attempt was made to investigate the effects of increased mass and dimensional characteristics on the uncontrolled response of a typical subsonic jet-transport airplane. To this end, the jet transport described heretofore was scaled up in mass, inertia, and dimensions to be similar to current "jumbo" jet designs. The same aerodynamic characteristics as those of the smaller transport were used for this larger version. This scaled-up version of the smaller transport was first analytically flown through the severe turbulence without autopilot operation, and the calculated motions are shown in the form of time histories in figure 13. These data show that the scaled-up airplane was grossly upset and was upset in the opposite direction (left wing down) from the smaller transport upset (shown in fig. 5). Additional flights computed for the scaled-up transport indicated that the upset in the opposite direction from the smaller transport upset was related to the higher angle of attack required to trim the scaled-up transport at the same Mach number and altitude used for the smaller transport. The main point to be noted in figure 13 is that the uncontrolled scaled-up airplane was upset – not the direction of the upset.

Although results are not shown, calculations indicated that the scaled-up transport, when controlled by the autopilot used on the smaller transport, did not experience the lateral upset. It should be noted, however, that the autopilot characteristics were not optimized for the larger transport.

CONCLUSIONS

An analytical study has been conducted to determine the capability of a simplified autopilot system to control a swept-wing subsonic jet-transport airplane in a particular sample of severe turbulence when the uncontrolled airplane is susceptible to lateral upsets due to spiral instability at Mach numbers slightly above its efficiency cruise Mach number. From the results of this study, the following conclusions were drawn concerning the operation of the simplified autopilot in one particular sample of severe turbulence:

1. The use of the attitude-hold automatic control system (ACS) (with gains normal for flight in still air) prevented the lateral upset (due to reversal of dihedral effect) of the subsonic jet transport in the severe turbulence sample.

2. The command loop gains on the attitude-hold ACS could be substantially reduced (down to 5 percent of normal for flight in still air) while reasonable control over the airplane in the particular severe turbulence sample is still maintained and while overall control activity is considerably reduced.

3. The heading-hold feature in the roll channel of the attitude-hold ACS seemed to have little or no effect on the airplane flight motions in the severe turbulence sample; this condition indicates that the heading-hold feature had minimal response to short-duration gusts and was not therefore necessary for operation in the severe turbulence sample.

4. The only effect of the pitch channel of the automatic control system being active, in conjunction with the roll and yaw channels, was a small reduction in the airplane pitching motions and normal accelerations.

5. An optimum configuration of the attitude-hold ACS for prevention of the lateral upset while operating in the severe turbulence sample only had the roll and yaw channels active (with or without the heading-hold feature in the roll channel) with the system gains substantially reduced below their normal values for cruise in still air.

6. The uncontrolled scaled-up swept-wing subsonic jet-transport airplane having aerodynamic characteristics the same as those of the smaller subsonic jet-transport airplane was also found to be susceptible to lateral upsets due to reversal of dihedral effect which can occur in severe turbulence.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., March 17, 1970.

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TABLE I.- DYNAMIC STABILITY CHARACTERISTICS

FOR EFFICIENCY CRUISE CONDITION

	Basic transport	Scaled-up transport
Short period:		
ω_n, rad/sec	1.62	0.62
P, sec	4.2	14.2
ζ	0.39	0.70
$2\zeta\omega_n$, rad/sec	1.27	0.87
Phugoid:		
P, sec	>100	96
Roll mode:		
t_R, sec	1.99	2.73
$t_{1/2}$, sec	1.38	1.89
Spiral mode:		
$t_{1/2}$, sec	2332	-95
Dutch roll:		
ω_n, rad/sec	1.40	0.96
P, sec	4.51	6.53
ζ	0.09	0.07
$C_{1/2}$	1.27	1.50
$\left\lvert\frac{\phi}{\beta}\right\rvert$	2.22	1.53

TABLE II.- CHARACTERISTICS OF ACS SERVOMECHANISM MODELS

ACS channel	Natural frequency, rad/sec	Damping ratio
Pitch	12	1.0
Roll	12	1.0
Yaw	107	.7

TABLE III.- ACS POSITION AND RATE LIMITS

ACS channel	Control surface	Surface deflection, deg	Surface deflection rate, deg/sec
Pitch	Elevator	$-5 < \delta_e < 5$	±20.0
Roll	Ailerons	$-12 < \delta_a < 12$	±20.0
Yaw	Rudder	$-7.5 < \delta_r < 7.5$	±20.0

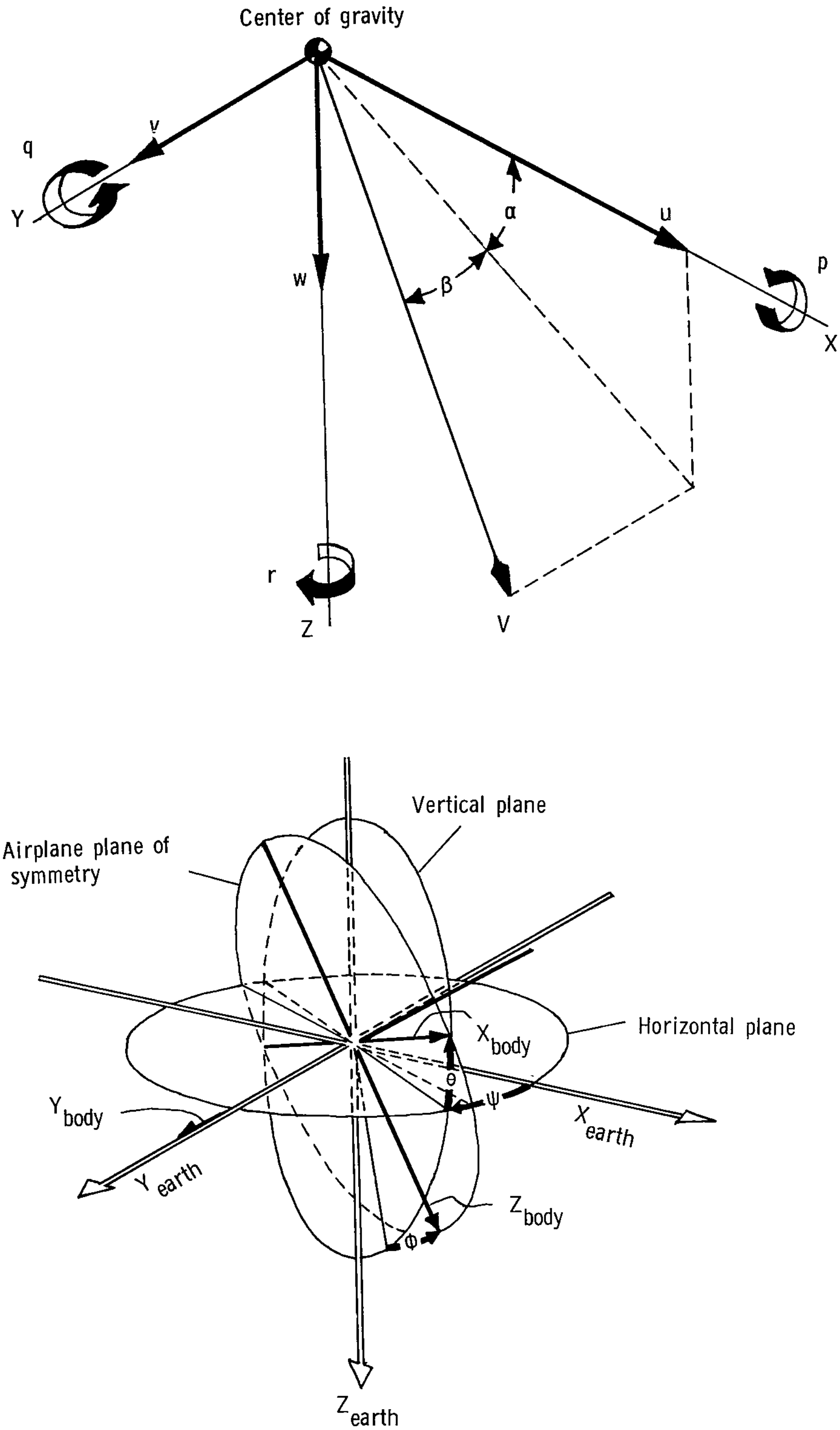


Figure 1.- Earth and body systems of axes and related angles. Arrows indicate positive directions of quantities.

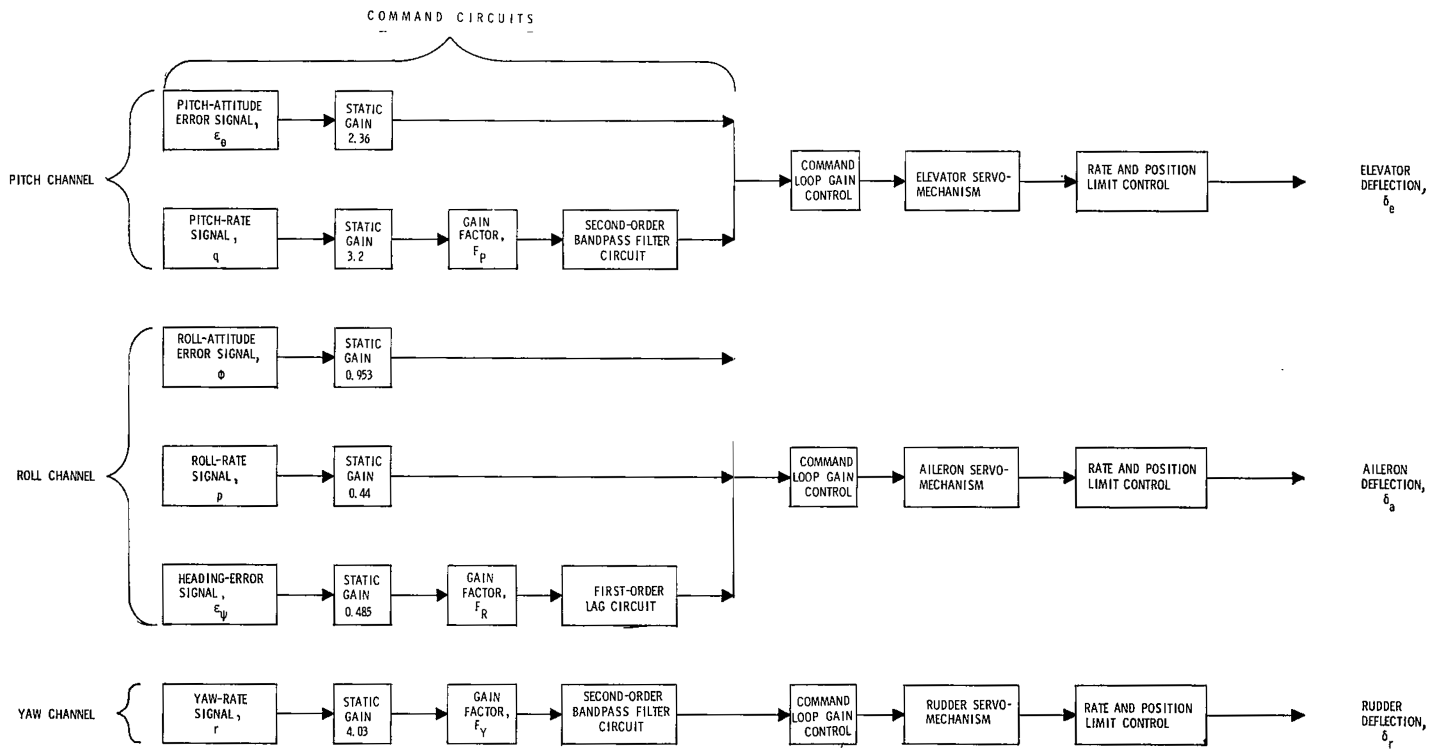
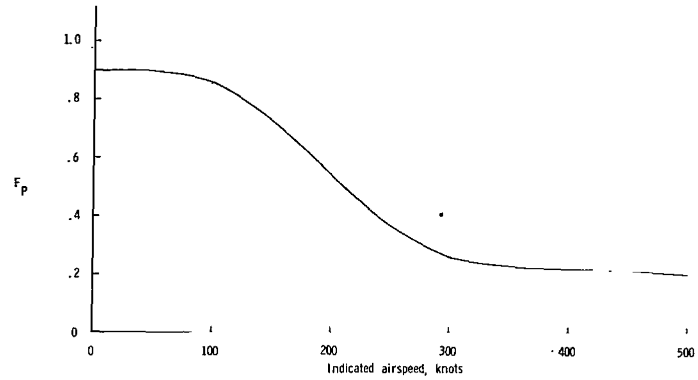
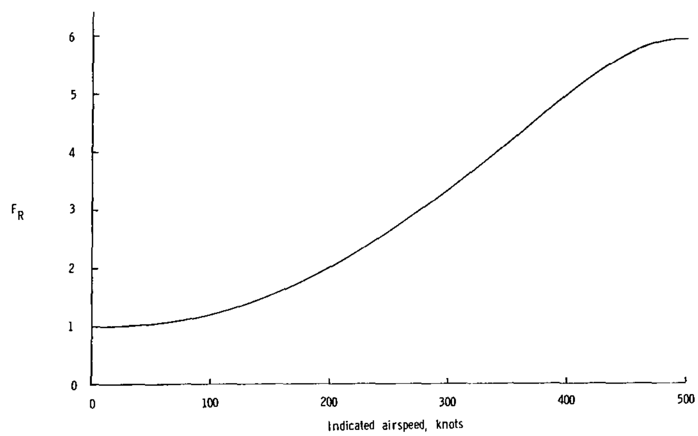


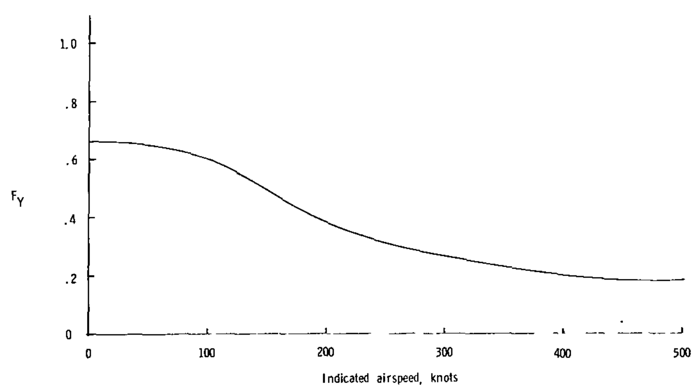
Figure 2.- Block diagram showing configuration of automatic control system (ACS).



(a) Variation of pitch-channel gain factor with indicated airspeed.



(b) Variation of roll-channel gain factor with indicated airspeed.



(c) Variation of yaw-channel gain factor with indicated airspeed.

Figure 3.- Variations of ACS gain factors with indicated airspeed .or three ACS channels.

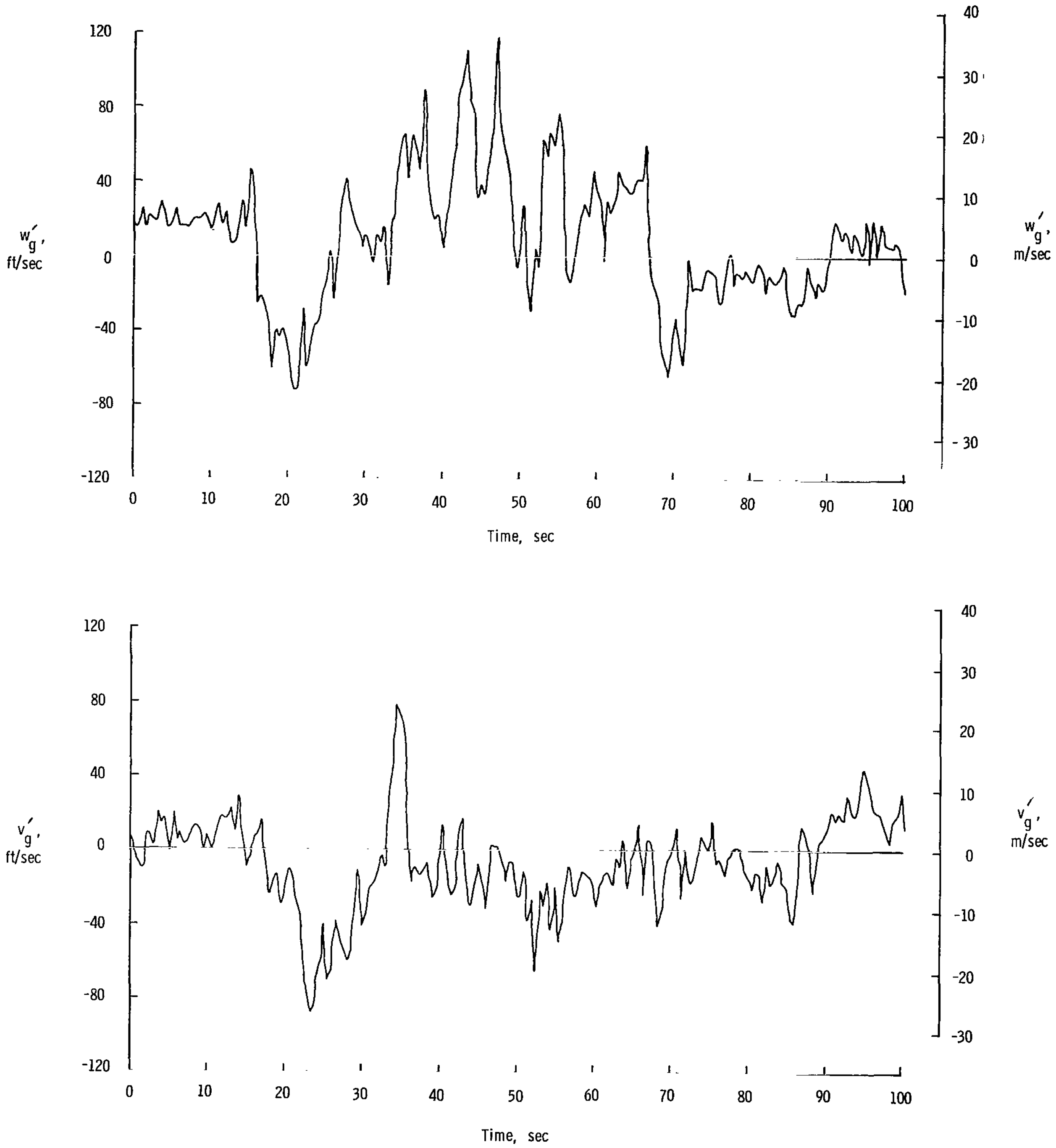


Figure 4.- Severe turbulence sample used in calculations.

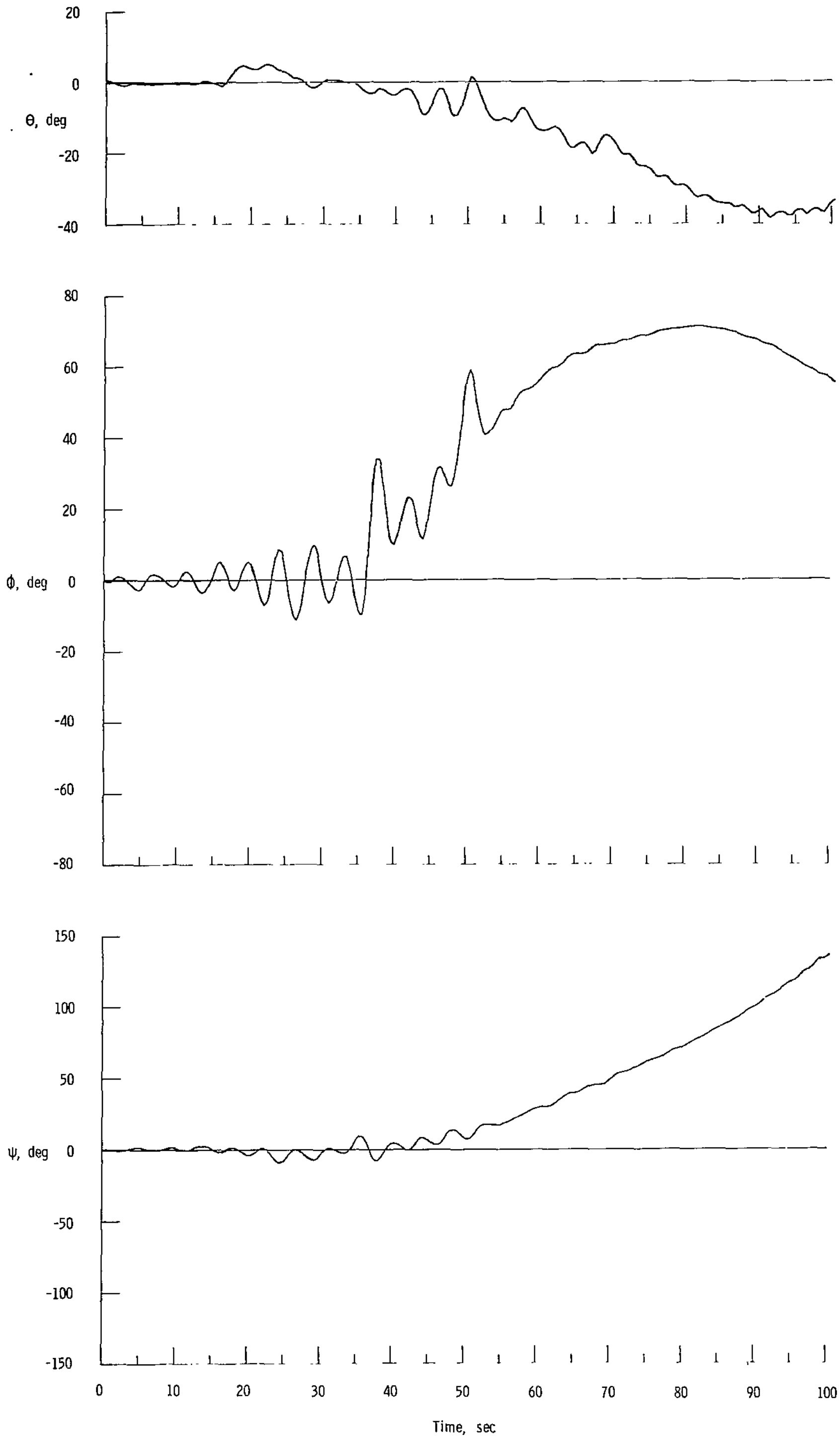


Figure 5.- Calculated time histories of uncontrolled subsonic jet-transport flight motions in severe turbulence.

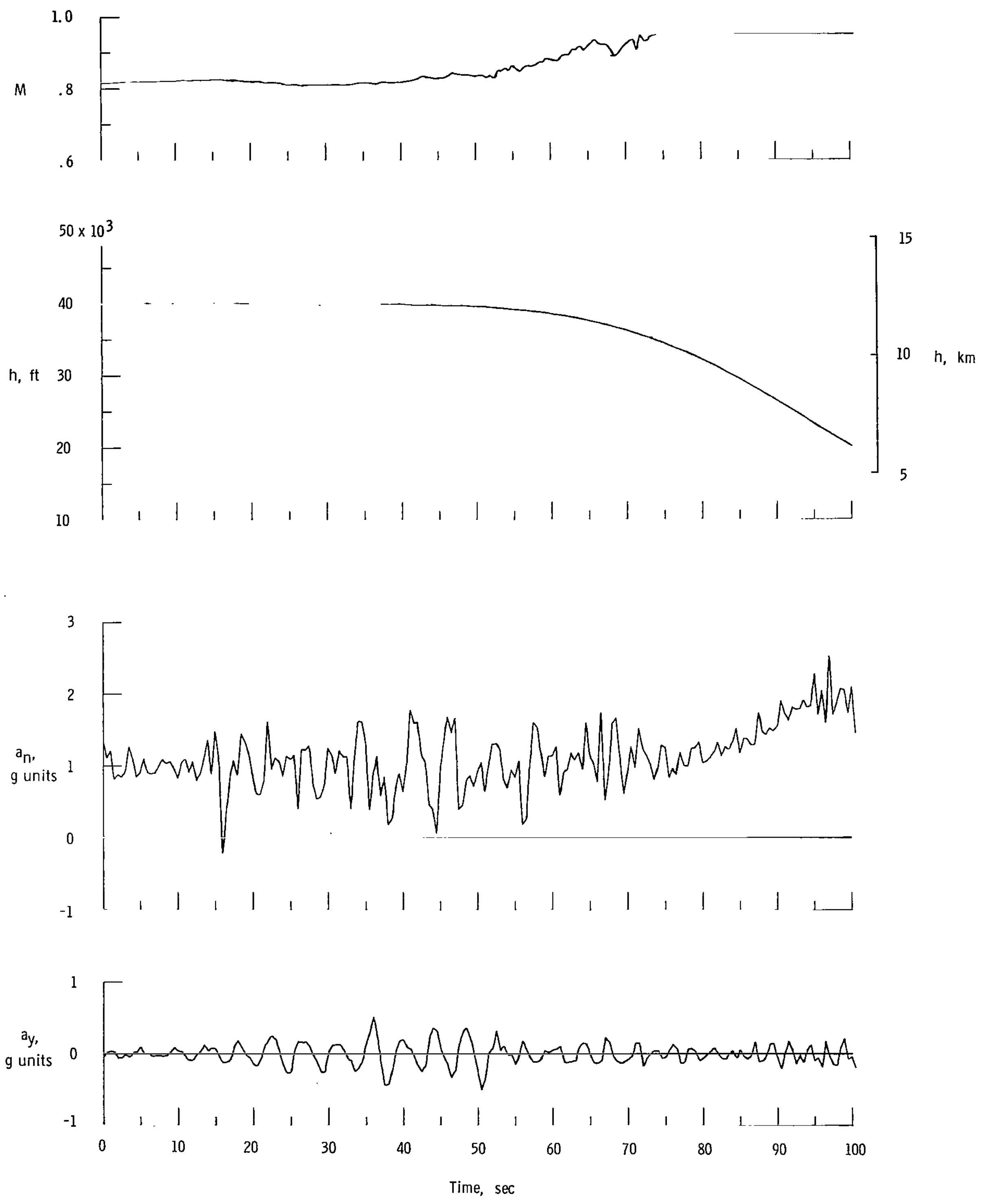


Figure 5.- Continued.

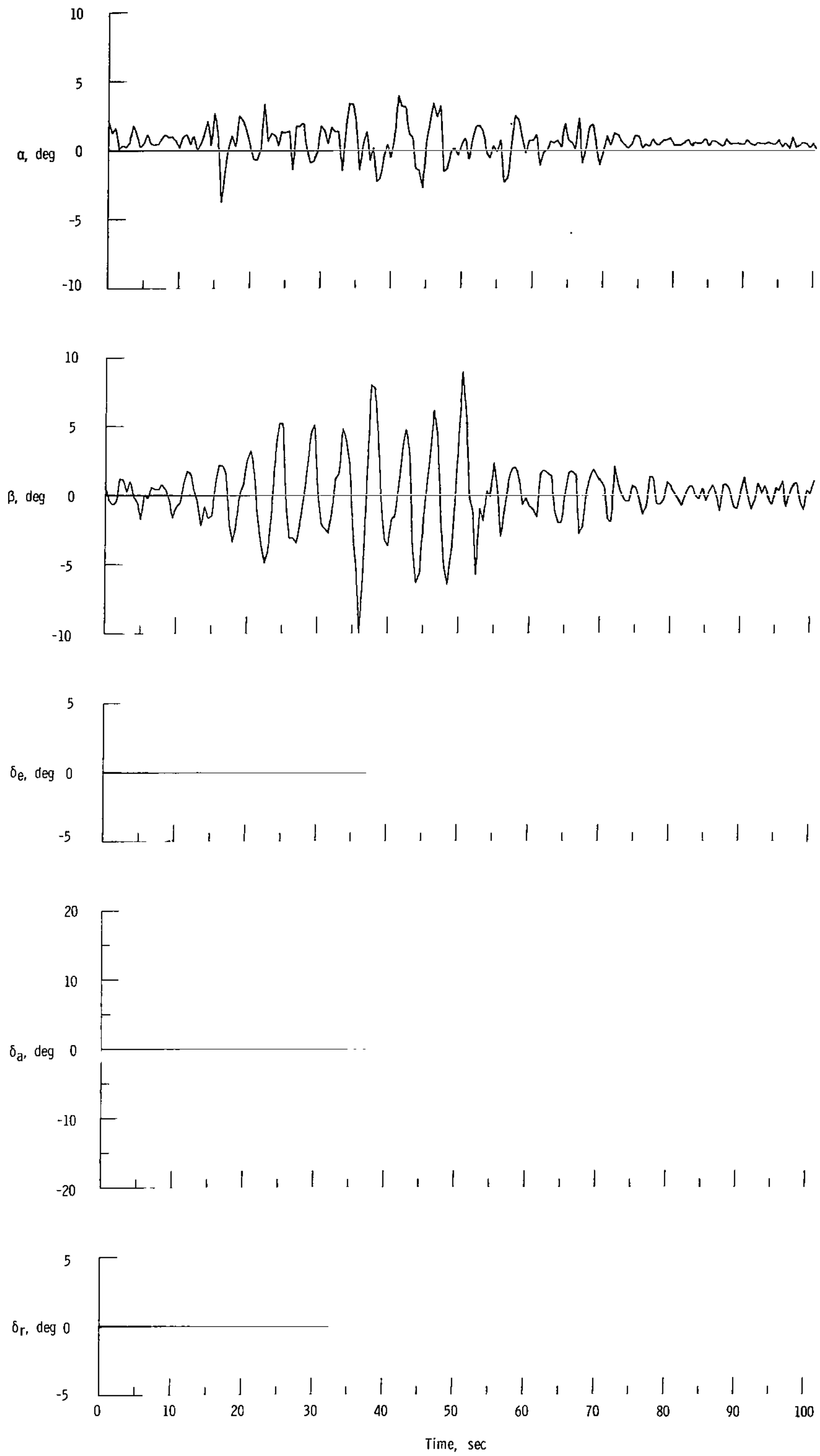


Figure 5.- Concluded.

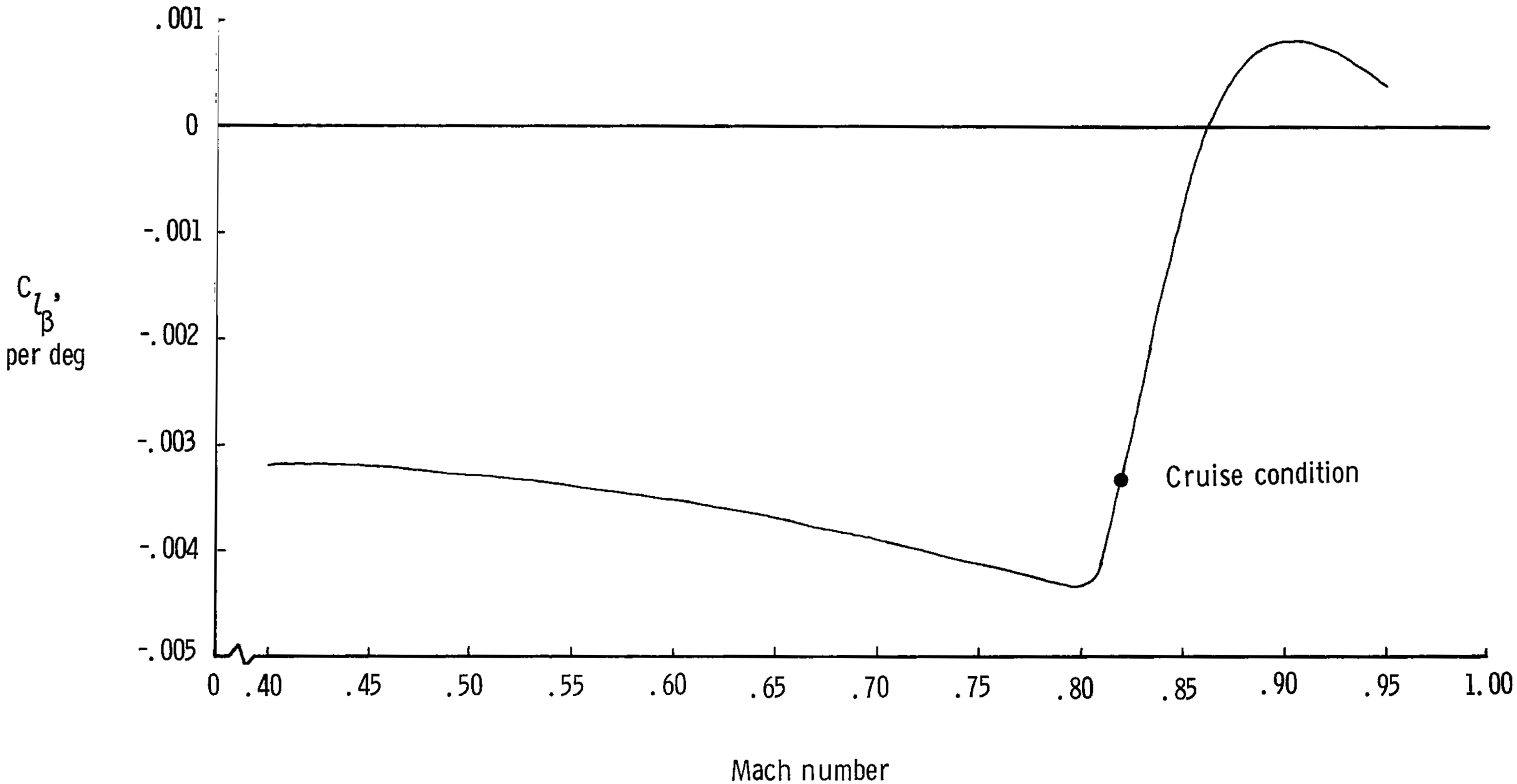


Figure 6.- Variation of effective dihedral with Mach number. $\alpha_{trim} = 0.84^{\circ}$.

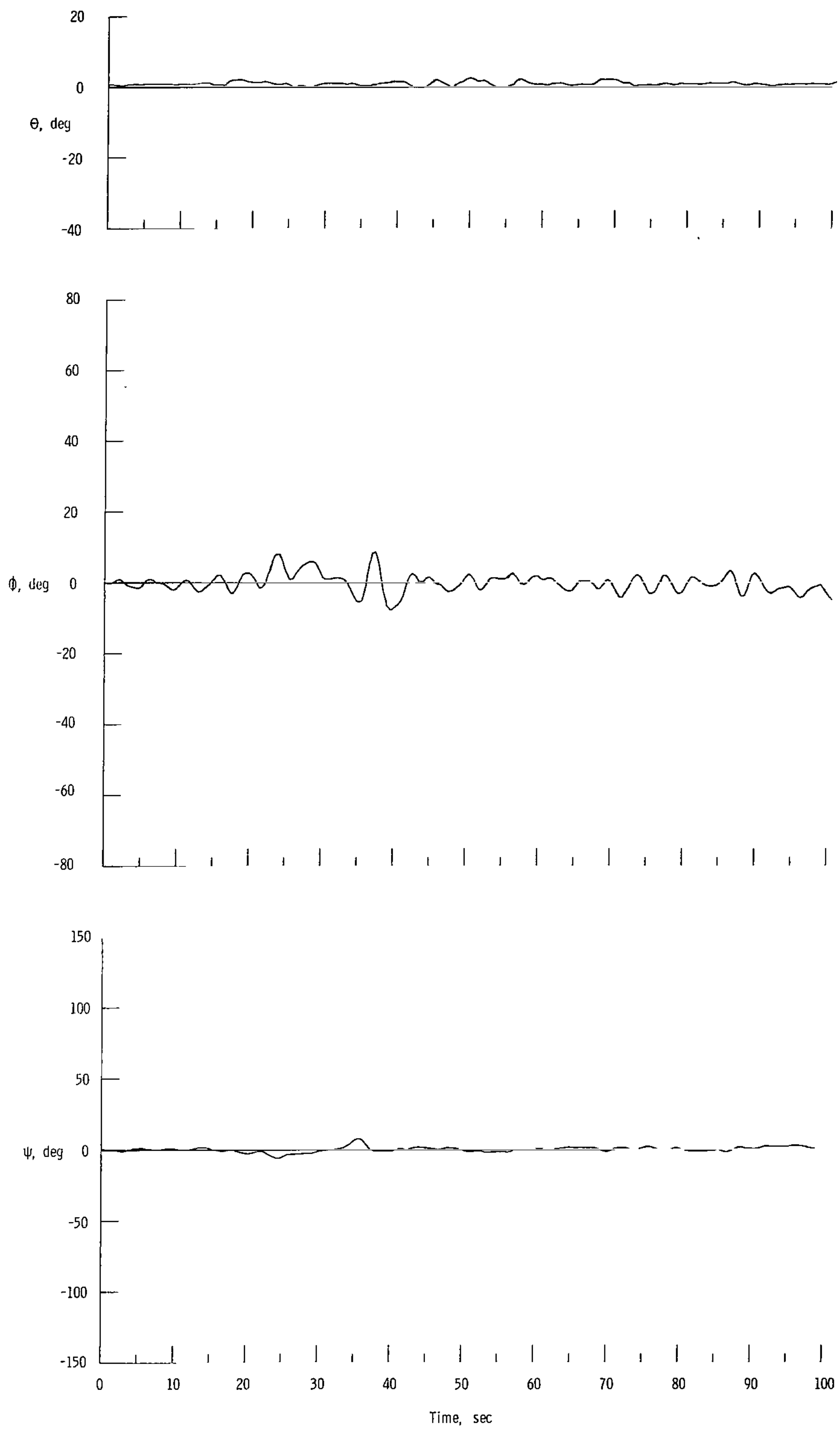


Figure 7.- Calculated time histories of controlled subsonic jet-transport flight motions in severe turbulence.

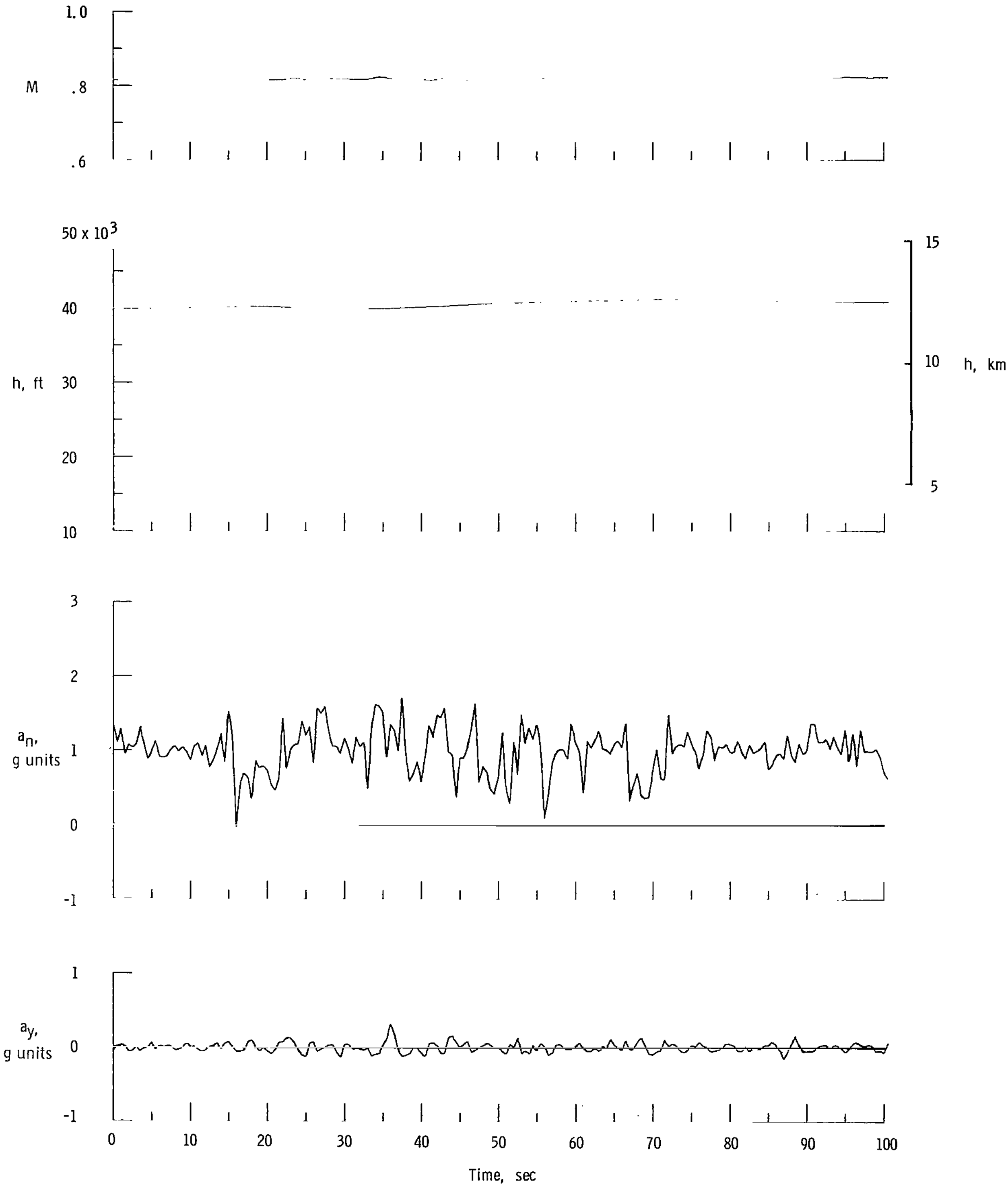


Figure 7.- Continued.

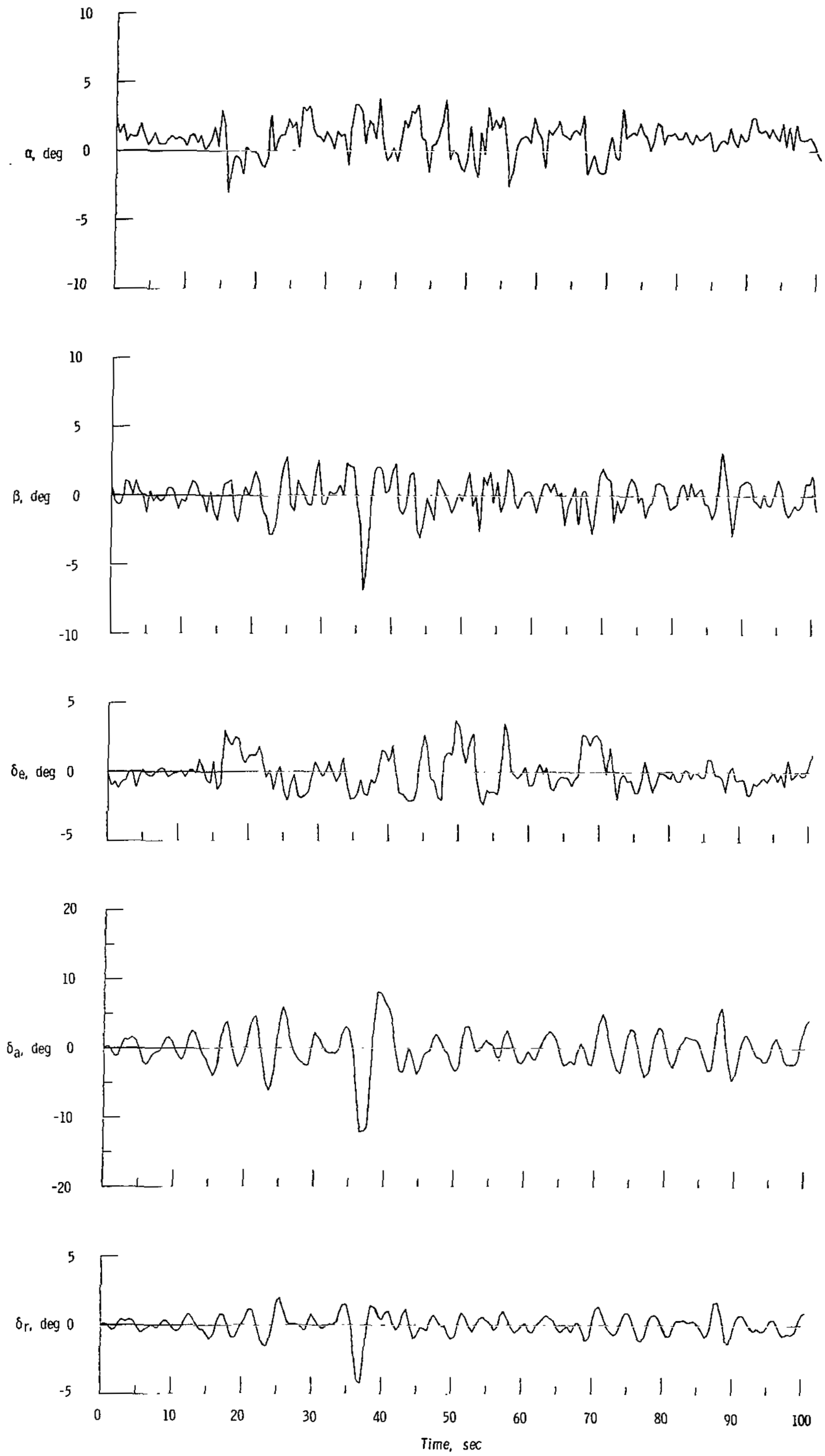


Figure 7.- Concluded.

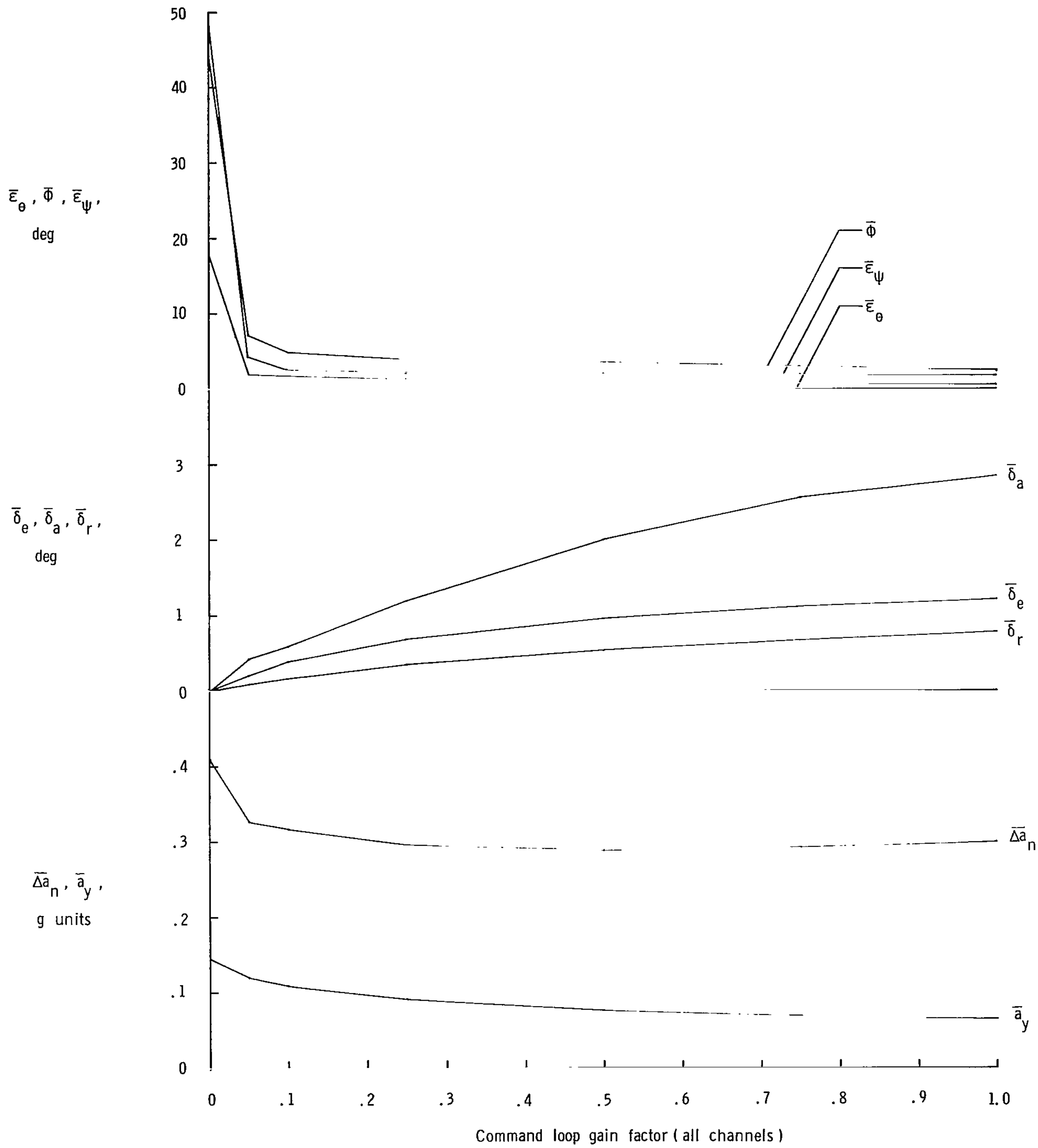
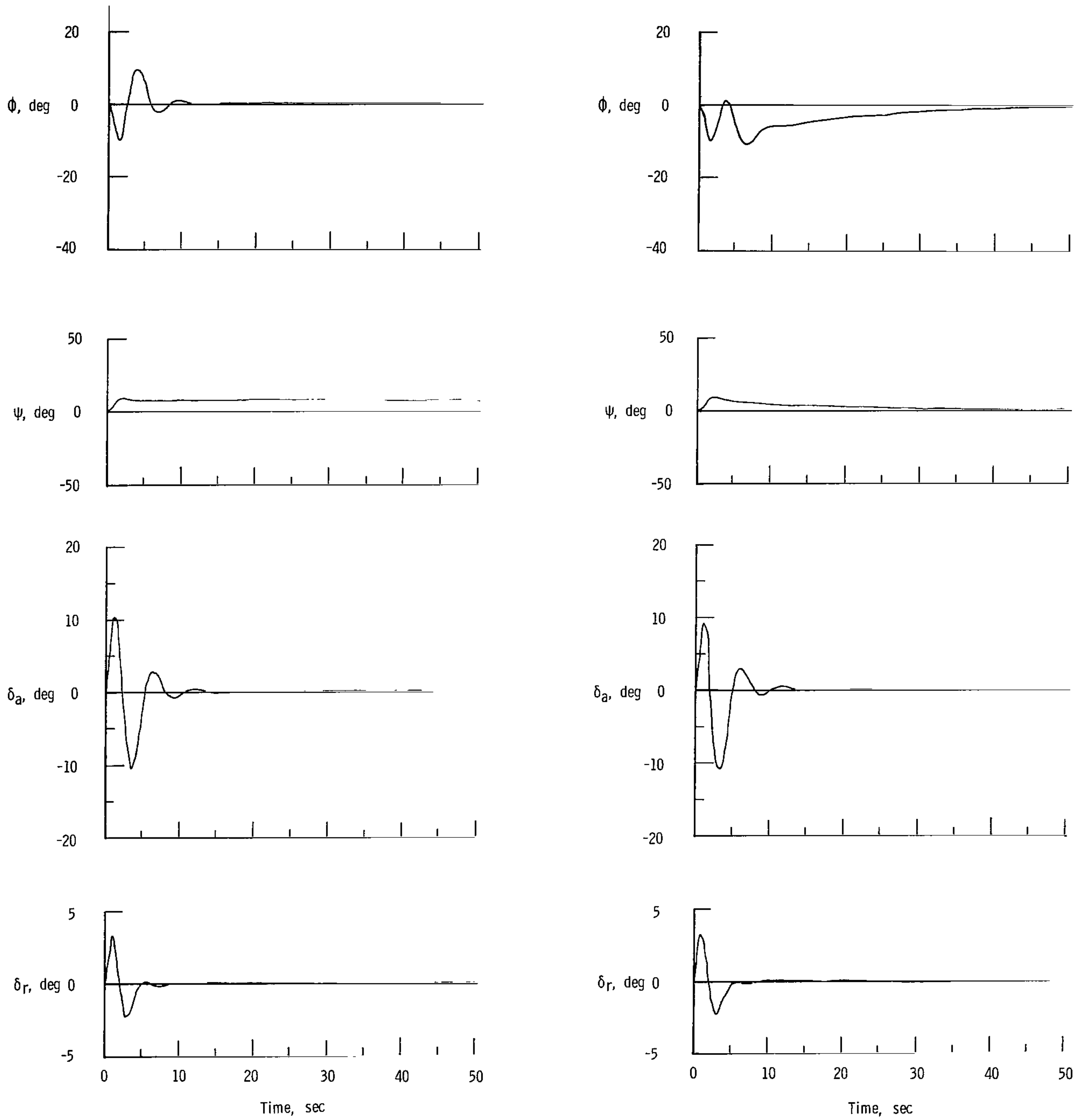


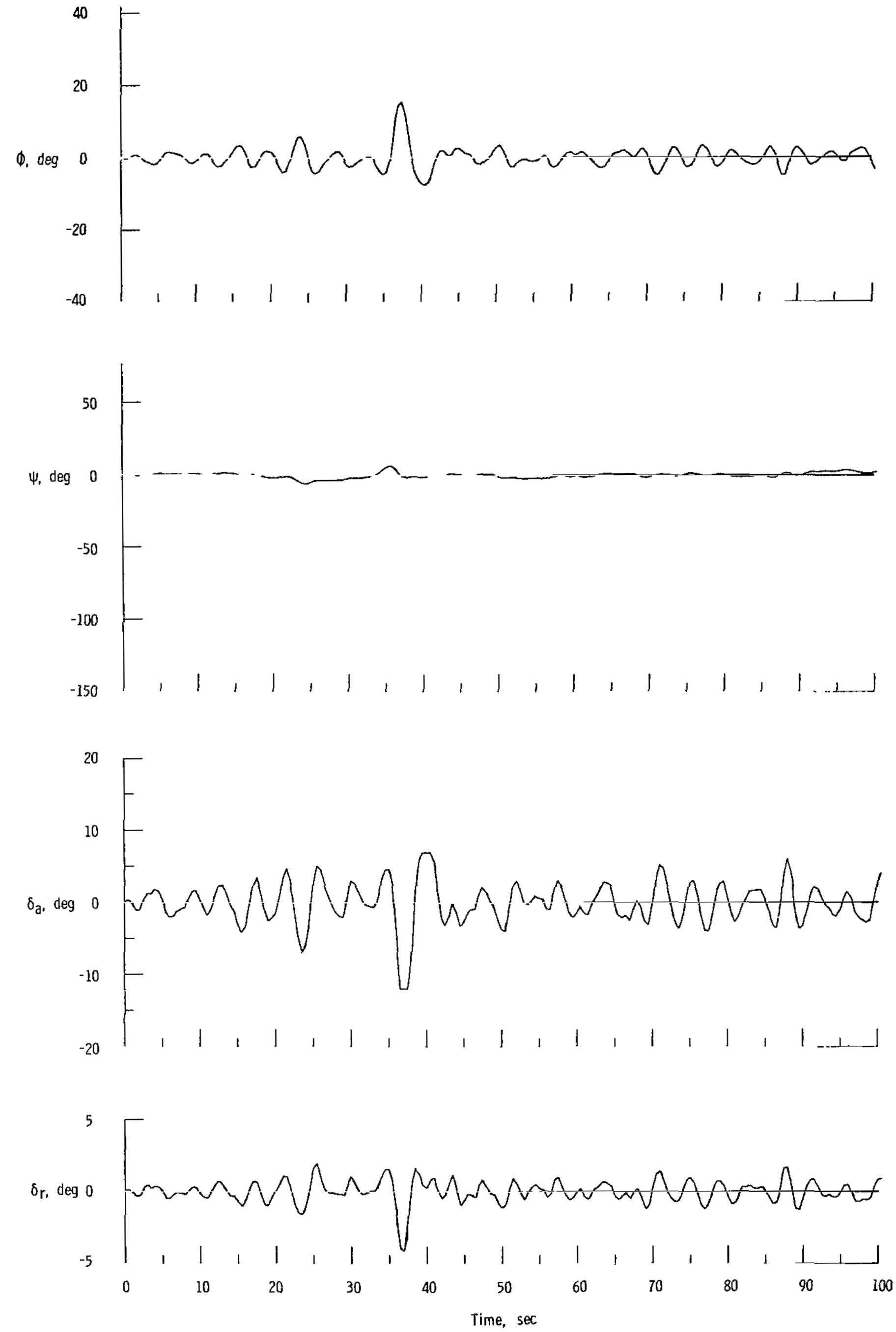
Figure 8.- Effect of variation in ACS command loop gains on rms values of flight parameters (computed for 100-second flights in turbulence). All ACS channels active; heading-hold mode active.



(a) Calculated response of airplane with ACS without heading-hold mode.

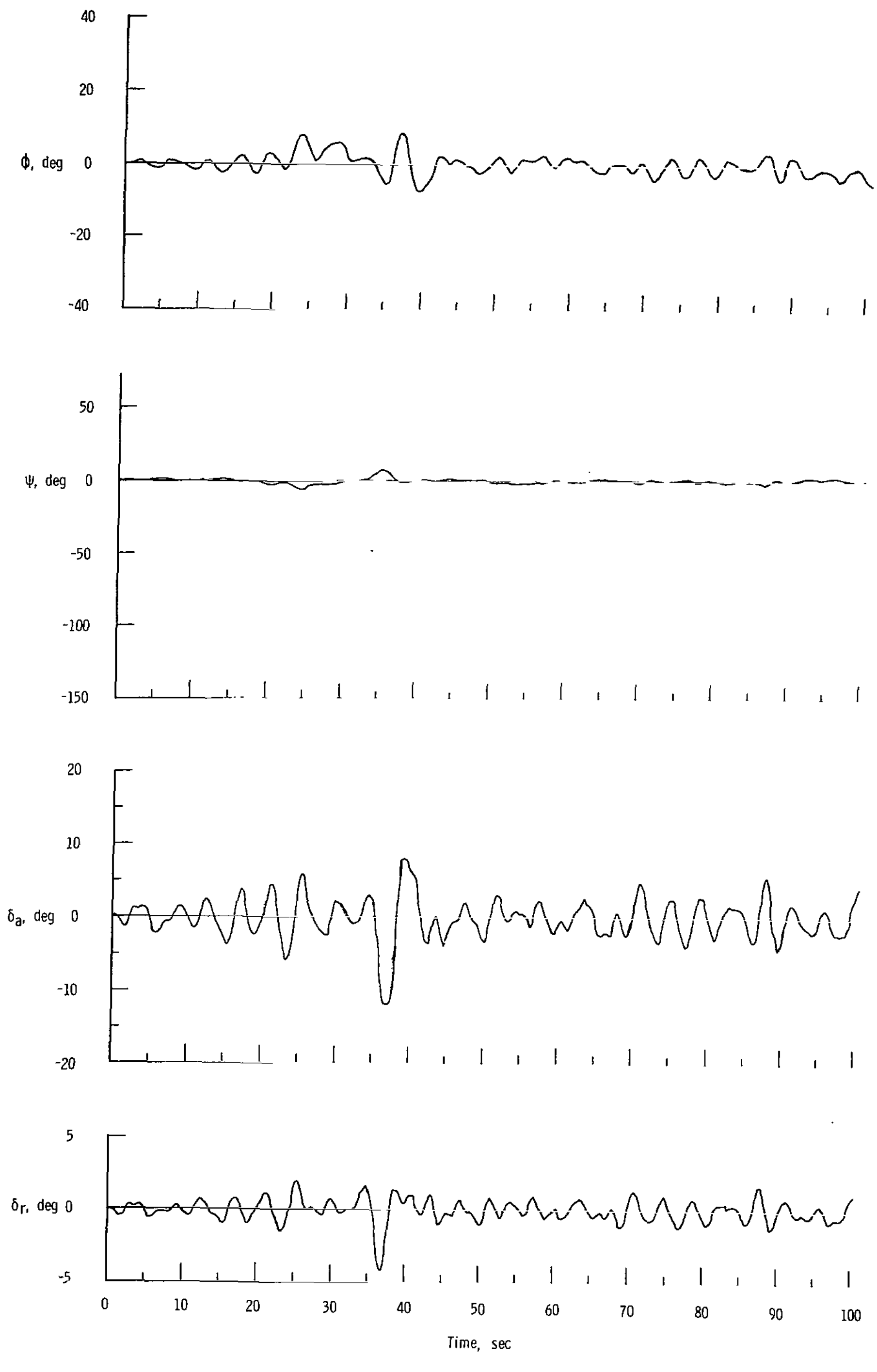
(b) Calculated response of airplane with ACS with heading-hold mode active.

Figure 9.- Computed time histories of flight motions of jet transport in step lateral gust (of 100 ft/sec (30.5 m/sec)) showing effect of ACS heading-hold feature.



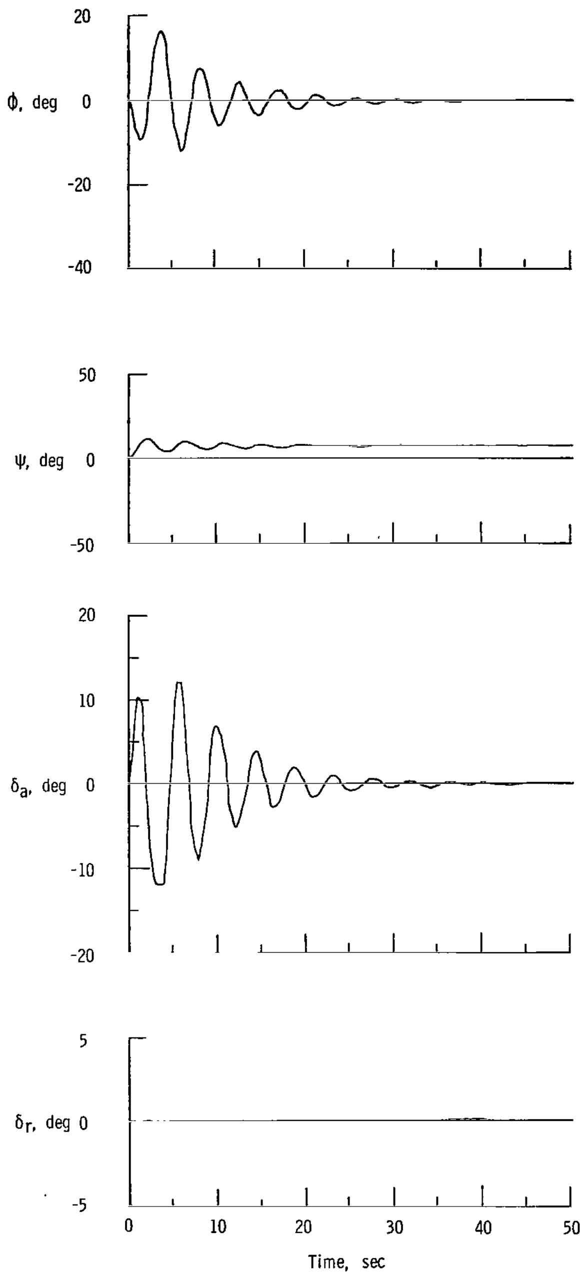
(a) System response without heading-hold mode.

Figure 10.- Calculated response of controlled airplane flight in turbulence showing effect of heading-hold feature.

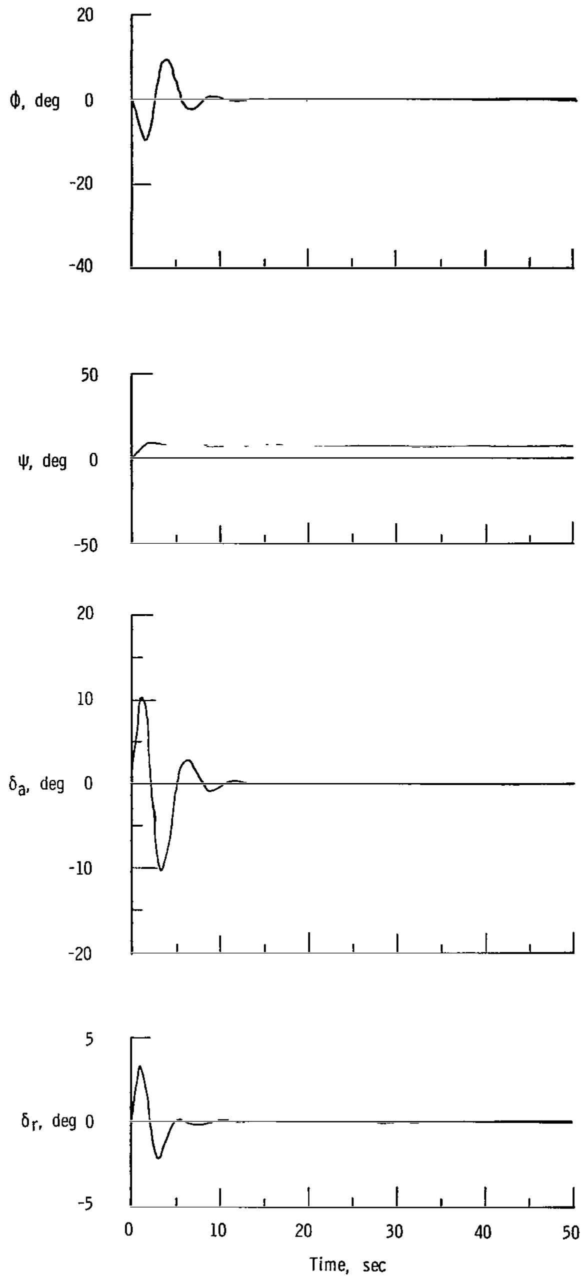


(b) System response with heading-hold mode active.

Figure 10.- Concluded.



(a) Computed response of airplane-ACS with only roll control, without heading-hold mode.



(b) Computed response of airplane-ACS with ACS roll and yaw channels on, without heading-hold mode.

Figure 11.- Calculated response of airplane-ACS combination to step lateral gust (of 100 ft/sec (30.5 m/sec)) showing effect of ACS yaw damper operated with roll channel, without heading-hold mode.

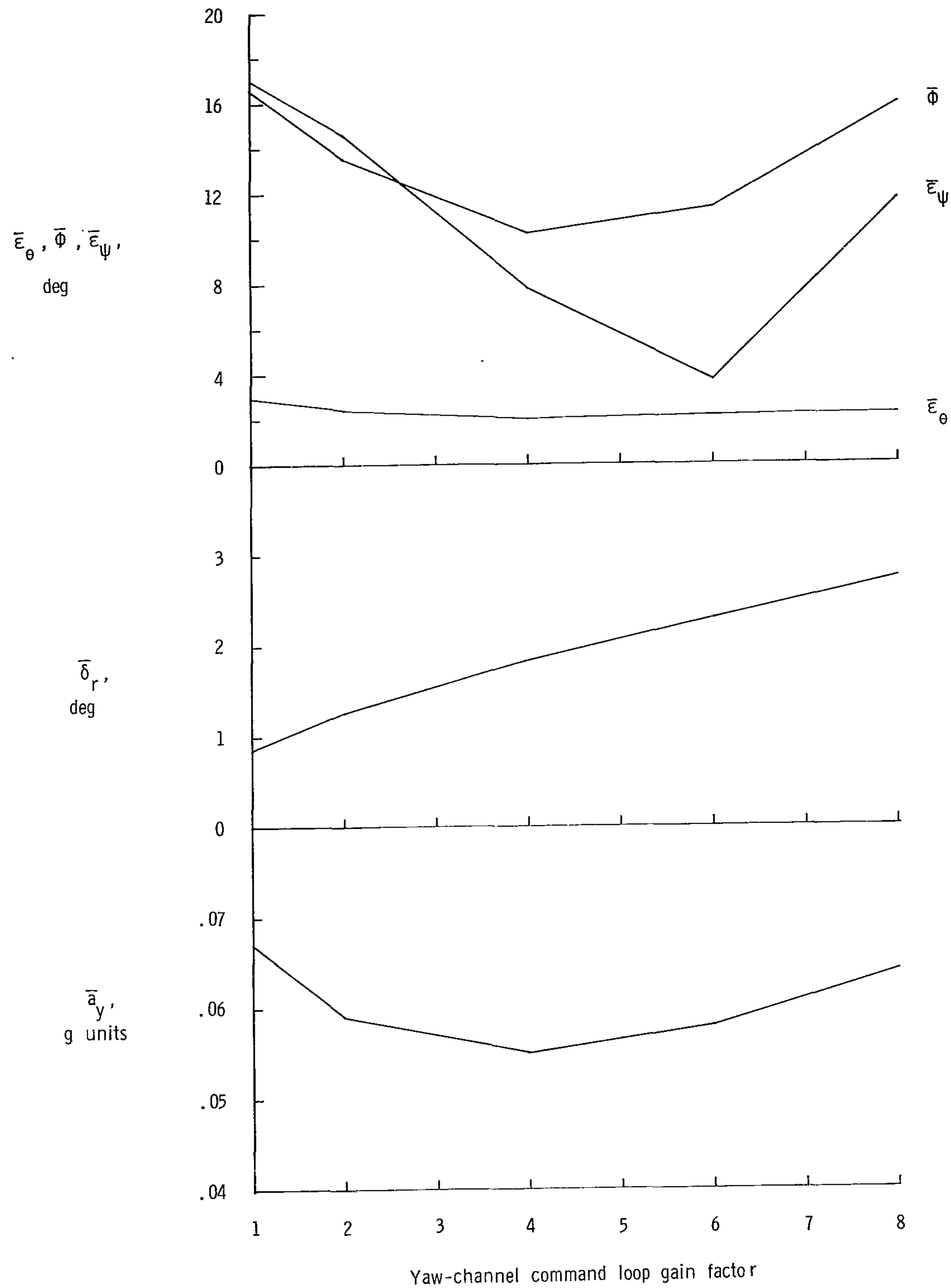


Figure 12.- Computed variation of airplane-ACS rms response (computed for 100-second flights in turbulence) to increasing ACS yaw-channel (yaw-damper) command loop gain. Only yaw channel active.

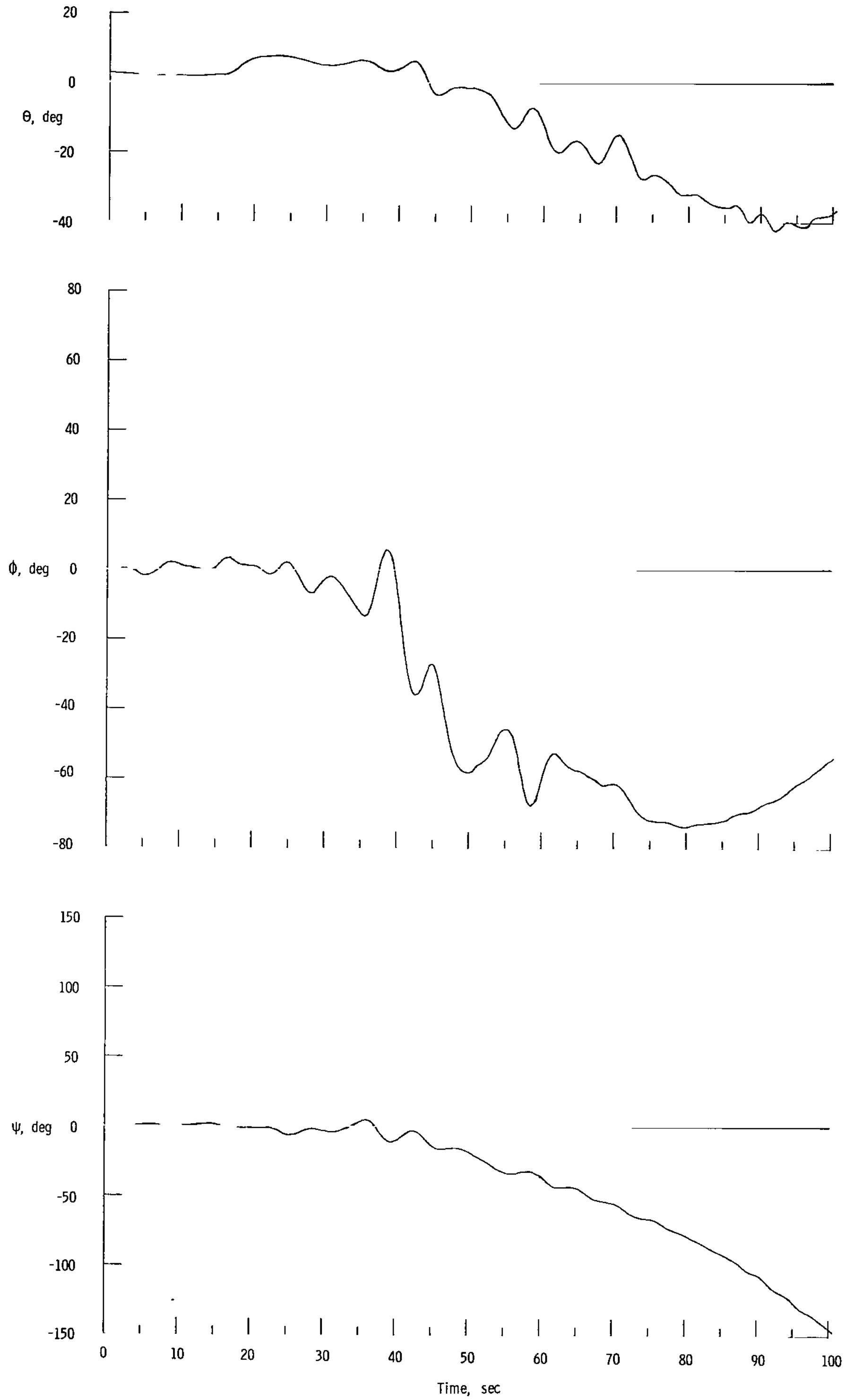


Figure 13.- Computed response of uncontrolled scaled-up jet transport to severe turbulence.

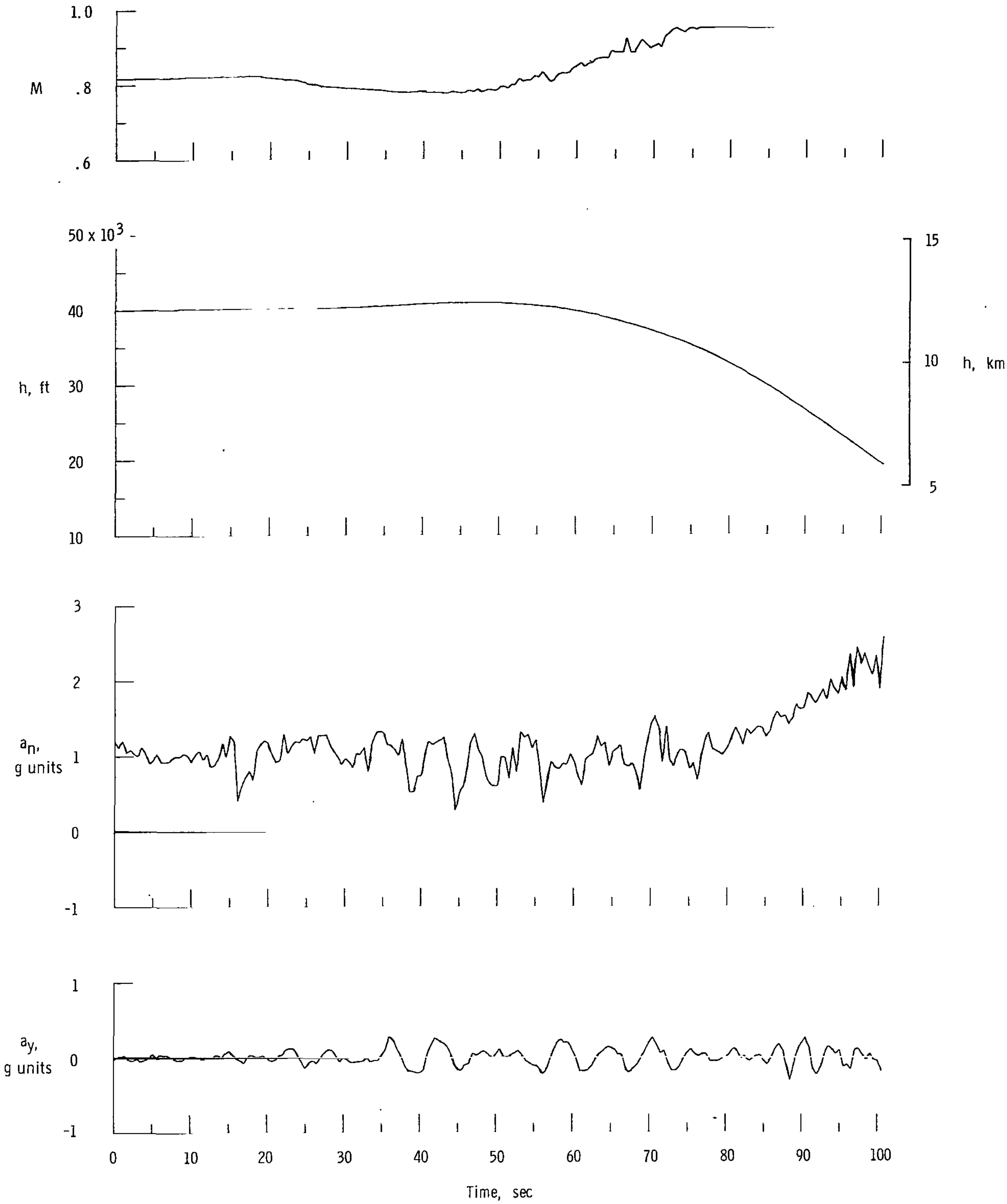


Figure 13.- Continued.

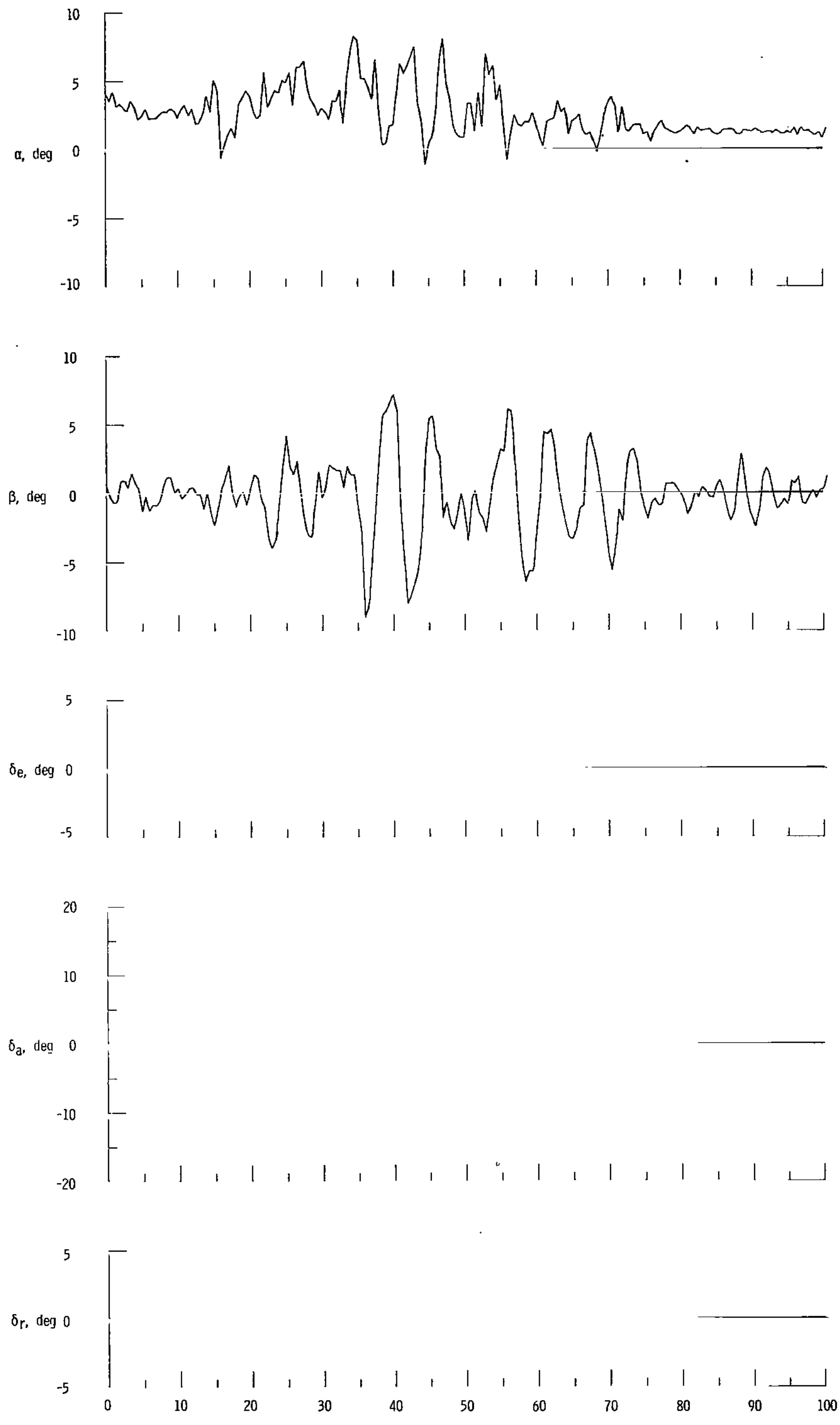


Figure 13.- Concluded.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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