NASA TECHNICAL NOTE

NASA TN D-6670

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NASA TN D-6670

INVESTIGATION OF AN AUTOMATIC SPIN-PREVENTION SYSTEM FOR FIGHTER AIRPLANES

by William P. Gilbert and Charles E. Libbey

Langley Research Center
Hampton, Va. 23365

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1972

1. Report No. NASA TN D-6670	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle INVESTIGATION OF AN AUTOMATIC SPIN-PREVENTION SYSTEM FOR FIGHTER AIRPLANES		5. Report Date March 1972
		6. Performing Organization Code
7. Author(s) William P. Gilbert and Charles E. Libbey		8. Performing Organization Report No. L-8112
		10. Work Unit No. 136-62-02-03
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Va. 23365		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Note
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

An investigation has been conducted to evaluate the effectiveness of an automatic spin-prevention system for current fighter airplanes as a first step in determining the feasibility of such a system. The concept makes use of the components of the conventional flight-control system with the addition of control logic to monitor angle of attack, yaw rate, and normal acceleration. Analytical techniques were used to study the system concept applied to three representative fighter configurations, and model flight tests were employed to evaluate a prototype system on a representative fighter configuration. Emphasis was placed on the development of the control logic required. A discussion of possible implementations of the system concept is presented. Results of the investigation indicated that a relatively simple system (with full control authority) was effective in preventing the developed spins of the fighter configurations considered and that the system design is dependent on the stall and spin characteristics of the particular airplane.

17. Key Words (Suggested by Author(s)) Spin prevention Spinning		18. Distribution Statement Unclassified – Unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 48	22. Price* $3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

INVESTIGATION OF AN AUTOMATIC SPIN-PREVENTION SYSTEM FOR FIGHTER AIRPLANES

By William P. Gilbert and Charles E. Libbey
Langley Research Center

SUMMARY

An investigation has been conducted to evaluate the effectiveness of an automatic spin-prevention system for fighter airplanes as a first step in determining the feasibility of such a system. The automatic system was conceived as using components of the conventional flight-control system, insofar as possible for reliability, with the addition of a special control-logic system to monitor angle of attack, rate of yaw, and normal acceleration. The system automatically applied recovery controls whenever the magnitudes of yaw rate and angle of attack exceeded preselected threshold values. The system was analytically evaluated using a digital computer program for three representative fighter configurations. Flight tests using a radio-controlled model and a simplified logic system were conducted to provide experimental verification of the effectiveness of the system.

The analytical results indicated that the automatic spin-prevention system (with full control authority) was effective in preventing the developed spin of the three fighter configurations considered. Outdoor flight-test results confirmed that such a system was effective in preventing spins, even with the human pilot holding pro-spin controls. Furthermore, the analytical results showed that the desired characteristics of the automatic spin-prevention system were dependent on the stall and spin characteristics of the particular airplane configuration.

INTRODUCTION

Recent experience has shown that most contemporary fighter airplanes exhibit poor stall characteristics and a strong tendency to spin. They also have poor spin characteristics and recovery from a fully developed spin is usually difficult or impossible. As a result of these unsatisfactory stall and spin characteristics, the developed spin is currently an undesirable and potentially dangerous flight condition which should be avoided. Experience has shown that spins can be avoided if the proper recovery technique is applied as quickly as possible following loss of control. It would, therefore, be highly desirable to use an automatic system to prevent the airplane from ever entering a developed spin. An electronic system capable of this task would have several inherent advantages over the human pilot, including (1) quicker and surer recognition of an incipient spin, (2) faster reaction time for initiation of recovery, (3) application of correct spin-recovery controls, and (4) elimination of tendencies toward spin reversal.

The idea of automatic spin-prevention, or recovery, systems is not new. Stick-pushers that prevent, or discourage, stalling the airplane are, in a sense, spin-prevention systems; but they restrict the pilot from exploiting the full potential-maneuver envelope of the airplane. The installation of more elaborate automatic spin-prevention, or recovery, systems has, until recent years, involved the addition of complete sensing, logic, and control systems at a time when such devices were not very reliable and would probably not have been maintained in proper operating condition because they were protecting against a very rare occurrence. The fact that modern tactical airplanes already incorporate most of the elements of automatic spin-prevention (or recovery) systems, together with a great increase in the reliability of avionics systems, makes the use of these automatic systems more practical. A concept for a spin-prevention system has therefore been developed which makes maximum use of full-time avionics systems already on the airplane (for reliability) and does not interfere with the ability of the pilot to maneuver the airplane into any desired situation except a spin. The present investigation was conducted to evaluate the effectiveness of this concept of an automatic spin-prevention system by means of both theoretical analysis and flight tests of a radio-controlled model equipped with a simplified version of the system.

SYMBOLS

All aerodynamic data and flight motions are referenced to the body system of axes shown in figure 1. The units for physical quantities used herein are presented in both the International System of Units (SI) and the U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units.

a_Z acceleration along Z body axis, g units

b wing span, meters (feet)

C_l rolling-moment coefficient

C_m pitching-moment coefficient

C_n yawing-moment coefficient

C_X longitudinal-force coefficient

C_Y side-force coefficient

C_Z vertical-force coefficient

$\bar{c}$ mean aerodynamic chord, meters (feet)

g local acceleration due to gravity, m/sec^2 (ft/sec^2)

h altitude, meters (feet)

I_X, I_Y, I_Z moments of inertia about X, Y, and Z body axes, respectively, $kg\text{-}m^2$ $(slug\text{-}ft^2)$

I_{XZ} product of inertia about X and Z body axes, $kg\text{-}m^2$ $(slug\text{-}ft^2)$

m mass of airplane, kilograms (slugs)

p,q,r body-axis rolling, pitching, and yawing angular rates, deg/sec or rad/sec

S wing area, $meters^2$ $(feet^2)$

T engine thrust, newtons (pounds)

t time, seconds

u,v,w components of airplane resultant velocity along X, Y, and Z body axes, m/sec (ft/sec)

V_R resultant velocity of airplane, m/sec (ft/sec)

X,Y,Z orthogonal reference-axis system

α angle of attack, degrees

β angle of sideslip, degrees

δ_a aileron deflection, positive when right-aileron trailing edge is down, degrees

δ_e elevator deflection, positive when trailing edge is down, degrees

δ_r rudder deflection, positive when trailing edge is left, degrees

θ pitch attitude, degrees

ρ air density, kg/m^3 (slugs/ft^3)

φ angle of bank, degrees

ψ angle of yaw, degrees

Stability derivatives:

$$C_{l_\beta} = \frac{\partial C_l}{\partial \beta} \qquad C_{n_\beta} = \frac{\partial C_n}{\partial \beta} \qquad C_{Y_\beta} = \frac{\partial C_Y}{\partial \beta}$$

$$C_{l_p} = \frac{\partial C_l}{\partial \frac{pb}{2V_R}} \qquad C_{n_p} = \frac{\partial C_n}{\partial \frac{pb}{2V_R}} \qquad C_{Y_p} = \frac{\partial C_Y}{\partial \frac{pb}{2V_R}}$$

$$C_{l_r} = \frac{\partial C_l}{\partial \frac{rb}{2V_R}} \qquad C_{n_r} = \frac{\partial C_n}{\partial \frac{rb}{2V_R}} \qquad C_{Y_r} = \frac{\partial C_Y}{\partial \frac{rb}{2V_R}}$$

$$C_{l_{\delta_a}} = \frac{\partial C_l}{\partial \delta_a} \qquad C_{n_{\delta_a}} = \frac{\partial C_n}{\partial \delta_a} \qquad C_{Y_{\delta_a}} = \frac{\partial C_Y}{\partial \delta_a}$$

$$C_{l_{\delta_r}} = \frac{\partial C_l}{\partial \delta_r} \qquad C_{n_{\delta_r}} = \frac{\partial C_n}{\partial \delta_r} \qquad C_{Y_{\delta_r}} = \frac{\partial C_Y}{\partial \delta_r}$$

$$C_{m_{\delta_e}} = \frac{\partial C_m}{\partial \delta_e} \qquad C_{X_{\delta_e}} = \frac{\partial C_X}{\partial \delta_e} \qquad C_{Z_{\delta_e}} = \frac{\partial C_Z}{\partial \delta_e}$$

$$C_{m_q} = \frac{\partial C_m}{\partial \frac{q\bar{c}}{2V_R}} \qquad C_{X_q} = \frac{\partial C_X}{\partial \frac{q\bar{c}}{2V_R}} \qquad C_{Z_q} = \frac{\partial C_Z}{\partial \frac{q\bar{c}}{2V_R}}$$

A dot over a symbol indicates a derivative with respect to time.

METHOD

The effectiveness of the automatic spin-prevention system was evaluated by both analytical and experimental techniques. The analytical studies were used to (1) formulate the logic and control elements of the system, (2) evaluate the system for three airplane configurations having different spin characteristics, and (3) consider secondary systems required to transfer control of the airplane from the automatic system back to the human pilot. To further verify the results of the theoretical analysis and substantiate the effectiveness of the concept of the automatic spin-prevention system, flight tests were conducted with one of the configurations used in the theoretical analysis (configuration A).

Description of Airplane Configurations

The three airplane configurations used in the analytical study had aerodynamic and inertial characteristics typical of current high-performance fighter airplanes. The mass and dimensional characteristics of the airplanes, herein referred to as configurations A, B, and C, are presented in table I; the aerodynamic data are tabulated in table II; and the control-system characteristics are presented in table III. Configuration A, which is a variable-sweep fighter configuration (considered for one wing-sweep angle only), was included in the study because the results of wind-tunnel tests had indicated significant nonlinearities in aerodynamic data and large asymmetric yawing moments at high angles of attack (ref. 1), and these aerodynamic characteristics were thought to be a critical test for the system. These nonlinearities and asymmetries were included in the analytical model of this configuration and are listed in table II. Configuration B is a delta-wing fighter configuration for which the static lateral-directional aerodynamic data were treated as the linearized stability derivatives C_{Y_β}, C_{l_β}, and C_{n_β}. Configuration C is a swept-wing fighter configuration which also had linearized lateral-directional data. Although the use of linearized lateral-directional characteristics does fail to account for the nonlinearities of the lateral-directional aerodynamics with sideslip known to exist at high angles (such as are evident for configuration A), this compromise was accepted in this study since the calculations with these data did exhibit a developed spin for both airplanes. Reasonable confidence was held in the data for configuration A since the calculated flat spin exhibited about the same spin angle of attack and rate of yaw as the flat spin of the radio-controlled model of configuration A.

The outdoor free-flight tests were made only for configuration A. Prior tests of a model of configuration A had shown that this design would enter a spin quite readily and that recovery from the developed spin would be marginal.

Description of Automatic Spin-Prevention System

The automatic spin-prevention system was designed to be capable of detecting an incipient spin and actuating the conventional control surfaces in an antispin sense without inhibiting the pilot's ability to maneuver the airplane over any of its maneuver envelope except for the spin. The system requires sensor signals which indicate the values of angle of attack, rate of yaw, and normal acceleration. Angle-of-attack sensors have recently become standard equipment in tactical airplanes; furthermore, being normally in almost continuous use, they are subjected to constant maintenance and are kept in peak operating condition. The system is composed of two subsystems, a primary subsystem and a secondary subsystem, and is shown schematically in figure 2.

Primary subsystem.- The primary subsystem is that part of the automatic spin-prevention system which senses and identifies the impending spin and initially commands controls for spin recovery (for current, fuselage-heavy fighter airplanes, these recovery controls normally consist of full-trailing-edge-up elevator, full ailerons with the spin, and full rudder against the spin). As shown in figure 2, the system monitors rate of yaw, angle of attack, and normal acceleration. When both angle of attack and rate of yaw exceed separate threshold values, the primary subsystem is activated. The normal-acceleration signal is used to determine if the spin entry is erect or inverted, and the yaw-rate signal is used to distinguish between left and right spin entries. The correct recovery-control commands are selected for the spin-entry attitude and direction determined and routed to the airplane flight-control system to actuate the control surfaces. These control commands (normally requiring full authority) are maintained until a change in sign of yaw rate is obtained after which time control is relinquished to the secondary subsystem or the pilot.

Secondary subsystem.- Ideally, the pilot should regain control of the airplane immediately after the primary recovery. However, since this may not be possible because of confusion or disorientation and to minimize the chances of a spin reversal, a secondary subsystem was used to assure control of the airplane (after the primary recovery) until the pilot took control and deactivated the secondary subsystem. This subsystem accepted control of the airplane if the pilot took no action and if the yaw rate was within a preselected dead band about zero; if the airplane yaw rate exceeded the dead band, the primary subsystem was reactivated. The secondary subsystem's control action was to center the pilot's rudder pedals and stick controller (neutral rudder and ailerons), apply a predetermined amount of nose-up longitudinal control (through the stick controller), and either maintain these fixed-reference controls or, in addition, actuate the conventional rate dampers of the stability-augmentation system. Hereafter, the maintenance of the fixed controls is called the fixed-reference control mode and the use of the rate-damper control in addition to the fixed-control positions is called the rate-damper control mode.

Calculations

The calculated motions consisted of attempted spin entries from straight and level flight. The calculations were based on nonlinear equations of motion, the aerodynamic data used were based on wind-tunnel tests, and a realistic representation of control-surface rates and maximum deflections was used.

The results obtained for each airplane configuration consist primarily of calculated time histories of the flight motions resulting from an intentional attempt to stall and spin the airplane and the ensuing attempt by the automatic spin-prevention system to effect recovery. The configurations were initially in trimmed, level flight at a true airspeed of 213 m/sec (700 ft/sec) and an altitude of 9140 meters (30 000 ft). Flight motions were calculated with the automatic system both operative and inoperative. The results of the calculations include (1) the spin characteristics of the configurations, (2) the effect of the automatic spin-prevention system on attempted spin entries from level flight, and (3) the effect of variations of the secondary-subsystem logic.

The performance of the automatic spin-prevention system was evaluated in two phases. In the first phase all configurations were considered. During this phase the angle-of-attack actuation threshold of the primary subsystem (generally set to be at or above the stall angle of attack) was set at 30° for configurations A and C and at 35° for configuration B. Two values of the yaw-rate actuation threshold were considered in the first phase, 11.5 deg/sec and 57.3 deg/sec. During the first phase the secondary-subsystem characteristics were held constant and included the rate-damper control mode and a ± 11.5 deg/sec yaw-rate dead band. In the second phase the control of the airplane by the secondary subsystem after an initial recovery by the primary subsystem, with the assumption that the pilot took no control action, was considered. The effect of the magnitude of the yaw-rate dead band (varied from 0.0 to ± 23.0 deg/sec), the secondary-subsystem control mode, and the elevator (horizontal stabilator for configuration A) reference position (considered for a full-trailing-edge-up position, -25°, and a trim setting, -5°) on the performance of the secondary subsystem was considered. All airplane configurations were considered in the second phase, but representative results are presented for configuration A only.

Flight Tests

The flight tests were conducted using an existing 1/9-scale radio-controlled model equipped with a simplified automatic spin-prevention system and an onboard tape recorder (for data acquisition). The outdoor flight test with the radio-controlled model involves launching an unpowered model from altitude with a helicopter, diving the model to gain speed, attempting a stall and/or spin entry, and recovering the model by parachute. Additional information on the drop-model free-flight technique and its application to spin studies is given in reference 2.

The simplified automatic spin-prevention system used in the free-flight model contained logic circuitry to represent only the primary subsystem. Rate of yaw (r) and angle of attack (α) were sensed as the primary variables, and no normal-accelerometer signal was used (all spins assumed erect). The system employed threshold levels for α and r of 35° and 11.5 deg/sec, respectively. The system sensed r and α, selected and applied the correct recovery controls if the thresholds were simultaneously exceeded, and maintained these control inputs to the model's control system until the initial yaw rate had been decreased to zero. At this point, control was returned to the pilot. The rate-gyro package (which sensed r), the logic package, and the nose-boom probe (used to sense α) are shown in figure 3. The electronic circuitry consisted of three sections: (1) sensing circuits which monitored signals from the model's sensors, (2) a logic circuit which controlled system actuation, and (3) a control section which generated the proper recovery-control signals. The logic package was extremely compact, even though no use of microminiaturized components was made and no particular attempt was made to achieve a compact construction.

For these tests the model was released at 1524 meters (5000 feet) at an airspeed of about 40 knots with neutral controls, allowed to dive to gain speed, then given pro-spin controls (normally full-trailing-edge-up elevator, full ailerons against the desired spin direction, and full rudder with the desired spin direction). The automatic system, when activated, moved the elevators to a neutral position, the ailerons to with the spin-entry direction, and the rudder to against the spin-entry direction.

RESULTS OF ANALYTICAL STUDY

The results of the analytical study are discussed as (1) representative spin characteristics of the individual airplane configurations, (2) the effect of the automatic spin-prevention system on spin characteristics, including variations in threshold value of yaw rate, and (3) effect of logic of the secondary subsystem in providing control in lieu of pilot control.

Representative Spins of Airplane Configurations

Flight motions of the three airplane configurations were calculated for representative spins which occurred following application of pro-spin controls from trimmed level flight at an airspeed of 213 m/sec (700 ft/sec) and an altitude of 9140 meters (30 000 feet). No attempt was made to effect recovery from the developed spin. The resulting spins are individually discussed for each configuration, and the results are presented in figure 4.

Configuration A.- The results of the calculations for configuration A are presented in the form of time histories of the more pertinent flight parameters in figure 4(a). A spin to the left was initiated by movement of the horizontal stabilator to full trailing edge up, the rudder to full trailing edge left, and the ailerons to full right wing down. The ensuing motion consisted of a directional divergence and a left roll of 360° at high angles of attack after which the configuration entered a fast-flat spin at an average angle of attack of about 83° and a yaw rate of about -160 deg/sec. At the end of 40 seconds, the configuration had completed about 10 turns, lost about 2400 meters (8000 feet) of altitude, and was descending at an airspeed of about 90 m/sec (300 ft/sec). This type of fast flat spin is particularly dangerous inasmuch as spin-tunnel tests have shown that recovery from this spin condition is not likely by use of conventional controls.

Configuration B.- An intentional spin for configuration B is shown in figure 4(b). For this flight, the controls were applied to produce a spin to the right. This configuration initially rolled 360° at high angles of attack followed by an extremely oscillatory spin in which large excursions in angle of attack occurred, and the spin rate was relatively slow at about 46 deg/sec. At the end of 60 seconds, the airplane had completed only five turns. Although recovery from a slow, oscillatory spin such as that calculated may be relatively satisfactory by use of conventional spin-recovery techniques, such a spin provides an example of erratic post-stall behavior which an automatic system must control.

Configuration C.- The motions calculated for an entry into a right spin for configuration C are presented in figure 4(c). This configuration rolled 360° and entered a relatively flat oscillatory spin having characteristics somewhat between those of configuration A and configuration B. The rate of yaw produced was about 86 deg/sec, and the airplane had completed about eight turns at the end of 40 seconds.

Effect of Automatic Spin-Prevention System

Figures 5 to 7 present the results of calculations made for attempted spin entries with the automatic spin-prevention system operative. These calculations were made for exactly the same initial conditions and spin-entry-control manipulations as were those of figure 4. Calculations were made for threshold yaw rates of 11.5 deg/sec and 57.3 deg/sec for each configuration; and the rate-damper control mode was utilized for the secondary subsystem (with a ± 11.5 deg/sec yaw-rate dead band).

No attempt was made to optimize the actuation threshold boundaries of the automatic system for each airplane configuration considered, although the results obtained with the system boundaries used did indicate that the proper threshold boundaries are dependent on the stall and spin characteristics of the particular airplane configuration.

Configuration A.- The calculated effect of the automatic spin-prevention system for configuration A is shown in figure 5. For a threshold yaw rate of 11.5 deg/sec (fig. 5(a)), the automatic spin-prevention system actuated before the application of pro-spin rudder and aileron because of the yaw-rate buildup caused by asymmetric yawing moments above the stall. The recovery from the motion was relatively rapid and smooth. The primary subsystem was activated at 3 seconds followed by the secondary subsystem (rate-damper control mode) 0.5 second later. Although the primary subsystem had 100-percent control authority, the controls reached only about one-half full deflection because of the rapidity of recovery and the control rates involved. This result indicates that it might be possible to base such a system on the limited authority generally available to automatic stability or control-augmentation systems. When the threshold yaw rate was increased to 57.3 deg/sec, a spin was prevented, but the overall control of the airplane was looser and larger control deflections (full authority) were required. (See fig. 5(b).) In this flight, pro-spin aileron and rudder were applied and the airplane rolled left 360°. When the yaw rate reached 57.3 deg/sec at about 10 seconds, the primary subsystem actuated the controls for recovery. When yaw rate was reversed at 14.5 seconds, control was transferred to the secondary subsystem; however, the secondary subsystem could not contain the yaw rate, and the primary subsystem was reactivated several times before the secondary subsystem could contain the yaw rate.

Configuration B.- The results obtained with the automatic spin-prevention system on configuration B are shown in figure 6. These data show that a developed spin was prevented for a yaw-rate threshold of 11.5 deg/sec. As was the case for configuration A, recovery was smooth; control of the airplane was transferred from the primary subsystem to the secondary subsystem at 9 seconds. When the yaw-rate threshold was increased to 57.3 deg/sec, a considerable time delay in actuation of the system was caused by the low yaw rates obtained. (See fig. 6(b).) The primary subsystem was actuated at 20 seconds, and the secondary subsystem was not initially able to maintain the yaw rate within the 11.5 deg/sec yaw-rate dead band; consequently, the primary subsystem reactivated on several occasions. As can be seen, a "hunting" of the yaw rate and control deflections resulted from the loose postrecovery control by the secondary subsystem. The airplane recovered after about two turns.

Configuration C.- The results obtained with the automatic spin-prevention system on configuration C are presented in figure 7. For this configuration, it was necessary to maintain a full-trailing-edge-up elevator position throughout recovery to avoid the development of negative angles of attack where no aerodynamic data were available. As shown in figure 7(a), the automatic system prevented the spin for a threshold yaw rate of 11.5 deg/sec. The configuration was maintained in essentially stable flight above the stall for this condition; however, the aerodynamic data for this configuration did not include asymmetries above the stall. When the yaw-rate threshold was increased to 57.3 deg/sec, as shown in figure 7(b), a considerably longer time was required to effect recovery, but a spin was prevented, and the airplane did not complete one turn during the motion.

Effect of Secondary-Subsystem Logic

The primary variables selected to configure the secondary-subsystem logic were (1) the reference elevator setting, (2) the mode of control employed by the subsystem, and (3) the size of the yaw-rate dead band within which the subsystem operated. A series of flights were computed to determine the effect of these variables on the ability of the secondary subsystem to control the postrecovery motions (motions occurring after the primary recovery) of all configurations in lieu of pilot control. Representative results are presented for configuration A in figures 8 to 12.

Calculations for each flight were initiated just prior to the initial reversal of yaw rate during the recovery of configuration A from an oscillatory spin. The flight calculated to obtain the initial conditions is presented in figure 8 in terms of angle-of-attack, yaw-rate, and control-deflection time histories. The postrecovery flights were initiated at about 33 seconds. For each of two reference elevator (horizontal stabilator for configuration A) settings (-25° and -5°), flights were computed for a range of yaw-rate dead bands (0 to ± 23.0 deg/sec) for both the fixed-reference and the rate-damper control modes of the secondary subsystem. The flights in which the horizontal-stabilator reference position was -5° for 0.0, ± 11.5, and ± 23.0 deg/sec yaw-rate dead bands are shown in figure 9. Figure 10 presents the computed results for 0 and ± 23.0 deg/sec yaw-rate dead bands with the horizontal stabilator held fixed in a full-trailing-edge-up position (-25°).

Unstalled post recovery.- When the horizontal-stabilator reference position was set at -5° (fig. 9), the airplane was recovered to unstalled postrecovery motions (consisting of a high-speed dive) for all yaw-rate dead bands considered. Both the rate-damper and fixed-reference control techniques reduced the postrecovery motion oscillations and control activity relative to the motions calculated with the continuous primary-subsystem control (fig. 9(a)). The results presented in figures 9(b) and 9(c) indicate that the secondary subsystem was capable of damping out the unstalled postrecovery motions.

The magnitude of the yaw-rate dead band had a significant effect on the performance of the secondary subsystem. The rate-damper control mode showed minimum airplane and control oscillations at ± 11.5 deg/sec dead band (fig. 9(b)), with control deteriorating for the ± 23.0 deg/sec and the 0.0 deg/sec dead bands. These oscillations steadily decreased with increasing dead band (up to the maximum ± 23.0 deg/sec dead band considered) for the fixed-reference control mode.

Stalled postrecovery.- The most obvious effect of the full-trailing-edge-up position of the horizontal stabilator (fig. 10) was to produce stalled postrecovery motions. Only when continuous primary-subsystem control (0.0 deg/sec yaw-rate dead band, fig. 10(a)) was provided, were the airplane lateral-directional asymmetries overpowered, and the airplane thus stabilized in the stalled condition. Considerable full-authority control activity was required. When recovered in a stalled condition (angle of attack near 35°), the airplane was not controlled by the secondary subsystem within the yaw-rate dead bands investigated; the control of the airplane motions consistently deteriorated with increasing dead band up to ±23.0 deg/sec, the largest value considered (fig. 10(b)).

Recovery to stalled postrecovery conditions required continuous primary-subsystem control (because of airplane directional-divergence tendencies), whereas recovery to unstalled postrecovery conditions (steep dive in this flight) allowed effective secondary-subsystem control (nonzero yaw-rate dead band) with significant reductions in airplane and control motions.

RESULTS OF FLIGHT TESTS

The results of the flight tests are discussed in terms of (1) the characteristics of the basic configuration, and (2) the effects of the automatic spin-prevention system.

Representative Spin of Configuration A

Tests conducted with configuration A indicated that the model would enter a spin quite easily (for instance, with only longitudinal control). A fast-flat spin was encountered from which no recovery could be effected. The overall results also showed that (1) use of ailerons against the spin was very powerful in producing the spin, and (2) neutralizing the elevator after less than one turn provided an increase in spin rate and development of the fast flat spin mode. Both of these results are important in that the control movements involved might be considered natural for a pilot, and delay in recognition of the fact that the airplane was entering a spin could easily result in delay of application of spin-recovery controls beyond one turn.

A typical spin time history for configuration A is shown in figure 11. The spin entry was initiated by deflecting the elevator 25° and began with a departure to the right. After one-half turn, pro-spin controls (right yaw and left roll control) were applied. After one turn all controls were neutralized, and the spin rate increased to about 150 deg/sec. After seven turns, recovery was attempted by applying yaw control (rudder) against and roll control (ailerons) with the spin and no recovery was obtained. After 13 turns, full-trailing-edge-up elevator was applied with little or no effect. The spin continued at a yaw rate of about 120 deg/sec. No recovery was effected. This record illustrates the poor spin-recovery characteristics of configuration A and serves to emphasize the fact that spins should not be allowed to develop for this configuration.

Effect of Automatic Spin-Prevention System

Two flights were made with the automatic spin-prevention system active, during which 19 attempts at spin entry were made. A spin never developed with the system on, even though the human pilot maintained full pro-spin stick and pedal deflection. One of the flights is presented in time-history form in figure 12. The variations of r, α, β, control-surface positions, and status of the spin-prevention system are shown. During this flight the pilot maintained pro-spin controls for a right spin for about 35 seconds, then pro-spin controls for a left spin after 52 seconds. As can be seen, the spin-prevention system was activated each time α and r exceeded their threshold values of 35° and 11.5 deg/sec, respectively. The system stopped rotation, nosed the airplane over, and prevented the spin. Because the human pilot maintained pro-spin stick and pedal deflections, the system was continually reactivated during this flight.

The recovery technique utilized by the system tested was the most effective possible; that is, all control surfaces were activated and full control authority was provided. Further research is needed in order to define the minimum number of control surfaces that need to be moved and the amount of control authority required by such a system.

IMPLEMENTATION OF THE SYSTEM

The results of this study indicate that a relatively simple automatic spin-prevention system can prevent an airplane from spinning. Implementation of such a system in an airplane would require tailoring it to the specific airplane and providing safety from system failures, especially those which might result in hard-over control movement. Furthermore, implementation of this type of system would require the determination of the conventional controls effective for recovery from spin entries and developed spins.

The thresholds for actuation of the simple system studied in the present analysis relative to the normal maneuvering envelope and the developed-spin envelopes of an airplane might be pictured as shown in figure 13(a). A broad boundary such as that shown in figure 13(b) might be visualized; on one side of this boundary return to the normal flight envelope can be effected by normal use of the controls, and on the other side, controls should be used in the spin-recovery sense. Such a boundary would not be sharp because it depends on many factors involved in the dynamics of the situation. In the present analysis, the spin-prevention-system threshold rates were simply kept well away from the normal maneuvering envelope so that the system would not interfere with the pilot's normal control of the airplane. It would be desirable for each specific airplane, however, to determine the spin-control boundary, such as that shown in figure 13(b), and to set the spin-prevention-system threshold rates to approximate it. Thereby a spin-prevention system with less than full control authority might be effected. At the present state of the art, however, it must be assumed that the dynamics of the spin entry might propel the airplane into the developed-spin range before the recovery control can take effect. If the developed spin occurs, experience has shown that full authority may be necessary. Provision of adequate safety for an automatic-control system with full authority is a key factor in the implementation of the system.

Future fighter airplanes are likely to have fly-by-wire, command-augmentation control systems which already have 100-percent authority; and incorporation of a spin-prevention system would involve only the addition of the spin-prevention logic in the control system. The basic safeguards needed with a full-authority control system are already in existence.

For airplanes with limited-authority stability-augmentation or autopilot systems, however, implementation of a spin-prevention system, with adequate safety, is more involved. Two types of systems might be envisioned: one in which control is applied through the automatic flight-control system and the other in which control is applied through the control stick and rudder pedals. Neither of these two systems would replace the current stall-warning systems which serve to indicate maximum performance. The two methods of applying a spin-prevention system would differ only in the method of actuating the control surfaces. Both systems would employ spin-prevention logic circuitry to interrogate yaw-rate, angle-of-attack, and normal-acceleration sensor signals and, if threshold levels are exceeded, select the proper set of recovery-control signals. The logic circuits would be provided with their own self-testing circuits capable of continuously monitoring the spin-prevention-circuit response to the sensor signals and effecting disengagement of the system and warning the pilot in case of a system failure. The independent automatic system would use the recovery-control signals to drive the autopilot or stability-augmentation-system servomechanisms and thereby make the control inputs directly to the primary-control system. Provision of full control authority with adequate safety, however, would require the same elaborate safety measures which are applied in a fly-by-wire command-control system. The pilot-dependent automatic system would employ the recovery-control signals to effect force-limited deflections of the pilot's stick and rudder pedals in the sense for recovery. The force limits would be determined in such a manner as to allow the system full authority if unopposed by the pilot, but to always allow the pilot override capability. The pilot-dependent system would be inherently safer than the independent system from the standpoint of hard-over control movement and would require less sophistication than the integrated automatic spin-prevention system. The pilot-dependent system probably would also be much easier to retrofit to an existing airplane.

CONCLUSIONS

Analytical and experimental studies of an automatic spin-prevention system for fighter airplanes, which allows the airplane to be flown beyond the stall, indicate the following conclusions:

1. The analytical studies showed that an automatic spin-prevention system using full-authority conventional controls and requiring only yaw-rate, angle-of-attack, and normal-acceleration information was effective in preventing the developed spins of three airplane configurations representative of current fighter airplanes.

2. The exact configuration of an automatic spin-prevention system for a particular airplane will be dependent on the airplane's stall and spin characteristics.

3. Adequate documentation of an airplane's stall and spin characteristics should include the determination of the airplane maneuver envelope and potential spin regions in terms of angle of attack and yaw rate, and the determination of the conventional controls effective for recovery from spin entries and developed spins.

4. Experimental results showed that a simple automatic spin-prevention system, using only yaw-rate and angle-of-attack information, was very effective in preventing spins of a fighter configuration known to be very prone to enter nonrecoverable spins.

5. The components of a flight-control system necessary for implementing an effective spin-prevention system (less the spin-prevention control logic) are generally available on current fighter airplanes.

6. Successful implementation of any type of automatic spin-prevention system may require the availability of up to full-control authority.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., January 26, 1972.

APPENDIX

EQUATIONS OF MOTION AND ASSOCIATED FORMULAS

The equations of motion used in calculating the flight motions for the present study and derived by assuming six-degree-of-freedom rigid-body motion and a nonrotating earth are listed below. A complete derivation of the equations of motion is presented in reference 3.

Rolling moment:

$$\dot{p} = \frac{I_Y - I_Z}{I_X} qr + \frac{I_{XZ}}{I_X}(\dot{r} + pq) + \frac{\rho V_R{}^2 Sb}{2I_X}\left(C_l + C_{l_{\delta_a}}\delta_a + C_{l_{\delta_r}}\delta_r\right) + \frac{\rho V_R Sb^2}{4I_X}\left(C_{l_p}p + C_{l_r}r\right)$$

Pitching moment:

$$\dot{q} = \frac{I_Z - I_X}{I_Y} pr + \frac{I_{XZ}}{I_Y}\left(r^2 - p^2\right) + \frac{\rho V_R{}^2 S\bar{c}}{2I_Y}\left(C_m + C_{m_{\delta_e}}\delta_e\right) + \frac{\rho V_R S\bar{c}^2}{4I_Y} C_{m_q}q$$

Yawing moment:

$$\dot{r} = \frac{I_X - I_Y}{I_Z} pq + \frac{I_{XZ}}{I_Z}(\dot{p} - qr) + \frac{\rho V_R{}^2 Sb}{2I_Z}\left(C_n + C_{n_{\delta_a}}\delta_a + C_{n_{\delta_r}}\delta_r\right) + \frac{\rho V_R Sb^2}{4I_Z}\left(C_{n_p}p + C_{n_r}r\right)$$

Longitudinal force:

$$\dot{u} = -g \sin\theta + vr - wq + \frac{\rho V_R{}^2 S}{2m}\left(C_X + C_{X_{\delta_e}}\delta_e\right) + \frac{\rho V_R S\bar{c}}{4m} C_{X_q}q + \frac{T}{m}$$

Side force:

$$\dot{v} = g \cos\theta \sin\varphi + wp - ur + \frac{\rho V_R{}^2 S}{2m}\left(C_Y + C_{Y_{\delta_a}}\delta_a + C_{Y_{\delta_r}}\delta_r\right) + \frac{\rho V_R Sb}{4m}\left(C_{Y_p}p + C_{Y_r}r\right)$$

Vertical force:

$$\dot{w} = g \cos\theta \cos\varphi + uq - vp + \frac{\rho V_R{}^2 S}{2m}\left(C_Z + C_{Z_{\delta_e}}\delta_e\right) + \frac{\rho V_R S\bar{c}}{4m} C_{Z_q}q$$

In addition, the following formulas were used:

$$V_R = \sqrt{u^2 + v^2 + w^2}$$

$$\alpha = \tan^{-1} \frac{w}{u}$$

$$\beta = \sin^{-1} \frac{v}{V_R}$$

$$\dot{h} = u \sin \theta - v \cos \theta \sin \varphi - w \cos \theta \cos \varphi$$

$$\dot{\theta} = q \cos \varphi - r \sin \varphi$$

$$\dot{\varphi} = p + q \tan \theta \sin \varphi + r \tan \theta \cos \varphi$$

$$\dot{\psi} = \frac{r \cos \varphi + q \sin \varphi}{\cos \theta}$$

$$a_Z = \frac{\dot{w} - uq + vp - g \cos \theta \cos \varphi}{g}$$

$$\text{Turns} = \int \frac{\dot{\psi}\, dt}{2\pi}$$

REFERENCES

1. Chambers, Joseph R.; Anglin, Ernie L.; and Bowman, James S., Jr.: Effects of a Pointed Nose on Spin Characteristics of a Fighter Airplane Model Including Correlation With Theoretical Calculations. NASA TN D-5921, 1970.

2. Libbey, Charles E.; and Burk, Sanger M., Jr.: A Technique Utilizing Free-Flying Radio-Controlled Models to Study the Incipient- and Developed-Spin Characteristics of Airplanes. NASA MEMO 2-6-59L, 1959.

3. Etkin, Bernard: Dynamics of Flight. John Wiley & Sons, Inc., c.1959.

TABLE I.- MASS AND DIMENSIONAL CHARACTERISTICS

Characteristics	Configuration A		Configuration B		Configuration C	
m, kg (slugs)	22 679	(1554.0)	11 264	(771.81)	11 264	(771.81)
S, m^2 (ft^2)	[a]48.8	(525)	64.6	(695)	35.8	(385)
b, m (ft)	[a]19.2	(63)	11.6	(38)	11.0	(36)
$\bar{c}$, m (ft)	[a]2.76	(9.04)	7.242	(23.76)	3.606	(11.83)
Center of gravity, percent $\bar{c}$	[a]45		30		33	
I_X, kg-m^2 (slug-ft^2)	71 993	(53 100)	18 439	(13 600)	15 875	(11 709)
I_Y, kg-m^2 (slug-ft^2)	405 384	(299 000)	173 542	(128 000)	112 062	(82 654)
I_Z, kg-m^2 (slug-ft^2)	459 277	(338 750)	187 100	(138 000)	120 988	(89 237)
I_{XZ}, kg-m^2 (slug-ft^2)	16 920	(12 480)	5 884	(4 340)	0	(0)

[a]Referenced to 16° wing-sweep geometry.

TABLE II.- AERODYNAMIC DATA

(a) Configuration A

α, deg	Aerodynamic coefficients for β, deg, of –								
	-40	-30	-20	-10	0	10	20	30	40
					C_X				
0	-0.05475	-0.05475	-0.05475	-0.05475	-0.05475	-0.05475	-0.05475	-0.05475	-0.05475
10	-.02404	-.02404	-.02404	-.02404	-.02404	-.02404	-.02404	-.02404	-.02404
20	-.02804	-.02804	-.02804	-.02804	-.02804	-.02804	-.02804	-.02804	-.02804
30	-.01335	-.02537	-.03205	-.03605	-.02003	-.02537	-.04273	-.03472	-.01602
35	.00801	-.01736	-.02137	-.02404	-.01736	-.02404	-.03205	-.02003	-.00401
40	.02804	.00267	-.01335	-.01469	-.01335	-.02404	-.02270	-.00801	.00534
45	.02270	.02270	-.00134	-.01202	-.01870	-.02003	0	-.00134	.00534
50	.02671	.03338	.00801	-.02003	-.02003	-.01335	.01469	.01469	.02537
55	.03739	.02804	.01068	-.01068	-.01202	0	.02804	.02671	.02804
60	.02804	.02938	.03205	.01202	.02003	.02003	.04273	.03873	.03739
65	.03873	.04407	.04941	.03338	.03873	.04407	.04140	.04273	.04674
70	.04407	.04140	.04674	.03605	.03472	.03873	.03739	.04941	.04807
80	.05475	.05609	.04540	.03605	.04140	.03739	.04674	.07478	.06677
90	.06009	.05742	.06276	.05341	.05475	.06009	.07612	.06944	.07612
					C_Y				
0	0.53076	0.39807	0.26538	0.13269	0	-0.13269	-0.26538	-0.39807	-0.53076
10	.56514	.42754	.28994	.15234	0	-.12286	-.26046	-.39806	-.53566
20	.52584	.40298	.28012	.15726	0	-.08846	-.21132	-.33418	-.45704
30	.53075	.38823	.26537	.11303	.05406	-.02457	-.14252	-.29486	-.40789
35	.56023	.41280	.30469	.17200	.04914	-.05897	-.19166	-.32926	-.42755
40	.59463	.43738	.34400	.23097	.04914	-.08846	-.24080	-.35875	-.44720
45	.57006	.53566	.39806	.25555	.03931	-.12777	-.28995	-.43738	-.47178
50	.57498	.56515	.45703	.28012	.02949	-.19166	-.33417	-.47669	-.50618
55	.59955	.54549	.43738	.28012	.04914	-.17692	-.31943	-.47178	-.49143
60	.58972	.55040	.39315	.28995	.11303	-.14743	-.30469	-.46195	-.50126
65	.58972	.57006	.38823	.29486	.08846	-.13269	-.32435	-.47178	-.50618
70	.59955	.55532	.50126	.22606	.02457	-.17692	-.41280	-.47669	-.50618
80	.58481	.53566	.46686	.28503	-.00491	-.22114	-.42263	-.47178	-.50126
90	.56023	.51600	.42263	.26537	.00983	-.23097	-.39806	-.47178	-.48652
					C_Z				
0	-0.05799	-0.05799	-0.05799	-0.05799	-0.05799	-0.05799	-0.05799	-0.05799	-0.05799
10	-.81182	-.81182	-.81182	-.81182	-.81182	-.81182	-.81182	-.81182	-.81182
20	-1.6353	-1.6353	-1.6353	-1.6353	-1.6353	-1.6353	-1.6353	-1.6353	-1.6353
30	-1.3337	-1.6468	-1.8324	-2.1107	-2.5283	-2.2731	-1.8672	-1.6237	-1.4381
35	-1.5193	-1.7512	-1.9832	-2.2963	-2.8414	-2.4239	-1.9716	-1.7164	-1.4613
40	-1.6932	-1.8556	-2.1223	-2.4819	-2.9226	-2.5746	-2.0644	-1.7860	-1.4845
45	-1.6932	-1.9832	-2.2383	-2.5399	-2.9110	-2.5862	-2.2267	-1.7976	-1.5541
50	-1.7164	-2.0760	-2.2383	-2.4471	-2.7602	-2.4587	-2.2383	-1.8208	-1.5773
55	-1.8092	-2.0296	-2.1687	-2.3891	-2.6210	-2.3775	-2.0992	-1.9020	-1.6584
60	-1.8092	-2.1223	-2.3195	-2.4123	-2.5631	-2.4123	-2.2383	-1.9716	-1.7164
65	-1.9136	-2.1919	-2.3543	-2.4355	-2.5978	-2.4587	-2.2383	-1.9716	-1.7860
70	-2.0412	-2.2151	-2.3079	-2.5051	-2.5978	-2.4007	-2.1919	-2.0760	-1.8672
80	-2.1223	-2.2963	-2.4355	-2.4819	-2.5515	-2.5051	-2.4123	-2.2267	-1.9716
90	-2.1223	-2.2383	-2.3543	-2.4935	-2.5978	-2.4703	-2.4007	-2.2267	-2.0064
					C_l				
0	0.04364	0.03202	0.02040	0.00878	0	-0.01446	-0.02608	-0.03770	-0.04932
10	.10015	.07501	.04987	.02473	0	-.02555	-.05069	-.07583	-.10097
20	.08013	.05905	.03797	.01689	0	-.02527	-.04635	-.06743	-.08851
30	.07729	.04270	.01162	-.00459	-.00716	-.01811	-.00568	-.04446	-.07094
35	.06300	.04297	.01635	-.00473	-.01567	-.01419	-.01203	-.04392	-.06837
40	.05243	.04297	.02081	-.00513	-.02094	-.01054	-.01865	-.04351	-.06608
45	.07337	.04324	.02716	.00595	-.01040	-.01013	-.02838	-.05324	-.07283
50	.07810	.04094	.02784	.01216	-.00419	-.01122	-.02811	-.05270	-.06540
55	.08310	.06689	.04716	.02054	.00122	-.02270	-.04689	-.05635	-.07878
60	.08283	.06756	.05040	.02446	.00257	-.02324	-.05108	-.06878	-.08202
65	.08364	.06675	.05459	.02648	.00068	-.02675	-.05000	-.06851	-.08270
70	.08716	.06635	.04702	.02770	.00135	-.02554	-.04729	-.06500	-.08432
80	.08540	.06500	.04378	.02621	-.00324	-.02324	-.04527	-.06635	-.08364
90	.08513	.06229	.04770	.02689	.00432	-.02459	-.04743	-.06243	-.08202

TABLE II.- AERODYNAMIC DATA – Continued

(a) Configuration A – Continued

α, deg	Aerodynamic coefficients for β, deg, of –								
	-40	-30	-20	-10	0	10	20	30	40
					C_m				
0	0.05738	0.05738	0.05738	0.05738	0.05738	0.05738	0.05738	0.05738	0.05738
10	-.21642	-.21642	-.21642	-.21642	-.21642	-.21642	-.21642	-.21642	-.21642
20	-.32349	-.32349	-.32349	-.32349	-.32349	-.32349	-.32349	-.32349	-.32349
30	-.07640	-.15597	-.46649	-.41212	-.69501	-.57175	-.50803	-.39519	.25069
35	.11954	-.17793	-.46170	-.50362	-.76088	-.61487	-.52656	-.35540	.06558
40	.32591	-.19988	-.44649	-.59171	-.76884	-.65458	-.53467	-.30159	-.11611
45	-.01630	-.02026	-.32489	-.63015	-.83027	-.68553	-.32815	-.46259	-.33607
50	-.17745	.03665	-.34542	-.66994	-.87954	-.69063	-.36595	-.54503	-.21319
55	-.31560	-.26044	-.75853	-.81288	-.93924	-.84009	-.42907	-.55299	-.48806
60	-.68176	-.41570	-.39101	-1.0083	-1.0582	-.91243	-.60207	-.70793	-.54703
65	-.76873	-.65961	-.51811	-1.1249	-1.1203	-.93360	-1.0127	-.90983	-.62669
70	-.69862	-1.1048	-1.2190	-1.0711	-1.2366	-1.2100	-1.4056	-.97285	-.73388
80	-.97349	-1.2941	-1.5835	-1.7176	-1.7870	-1.7042	-1.5626	-1.1802	-.95774
90	-1.2199	-1.5466	-1.7569	-1.9949	-2.2701	-1.9980	-1.7815	-1.4643	-1.0814
					C_n				
0	-0.05437	-0.04085	-0.02733	-0.01381	0	0.01323	0.02675	0.04027	0.05379
10	-.03972	-.03011	-.02050	-.01089	0	.00833	.01794	.02755	.03716
20	-.00597	-.00515	-.00433	-.00351	0	-.00187	-.00105	-.00023	.00059
30	.05000	.03257	.04437	.02085	-.00584	-.04413	-.04432	-.05194	-.04417
35	.05265	.03998	.03807	.03627	-.00715	-.05908	-.04729	-.05734	-.06126
40	.05487	.04711	.03149	.05140	-.01611	-.07474	-.05055	-.06317	-.07835
45	.06047	.03425	.00685	.02701	-.02480	-.06757	-.00870	-.06445	-.08460
50	.05398	.01695	-.00982	-.02688	-.03349	-.02011	.00091	-.06191	-.08538
55	.03855	-.00187	-.03703	-.02543	.00789	.02198	.01525	-.04962	-.06555
60	.04171	-.02543	-.05026	.01767	.08649	.03504	.01368	-.03081	-.05082
65	.02957	-.02887	-.06256	-.00762	.08312	.05892	-.02481	-.02822	-.04056
70	-.00685	-.00649	.01352	-.05226	-.04174	-.02197	-.07930	-.00351	-.02611
80	-.02321	-.04728	.01303	-.00475	.01026	-.00165	-.01137	.04204	.00787
90	-.02166	.00502	-.00655	-.00131	-.00490	.00382	.01888	.00821	.02018
					$C_{X_{\delta_e}}$, per deg				
0	0.00392	0.00392	0.00392	0.00392	0.00392	0.00392	0.00392	0.00392	0.00392
10	.00199	.00199	.00199	.00199	.00199	.00199	.00199	.00199	.00199
20	.00064	.00064	.00064	.00064	.00064	.00064	.00064	.00064	.00064
30	-.00087	-.00134	-.00119	-.00126	-.00175	-.00004	-.00132	-.00174	-.00121
35	-.00147	-.00193	-.00215	-.00226	-.00267	-.00181	-.00232	-.00196	-.00153
40	-.00206	-.00252	-.00311	-.00325	-.00359	-.00358	-.00331	-.00217	-.00184
45	-.00257	-.00274	-.00353	-.00410	-.00420	-.00410	-.00340	-.00266	-.00206
50	-.00308	-.00295	-.00395	-.00494	-.00481	-.00461	-.00348	-.00314	-.00227
55	-.00342	-.00353	-.00356	-.00459	-.00439	-.00480	-.00339	-.00298	-.00265
60	-.00376	-.00411	-.00316	-.00423	-.00396	-.00498	-.00330	-.00282	-.00303
65	-.00374	-.00435	-.00381	-.00441	-.00445	-.00465	-.00361	-.00358	-.00341
70	-.00371	-.00459	-.00446	-.00459	-.00493	-.00432	-.00391	-.00433	-.00378
80	-.00386	-.00399	-.00487	-.00554	-.00561	-.00540	-.00514	-.00347	-.00366
90	-.00386	-.00399	-.00487	-.00554	-.00561	-.00540	-.00514	-.00347	-.00366
					$C_{m_{\delta_e}}$, per deg				
0	-0.03499	-0.03499	-0.03499	-0.03499	-0.03499	-0.03499	-0.03499	-0.03499	-0.03499
10	-.03511	-.03511	-.03511	-.03511	-.03511	-.03511	-.03511	-.03511	-.03511
20	-.03763	-.03763	-.03763	-.03763	-.03763	-.03763	-.03763	-.03763	-.03763
30	-.01361	-.00929	-.01685	-.02623	-.04062	-.03264	-.01888	-.02072	.00562
35	-.00856	-.01511	-.01301	-.02081	-.03550	-.02654	-.01624	-.01021	.00822
40	-.00350	-.02093	-.00916	-.01539	-.03037	-.02044	-.01359	.00030	.01081
45	-.00126	-.00706	-.00900	-.01121	-.02267	-.01503	-.00976	-.00086	.00835
50	.00099	.00682	-.00883	-.00702	-.01497	-.00962	-.00592	-.00201	.00589
55	-.00887	.00911	.00595	-.00478	-.00782	-.00369	-.00319	-.00275	-.00147
60	-.01873	.01140	.02073	-.00254	-.00066	.00224	-.00045	-.00349	-.00882
65	-.01389	-.00308	.00471	.00230	.00188	.00694	.00001	-.00708	-.01004
70	-.00905	-.01755	-.01131	.00713	.00442	.01163	.00047	-.01067	-.01125
80	-.00864	-.00608	-.01155	-.00825	-.00670	-.00917	-.00968	-.00619	-.01301
90	-.00864	-.00608	-.01155	-.00825	-.00670	-.00917	-.00968	-.00619	-.01301

TABLE II.- AERODYNAMIC DATA – Continued

(a) Configuration A – Continued

α, deg	Aerodynamic coefficients for β, deg, of –								
	-40	-30	-20	-10	0	10	20	30	40
				$C_{Z_{\delta_e}}$, per deg					
0	-0.01943	-0.01943	-0.01943	-0.01943	-0.01943	-0.01943	-0.01943	-0.01943	-0.01943
10	-.02052	-.02052	-.02052	-.02052	-.02052	-.02052	-.02052	-.02052	-.02052
20	-.02036	-.02036	-.02036	-.02036	-.02036	-.02036	-.02036	-.02036	-.02036
30	-.00528	-.01267	-.01310	-.01993	-.03313	-.02746	-.01129	-.01151	-.01700
35	-.00424	-.00668	-.01149	-.01799	-.03000	-.02378	-.00973	-.01026	-.01137
40	-.00319	-.00068	-.00988	-.01605	-.02687	-.02010	-.00816	-.00900	-.00574
45	-.00229	-.00353	-.00717	-.01193	-.02193	-.01425	-.00867	-.00604	-.00422
50	-.00139	-.00638	-.00446	-.00781	-.01698	-.00839	-.00918	-.00307	-.00270
55	-.00047	-.00695	-.00767	-.00813	-.01559	-.00871	-.00830	-.00537	-.00352
60	.00046	-.00752	-.01088	-.00844	-.01420	-.00903	-.00741	-.00766	-.00434
65	-.00268	-.00600	-.00617	-.00722	-.01271	-.00697	-.00684	-.00496	-.00398
70	-.00582	-.00448	-.00145	-.00599	-.01122	-.00490	-.00627	-.00225	-.00362
80	-.00693	-.00618	-.00487	-.00188	-.00772	-.00422	-.00666	-.00683	-.00707
90	-.00693	-.00618	-.00487	-.00188	-.00772	-.00422	-.00666	-.00688	-.00707
				$C_{l_{\delta_a}}$, per deg					
0	-0.00160	-0.00160	-0.00160	-0.00160	-0.00160	-0.00160	-0.00160	-0.00160	-0.00160
10	-.00159	-.00159	-.00159	-.00159	-.00159	-.00159	-.00159	-.00159	-.00159
20	-.00191	-.00191	-.00191	-.00191	-.00191	-.00191	-.00191	-.00191	-.00191
30	.00001	.00082	.00028	-.00050	-.00148	.00001	-.00142	-.00025	-.00031
35	.00015	.00038	.00008	-.00056	.00036	.00048	-.00110	-.00046	-.00032
40	.00029	-.00006	-.00012	-.00063	.00220	.00094	-.00077	-.00067	-.00033
45	.00002	.00017	-.00021	-.00027	.00113	.00022	-.00064	-.00038	-.00081
50	-.00025	.00039	-.00029	.00010	.00006	-.00051	-.00050	-.00008	-.00129
55	-.00038	-.00074	-.00151	-.00063	-.00068	.00005	.00038	-.00076	-.00063
60	-.00018	-.00042	-.00086	-.00114	-.00101	-.00054	-.00006	-.00031	-.00054
65	-.00006	-.00032	-.00081	-.00095	-.00052	-.00029	.00027	-.00012	-.00065
70	-.00032	-.00039	-.00029	-.00125	-.00086	-.00051	.00013	-.00046	-.00069
80	-.00036	-.00009	-.00007	-.00036	-.00010	-.00036	-.00030	-.00018	-.00048
90	.00001	.00003	-.00016	-.00021	-.00078	-.00050	-.00007	-.00026	-.00033
				$C_{Y_{\delta_a}}$, per deg					
0	0.00150	0.00150	0.00150	0.00150	0.00150	0.00150	0.00150	0.00150	0.00150
10	.00152	.00152	.00152	.00152	.00152	.00152	.00152	.00152	.00152
20	.00055	.00055	.00055	.00055	.00055	.00055	.00055	.00055	.00055
30	-.00468	-.00839	-.00758	-.00432	.00008	.00096	-.00421	-.00145	-.00262
35	-.00513	-.00661	-.00952	-.00698	-.00067	-.00034	-.00553	-.00474	-.00315
40	-.00558	-.00482	-.01145	-.00963	-.00142	-.00163	-.00685	-.00803	-.00367
45	-.00610	-.00597	-.00962	-.00635	-.00294	-.00246	-.00767	-.00687	-.00222
50	-.00661	-.00712	-.00779	-.00307	-.00445	-.00328	-.00849	-.00571	-.00077
55	-.00957	-.00765	-.00981	-.00606	-.00841	-.01025	-.01396	-.00471	-.00374
60	-.00958	-.01014	-.00689	-.01403	-.01579	-.00771	-.01044	-.00419	-.00226
65	-.00858	-.01360	-.01039	-.01751	-.01134	-.00569	-.01446	-.00720	-.00276
70	-.00807	-.00814	-.01071	-.01263	-.00495	.00023	-.01061	-.00472	-.00177
80	-.00610	-.00867	-.00827	-.01304	-.00550	-.00532	-.00364	-.00221	-.00226
90	-.00514	-.00720	-.00584	-.00858	-.00747	-.00235	-.00160	-.00221	-.00323
				$C_{n_{\delta_a}}$, per deg					
0	-0.00045	-0.00045	-0.00045	-0.00045	-0.00045	-0.00045	-0.00045	-0.00045	-0.00045
10	-.00019	-.00019	-.00019	-.00019	-.00019	-.00019	-.00019	-.00019	-.00019
20	.00004	.00004	.00004	.00004	.00004	.00004	.00004	.00004	.00004
30	.00070	.00177	.00187	.00121	.00128	.00137	-.00092	.00051	.00078
35	.00097	.00150	.00188	.00081	.00232	.00304	.00052	.00036	.00083
40	.00123	.00122	.00188	.00041	.00336	.00471	.00195	.00020	.00087
45	.00142	.00267	.00309	.00474	.00402	.00319	-.00046	.00002	.00175
50	.00161	.00412	.00430	.00907	.00468	.00167	-.00286	-.00016	.00263
55	.00317	.00434	.00690	.00860	.00221	-.00042	-.00392	.00133	.00186
60	.00250	.00740	.00738	.00066	-.00436	-.00132	-.00431	.00014	.00205
65	-.00004	.00373	.00508	-.00013	-.00275	-.00111	.00417	.00205	.00363
70	.00212	-.00002	.00465	.00187	.00935	.00870	.00145	.00110	.00234
80	.00216	.00310	.00253	.00192	.00111	.00181	.00054	-.00368	.00055
90	.00163	.00137	.00278	.00136	.00317	.00085	-.00223	.00026	.00089

TABLE II.- AERODYNAMIC DATA – Continued

(a) Configuration A – Concluded

α, deg	Aerodynamic coefficients for β, deg, of – -40	-30	-20	-10	0	10	20	30	40
					$C_{l_{\delta_r}}$, per deg				
0	0.00017	0.00017	0.00017	0.00017	0.00017	0.00017	0.00017	0.00017	0.00017
10	.00011	.00011	.00011	.00011	.00011	.00011	.00011	.00011	.00011
20	.00010	.00010	.00010	.00010	.00010	.00010	.00010	.00010	.00010
30	.00004	-.00003	.00018	.00017	.00023	-.00070	-.00003	-.00030	.00012
35	-.00013	0	.00013	.00023	-.00006	-.00028	.00006	-.00011	.00011
40	-.00029	.00003	.00007	.00029	-.00035	.00014	.00015	.00008	.00010
45	-.00012	-.00021	.00006	.00011	-.00031	.00008	.00008	.00008	-.00001
50	.00006	-.00044	.00005	-.00007	-.00026	.00002	0	.00008	-.00012
55	.00003	.00002	.00011	-.00001	-.00002	.00007	.00001	.00009	.00002
60	-.00008	-.00011	.00007	.00001	.00004	.00007	.00001	.00006	.00007
65	-.00010	.00007	.00010	.00008	.00009	-.00005	-.00005	.00003	.00004
70	.00004	.00005	.00006	.00008	.00002	-.00003	.00005	.00003	.00005
80	.00004	-.00001	.00005	.00017	-.00009	.00006	.00005	.00001	.00004
90	-.00002	.00002	.00008	.00011	.00015	-.00001	-.00003	0	.00003
					$C_{Y_{\delta_r}}$, per deg				
0	0.00484	0.00484	0.00484	0.00484	0.00484	0.00484	0.00484	0.00484	0.00484
10	.00450	.00450	.00450	.00450	.00450	.00450	.00450	.00450	.00450
20	.00448	.00448	.00448	.00448	.00448	.00448	.00448	.00448	.00448
30	.00150	.00109	.00150	.00277	.00514	.00085	.00076	.00002	.00059
35	.00148	.00058	.00098	.00215	.00431	.00137	.00062	-.00105	.00102
40	.00146	.00006	.00045	.00152	.00347	.00189	.00048	-.00211	.00145
45	.00080	.00052	.00042	.00059	.00123	.00076	.00043	-.00099	.00105
50	.00014	.00098	.00038	-.00034	-.00102	-.00038	.00038	.00013	.00065
55	.00063	.00066	.00056	-.00051	-.00070	-.00122	-.00030	.00063	.00047
60	-.00020	.00066	-.00125	-.00068	.00143	-.00058	.00019	-.00004	.00081
65	.00030	.00148	-.00041	.00165	.00261	.00075	.00154	-.00021	.00032
70	.00146	.00132	.00202	.00186	.00132	.00161	-.00008	.00046	.00048
80	.00164	.00183	.00238	.00283	.00117	.00114	.00060	.00113	.00098
90	.00082	.00118	.00107	.00150	.00166	-.00036	.00008	-.00037	-.00103
					$C_{n_{\delta_r}}$, per deg				
0	-0.00135	-0.00135	-0.00135	-0.00135	-0.00135	-0.00135	-0.00135	-0.00135	-0.00135
10	-.00128	-.00128	-.00128	-.00128	-.00128	-.00128	-.00128	-.00128	-.00128
20	-.00126	-.00126	-.00126	-.00126	-.00126	-.00126	-.00126	-.00126	-.00126
30	-.00035	-.00043	.00002	-.00098	-.00133	-.00104	-.00033	-.00010	.00054
35	-.00038	-.00012	-.00017	-.00009	-.00136	-.00097	-.00050	.00020	.00040
40	-.00040	.00020	-.00035	.00081	-.00138	-.00089	-.00067	.00050	.00026
45	-.00036	.00012	-.00013	-.00054	-.00169	-.00084	-.00007	.00044	.00030
50	-.00031	.00003	.00009	-.00188	-.00199	-.00079	.00053	.00038	.00033
55	-.00022	-.00074	-.00122	-.00240	-.00122	-.00037	.00008	.00015	.00041
60	.00053	-.00157	-.00271	-.00152	.00148	-.00024	.00058	.00055	.00005
65	.00065	-.00113	-.00257	-.00155	.00244	.00192	.00180	0	-.00020
70	-.00070	.00005	.00176	.00002	.00003	.00208	.00104	-.00039	-.00043
80	-.00047	-.00050	-.00029	-.00017	.00022	-.00010	-.00009	.00141	0
90	-.00025	-.00044	-.00049	-.00009	-.00032	.00009	.00057	.00017	.00006

α, deg	C_{Y_p}, per rad	C_{l_p}, per rad	C_{n_p}, per rad	C_{Z_q}, per rad	C_{X_q}, per rad	C_{m_q}, per rad	C_{Y_r}, per rad	C_{l_r}, per rad	C_{n_r}, per rad
0	-0.09003	-0.14991	-0.00938	-9.5521	0.07752	-23.812	0.67455	0.04427	-0.15449
10	-.07966	-.16058	-.00187	-5.1415	.48897	-23.265	.65396	.12244	-.17330
20	-.21263	-.21505	.00617	-8.7173	1.2158	-27.795	.91496	.29570	-.25034
30	-.16100	-.34960	.02382	-29.277	3.0956	-34.683	.79265	.56725	-.29630
35	.48037	-.59684	.01354	-43.043	3.0868	-38.032	-.05590	.88361	-.24858
40	1.0398	-.54280	.00242	-57.443	3.3882	-40.580	-1.4989	1.2342	-.19695
45	.44946	-.31589	-.03497	-66.266	3.2705	-39.732	-1.1569	.80645	-.04539
50	.02815	-.15395	-.05130	-67.855	3.6210	-29.961	-.96371	.33907	.21864
55	-.29888	-.14661	-.13921	-56.704	3.5210	-25.280	.80648	.12032	.86858
60	-.20904	-.13798	-.05000	-49.205	2.9647	-21.551	.07237	.05703	.30597
65	-.46779	-.10665	-.08551	-39.265	3.0295	-16.133	.49727	.05928	.40587
70	-.12746	-.09241	-.15002	-29.306	3.3316	-13.846	-.14060	-.02969	.22394
80	.47917	-.14503	-.25525	-10.426	4.2302	-.85960	.15104	.02557	-.03292
90	.28990	-.14094	-.25604	-1.2256	1.9739	-15.888	.01011	-.01665	-.18192

TABLE II.- AERODYNAMIC DATA – Continued

(b) Configuration B

α, deg	C_X	C_Z	C_m	C_{l_β}, per deg	C_{n_β}, per deg	C_{Y_β}, per deg
0	-0.0333	0.020	-0.0035	-0.00012	0.00100	-0.0070
5	-.0131	-.189	-.0049	-.00060	.00100	-.0080
10	-.0129	-.430	-.0090	-.00115	.00090	-.0085
15	.0067	-.691	-.0148	-.00150	.00060	-.0085
20	.0063	-.948	-.0350	-.00108	0	-.0080
25	.0050	-1.144	-.0580	-.00092	-.00100	-.0070
30	.0176	-1.269	-.0790	.00087	-.00230	-.0056
35	-.0096	-1.320	-.0916	.00002	-.00230	-.0034
40	-.0185	-1.268	-.0955	-.00125	-.00220	-.0010
45	-.0192	-1.201	-.0903	-.00160	-.00180	-.0018
50	-.0172	-1.175	-.0873	-.00170	-.00150	-.0025
55	.0014	-1.205	-.0995	-.00180	-.00130	-.0020
60	.0186	-1.256	-.1183	-.00180	-.00130	-.0015
65	.0181	-1.293	-.1308	-.00203	-.00120	-.0012
70	.0187	-1.346	-.1470	-.00215	-.00110	-.0010
75	.0338	-1.388	-.1715	-.00217	-.00110	-.0015
80	.0351	-1.416	-.1900	-.00210	-.00120	-.0019
85	.0338	-1.422	-.2113	-.00204	-.00120	-.0020
90	.0330	-1.417	-.2310	-.00200	-.00110	-.0020

α, deg	$C_{X_{\delta_e}}$, per deg	$C_{Z_{\delta_e}}$, per deg	$C_{m_{\delta_e}}$, per deg	$C_{Y_{\delta_a}}$, per deg	$C_{l_{\delta_a}}$, per deg	$C_{n_{\delta_a}}$, per deg	$C_{Y_{\delta_r}}$, per deg	$C_{l_{\delta_r}}$, per deg	$C_{n_{\delta_r}}$, per deg
0	0.00102	-0.00924	-0.00362	0.00214	-0.002	-0.0005	0.0016	0.00008	-0.00052
5	.00106	-.00957	-.00382	↓	-.00209	-.00057	↓	.00007	-.00053
10	.00108	-.01005	-.004	↓	-.00214	-.00059	↓	.00008	-.00056
15	.00104	-.01092	-.00411	.00243	-.00213	-.00051	.00148	.00011	-.00059
20	.00095	-.012	-.00416	.00229	-.00193	-.00043	.00132	.00018	-.00064
25	.00077	-.01135	-.00416	.00143	-.00157	-.00041	.0012	.00028	-.0007
30	.00039	-.00811	-.00368	.00071	-.00086	-.00027	.0012	.00038	-.00074
35	.00035	-.00762	-.00348	0	-.00057	-.00021	.00112	.00044	-.0004
40	.00039	-.00735	-.00332	-.00057	-.00057	-.00011	.00088	.00039	-.00013
45	.00043	-.00622	-.00297	-.00071	-.00066	-.00003	.0004	.00011	-.00004
50	.00044	-.00508	-.00265	-.00071	-.00071	.00004	0	-.00003	-.00002
55	.00036	-.00541	-.00254	-.00043	-.0006	.00013	↓	-.00003	-.00003
60	.00024	-.00551	-.00249	0	-.00057	.00019	↓	-.00001	-.00004
65	.00002	-.00476	-.00243	.00029	-.00049	.00026	↓	0	-.00004
70	-.00019	-.00405	-.00232	0	-.00043	.00031	↓	↓	0
75	-.00048	-.004	-.00208	↓	-.00031	.00031	↓	↓	.00004
80	-.00074	-.004	-.00184	↓	-.00029	.00023	↓	↓	0
85	-.00094	-.00335	-.00173	↓	-.00029	.00024	↓	↓	0
90	-.00108	-.00265	-.00168	↓	-.00026	.00029	↓	↓	.00007

α, deg	C_{Y_p}, per rad	C_{l_p}, per rad	C_{n_p}, per rad	C_{X_q}, per rad	C_{Z_q}, per rad	C_{m_q}, per rad	C_{Y_r}, per rad	C_{l_r}, per rad	C_{n_r}, per rad
0	0	-0.15	0.02	0	0	-1.1	0	0.2	-0.19
5	↓	-.17	↓	↓	↓	↓	↓	.29	-.2
10	↓	-.19	↓	↓	↓	↓	↓	.40	-.212
15	↓	-.215	.03	↓	↓	↓	↓	.55	-.235
20	↓	-.25	.058	↓	↓	↓	↓	.75	-.28
25	↓	-.29	.06	↓	↓	↓	↓	.90	-.37
30	↓	-.32	.001	↓	↓	↓	↓	.54	-.54
35	↓	-.29	-.124	↓	↓	↓	↓	.40	-.517
40	↓	-.225	-.021	↓	↓	↓	↓	.30	-.45
45	↓	-.182	.12	↓	↓	↓	↓	.22	-.35
50	↓	-.155	.15	↓	↓	↓	↓	.10	-.24
55	↓	-.132	.18	↓	↓	↓	↓	.05	-.17
60	↓	-.117	.22	↓	↓	↓	↓	0	-.12
65	↓	-.11	.16	↓	↓	↓	↓	↓	-.08
70	↓	↓	.05	↓	↓	↓	↓	↓	-.06
75	↓	↓	0	↓	↓	↓	↓	↓	-.06
80	↓	-.120	0	↓	↓	↓	↓	↓	-.08
85	↓	-.128	.05	↓	↓	↓	↓	↓	-.05
90	↓	-.135	.14	↓	↓	↓	↓	↓	-.044

TABLE II.- AERODYNAMIC DATA – Concluded

(c) Configuration C

α, deg	C_X	C_Z	C_m	C_{l_β}, per deg	C_{n_β}, per deg	C_{Y_β}, per deg
0	-0.020	0.050	-0.0037	-0.00130	0.00300	-0.0160
10	.013	-.536	-.091	-.00200	.00220	-.0170
20	.016	-1.037	-.134	-.00280	-.00030	-.0170
30	-.002	-1.317	-.304	-.00160	-.00340	-.0150
40	-.017	-1.425	-.376	-.00180	-.00430	-.0190
50	-.010	-1.598	-.463	-.00120	-.00380	-.0230
60	.016	-1.730	-.584	-.00190	-.00400	-.0270
70	.019	-1.849	-.735	-.00350	-.00430	-.0310
80	.035	-1.926	-.829	-.00370	-.00400	-.0290
90	.060	-2.010	-.883	-.00370	-.00280	-.0250

α, deg	$C_{X_{\delta_e}}$, per deg	$C_{Z_{\delta_e}}$, per deg	$C_{m_{\delta_e}}$, per deg	$C_{l_{\delta_r}}$, per deg	$C_{n_{\delta_r}}$, per deg	$C_{Y_{\delta_r}}$, per deg	$C_{l_{\delta_a}}$, per deg	$C_{n_{\delta_a}}$, per deg	$C_{Y_{\delta_a}}$, per deg
0	0.001	-0.0065	-0.0100	0.00028	-0.0019	0	-0.0018	-0.0007	0
10	.0022	-.0068	-.0130	.00028	-.0019		-.0016	-.0004	
20	.0017	-.0074	-.0115	.00017	-.0018		-.0011	-.0001	
30	-.0007	-.0079	-.0110	.00023	-.0012		-.0006	.0002	
40	-.0030	-.0011	-.0044	.00013	-.0006		-.0003	.0003	
50	-.0020	-.0023	-.0028	.00017	-.0005			.0004	
60	-.0020	-.0024	-.0039	.00025	-.0004			.0006	
70	-.0033	-.0032	-.0048	.00028	-.0003		-.0002	.0007	
80	-.0036	-.0029	-.0058	.00032	-.0001		-.0001	.0008	
90	-.0040	-.0040	-.0042	.00032	.0002		0	.0008	

α, deg	C_{Y_p}, per rad	C_{l_p}, per rad	C_{n_p}, per rad	C_{Z_q}, per rad	C_{X_q}, per rad	C_{m_q}, per rad	C_{Y_r}, per rad	C_{l_r}, per rad	C_{n_r}, per rad
0	0	-0.29	0	0	0	-2.0	0	0	-0.25
10		-.32							-.32
20		-.31							-.46
30		-.26							-.27
40		-.22							-.23
50		-.21							-.10
60		-.16							-.22
70		-.13							-.35
80		-.11							-.32
90		-.09							-.27

TABLE III.- CHARACTERISTICS OF CONTROL SYSTEMS

(a) Authority of primary subsystem

Control command	Configuration A	Configuration B	Configuration C
Rudder	$\pm 30^{\circ}$	$\pm 25^{\circ}$	$\pm 6^{\circ}$
Elevator up	-25°	-25°	-30°
Elevator down	10°	10°	10°
Aileron	$\pm 15^{\circ}$	$\pm 7^{\circ}$	$\pm 15^{\circ}$

(b) Authority of secondary subsystem rate damper

[Constant for all configurations]

Control command	Position limit	Rate limit
Rudder	$\pm 5^{\circ}$	± 35 deg/sec
Elevator	$\pm 12^{\circ}$	± 84 deg/sec
Aileron	$\pm 11^{\circ}$	± 84 deg/sec

(c) Control-surface deflection limits

Control command	Configuration A	Configuration B	Configuration C
Rudder	$\pm 30^{\circ}$	$\pm 25^{\circ}$	$\pm 6^{\circ}$
Elevator up	-30°	-25°	-30°
Elevator down	10°	10°	10°
Aileron	$\pm 18^{\circ}$	$\pm 7^{\circ}$	$\pm 15^{\circ}$

(d) Servo rate limits

Control deflection	Rate limit
Rudder	± 106 deg/sec
Elevator	± 36 deg/sec
Aileron	± 36 deg/sec

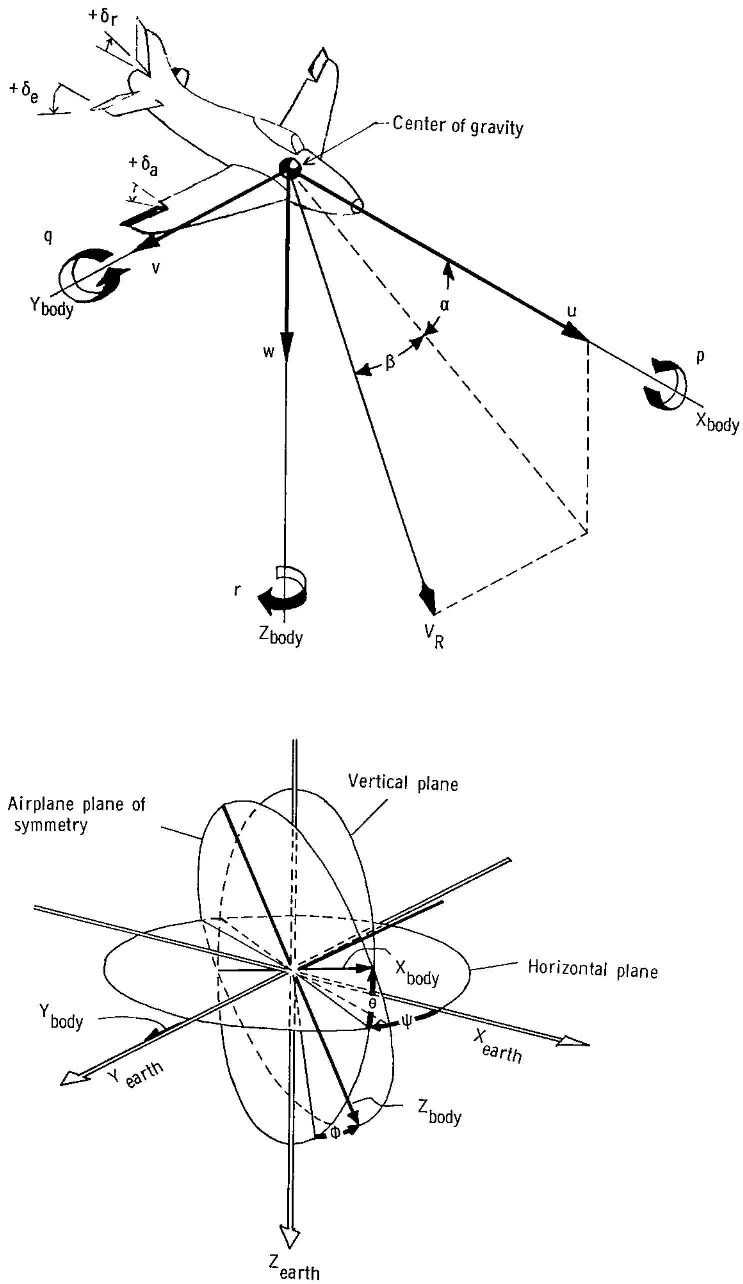


Figure 1.- Body system of axes and related angles. Arrows indicate positive directions of quantities.

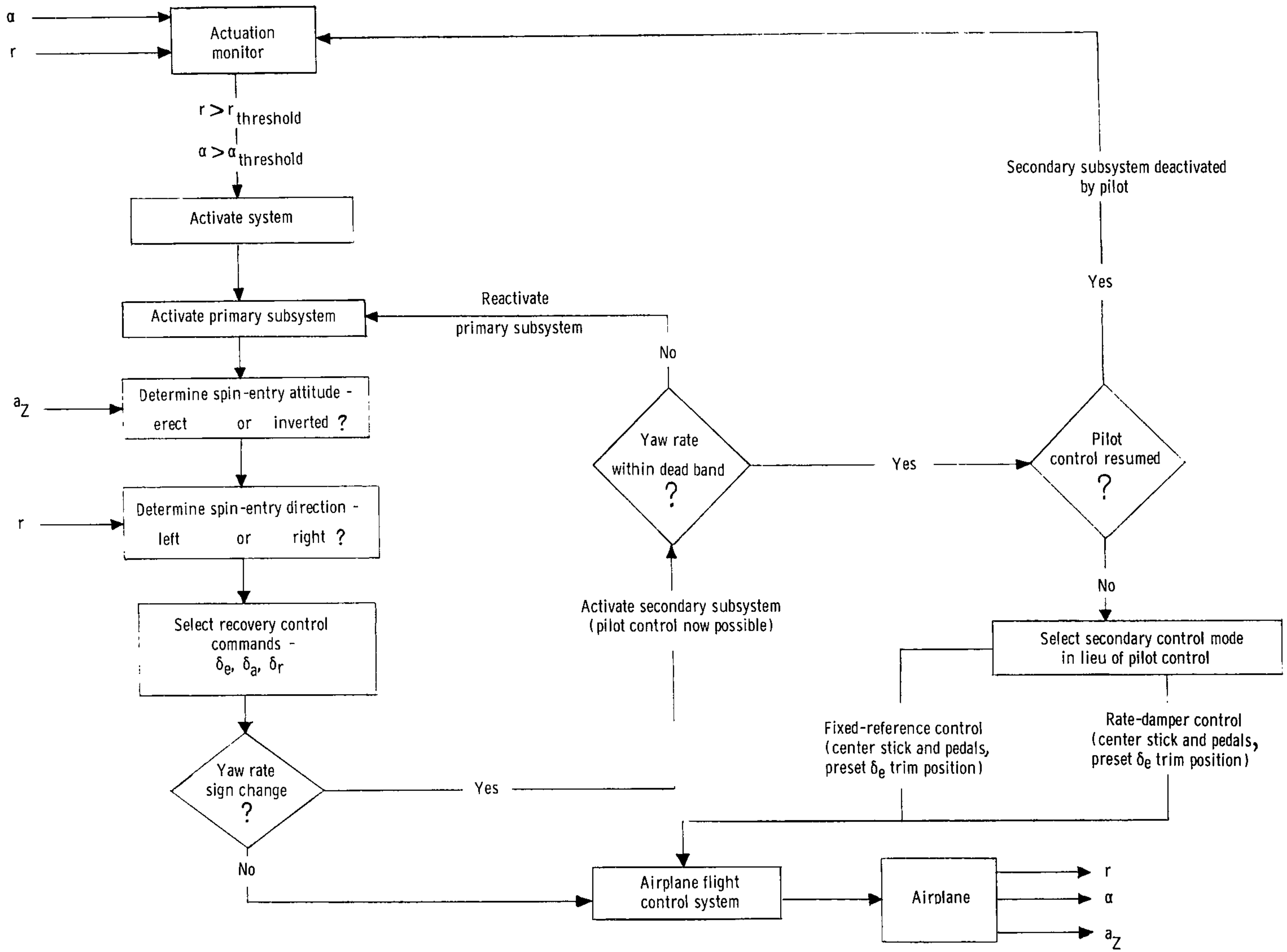
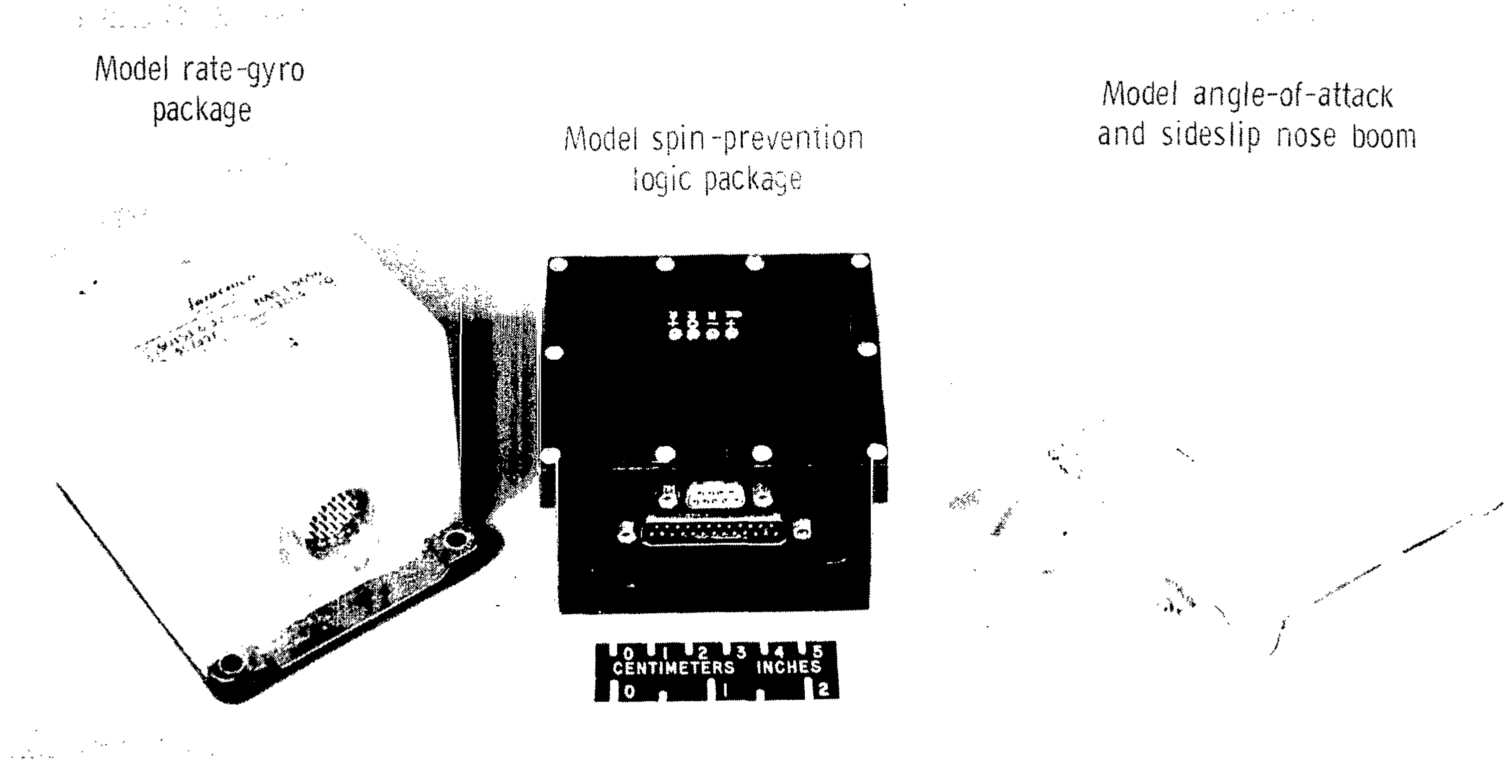
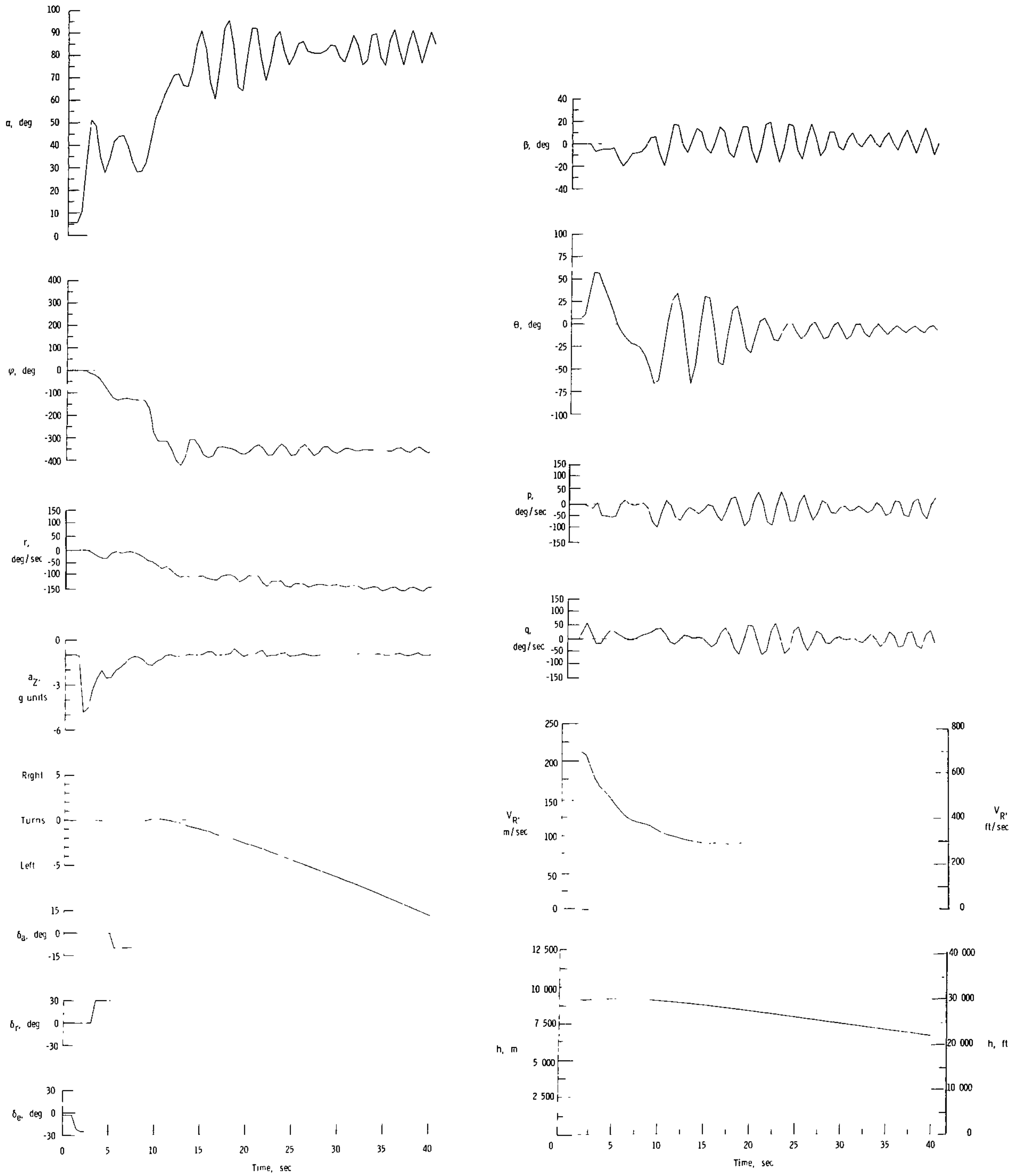


Figure 2.- Schematic diagram of logic of automatic spin-prevention system.



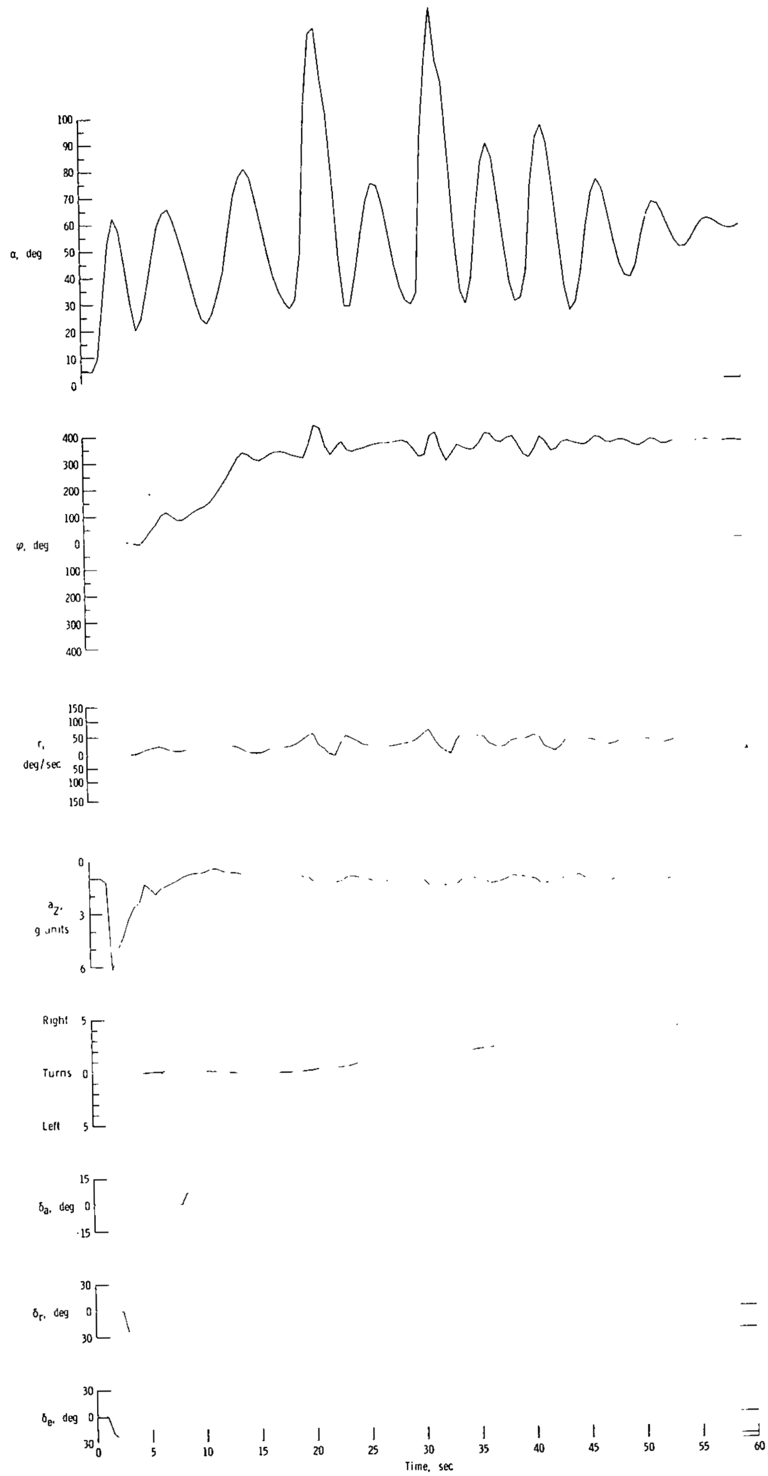
L-71-1963.1

Figure 3.- Automatic spin-prevention system and sensors used in remote-control model.



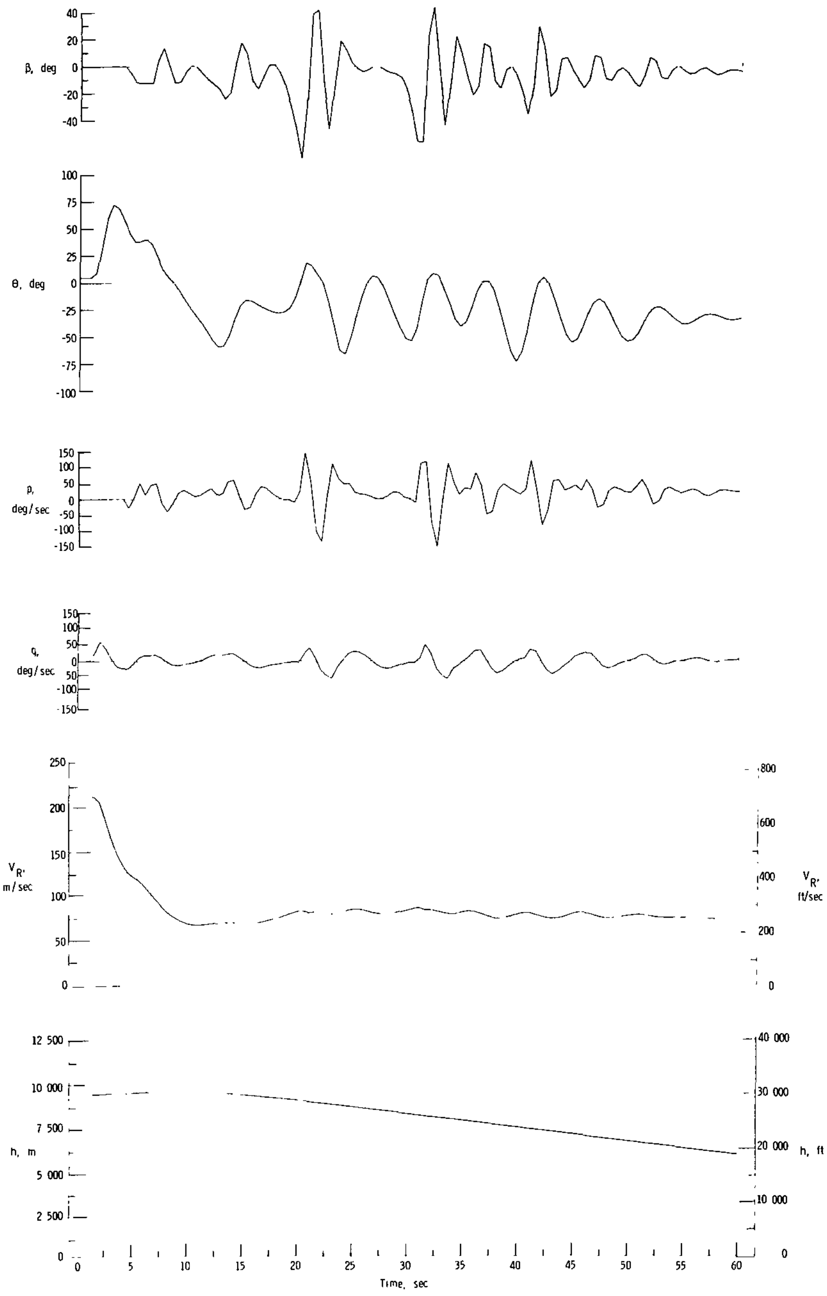
(a) Configuration A.

Figure 4.- Representative calculated spins of airplane configurations.



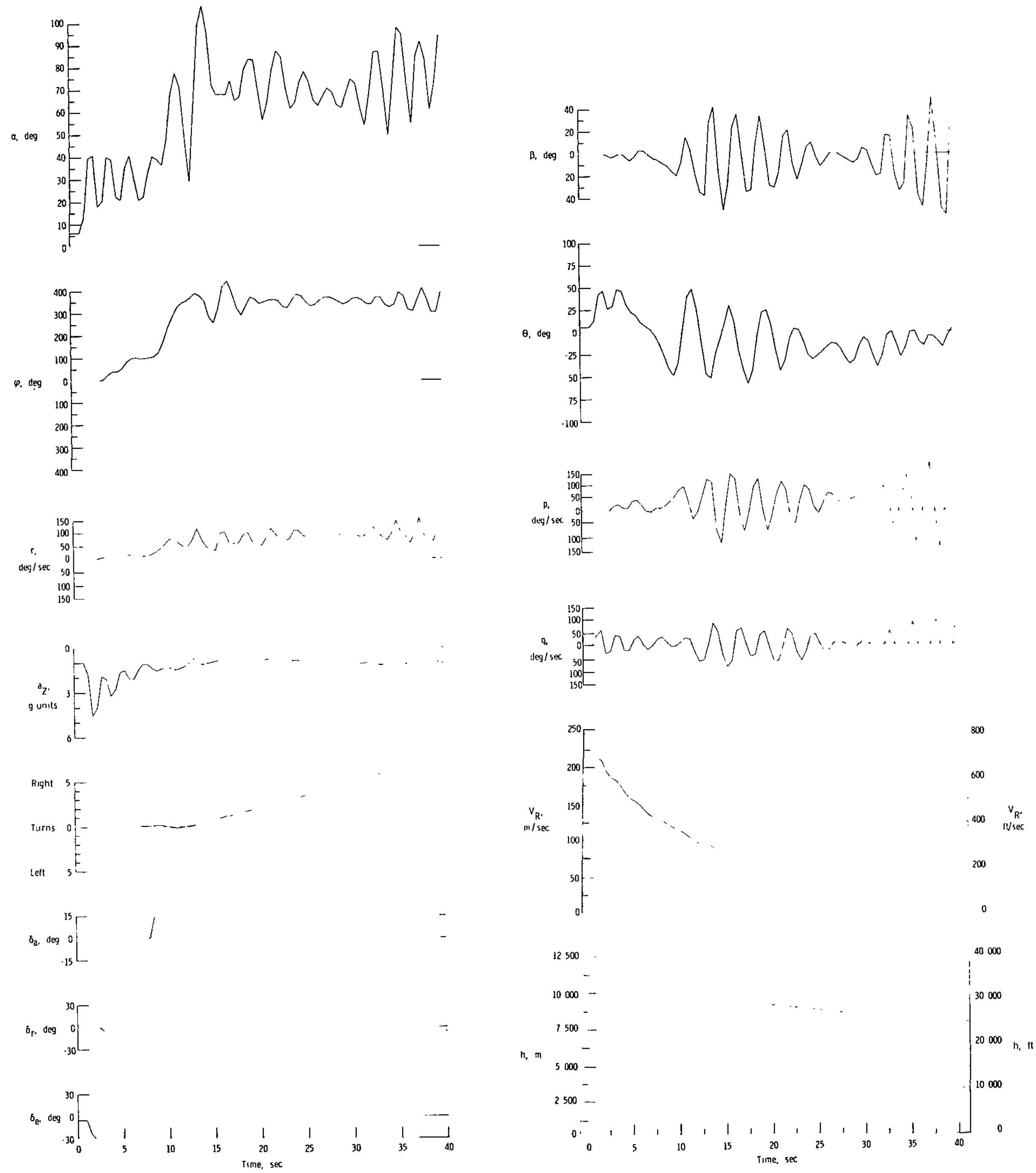
(b) Configuration B.

Figure 4.- Continued.



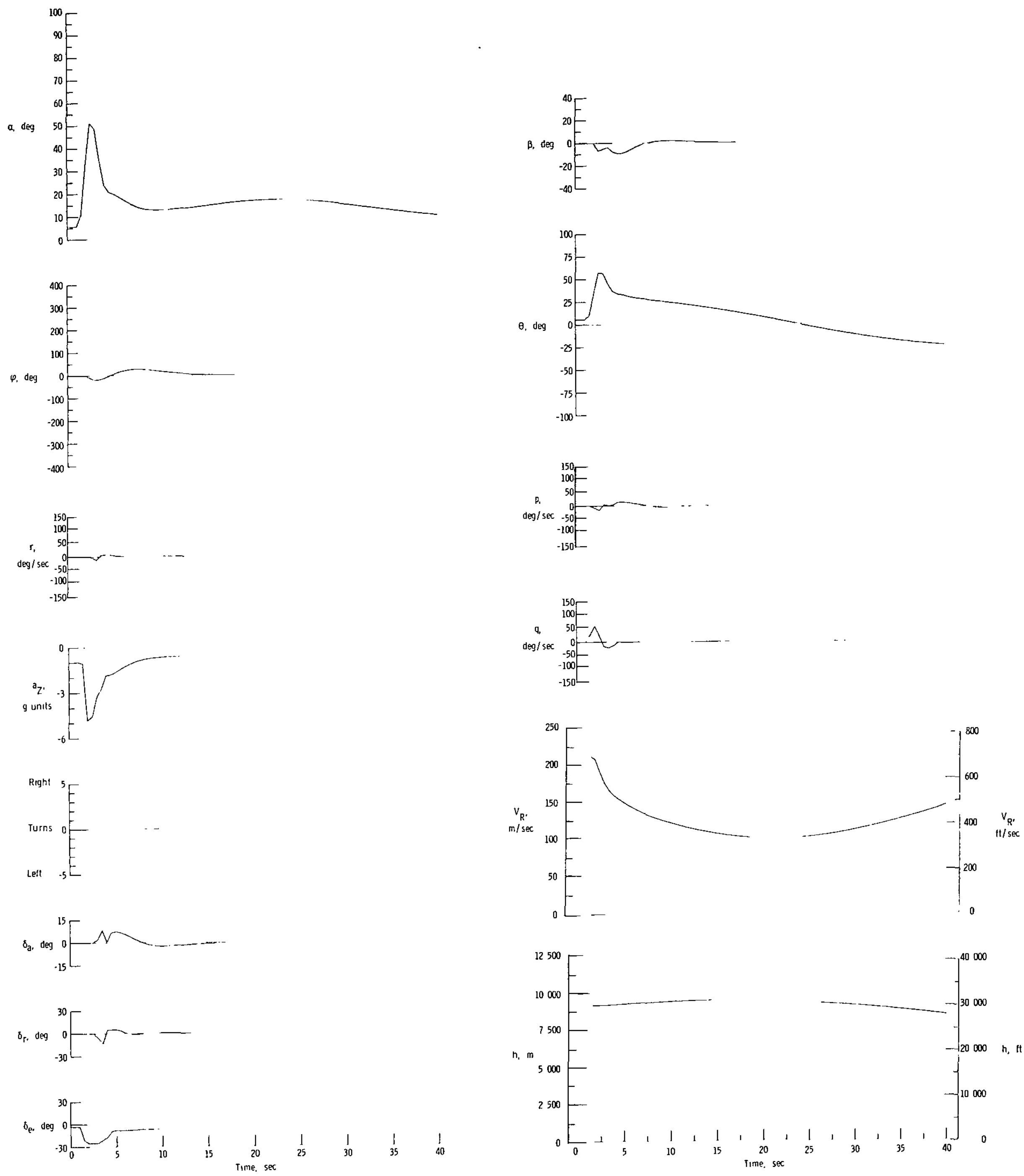
(b) Concluded.

Figure 4.- Continued.



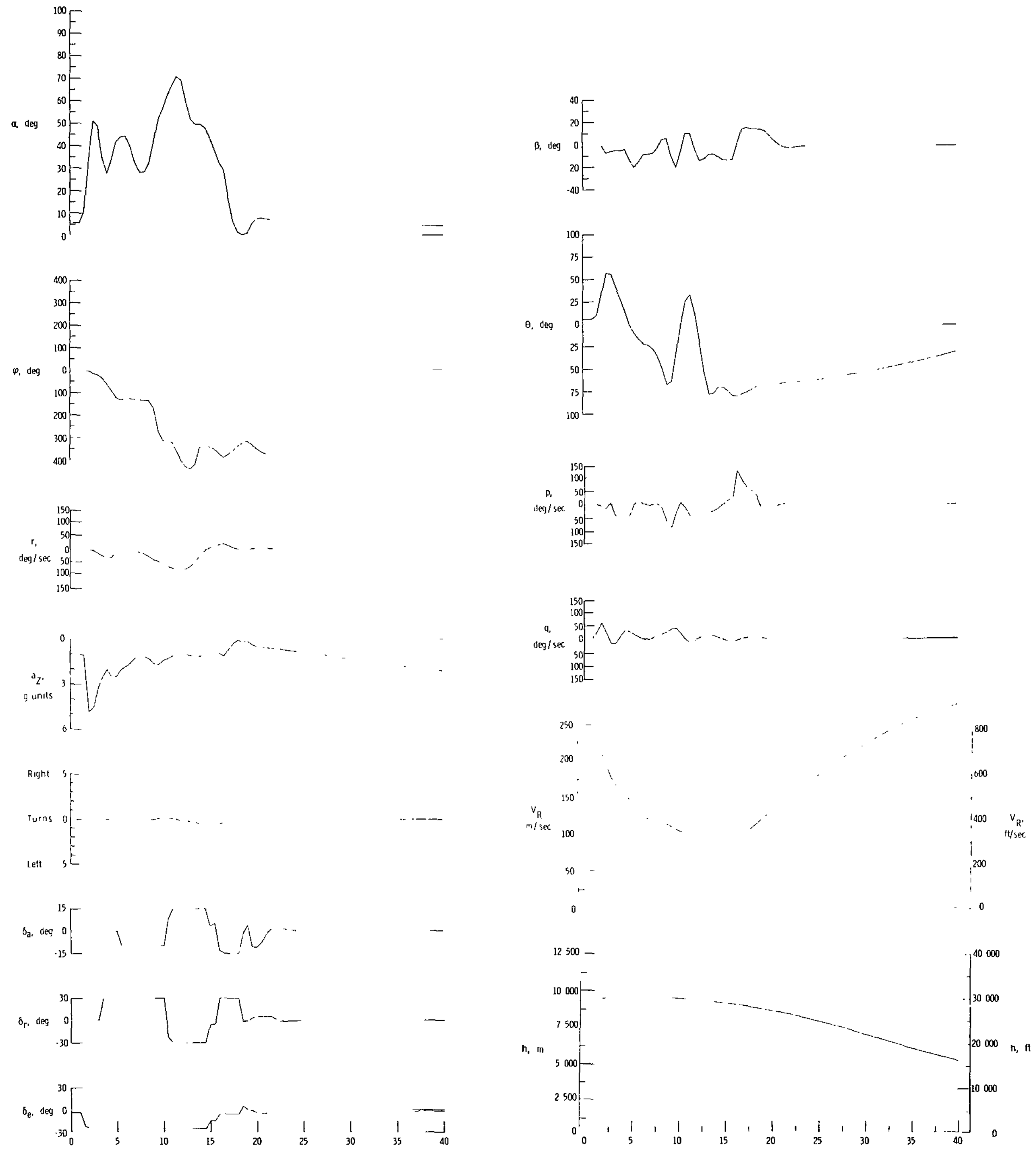
(c) Configuration C.

Figure 4.- Concluded.



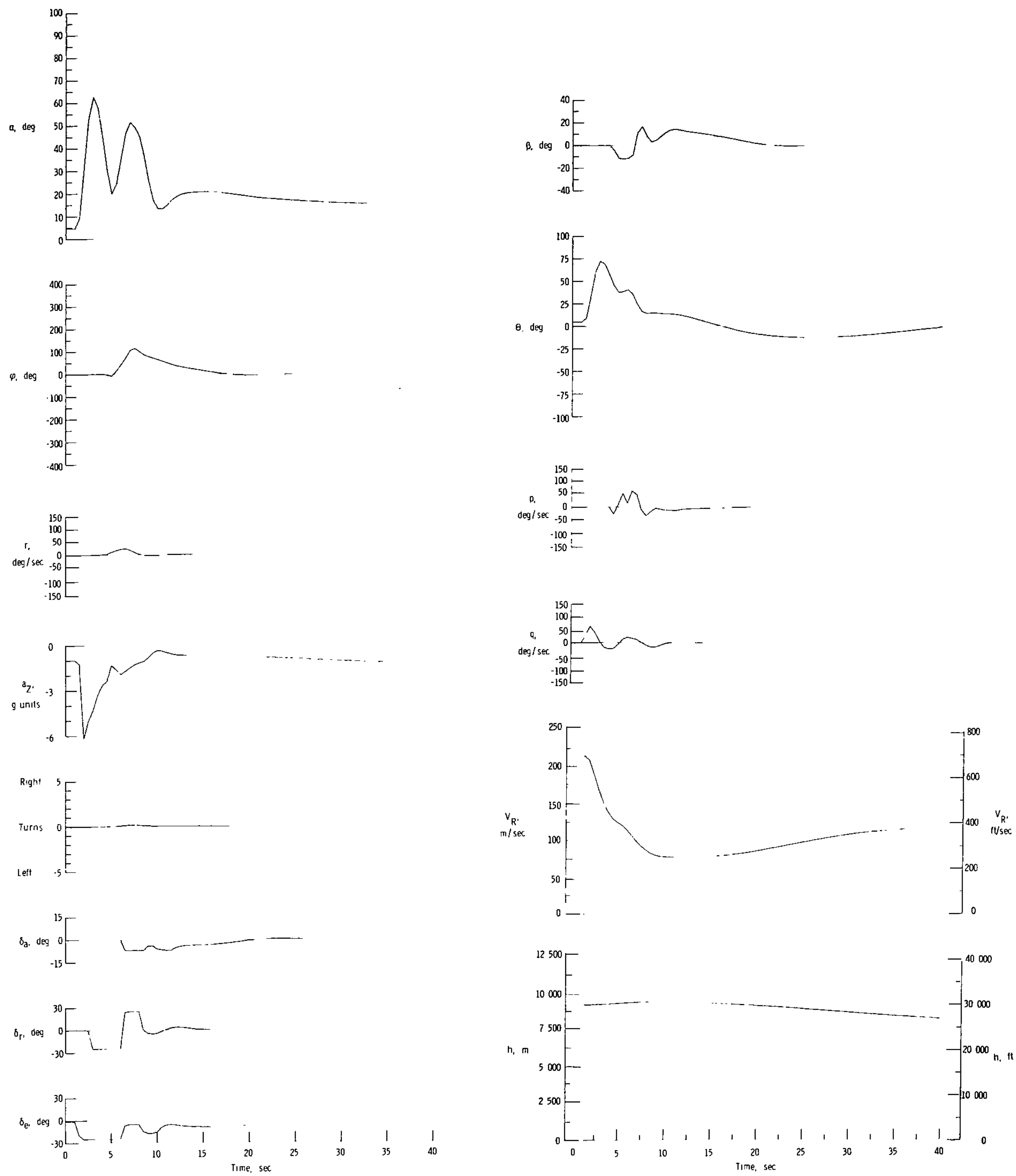
(a) Yaw-rate threshold = 11.5 deg/sec.

Figure 5.- Calculated effect of automatic spin-prevention system for configuration A.



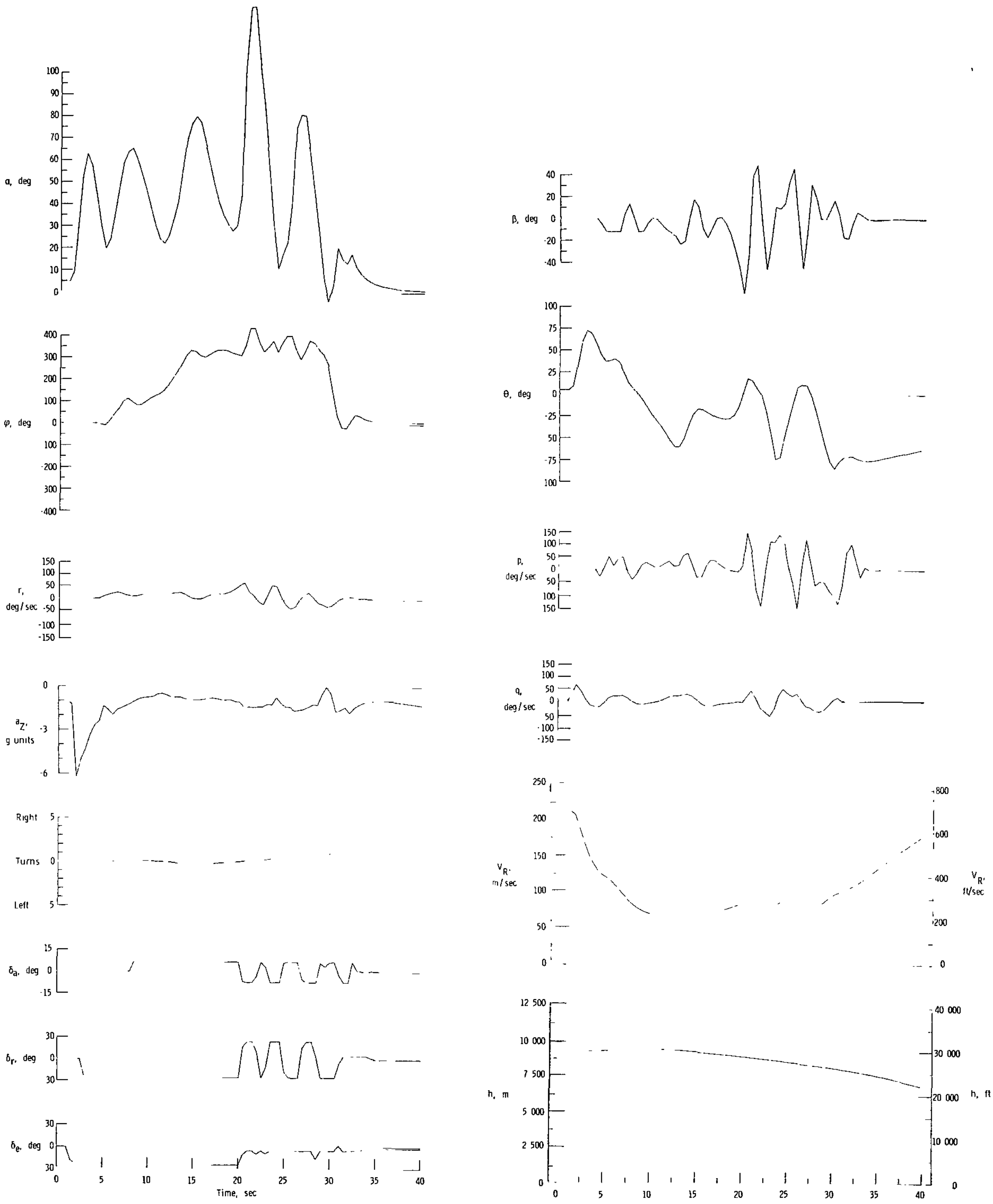
(b) Yaw-rate threshold = 57.3 deg/sec.

Figure 5.- Concluded.



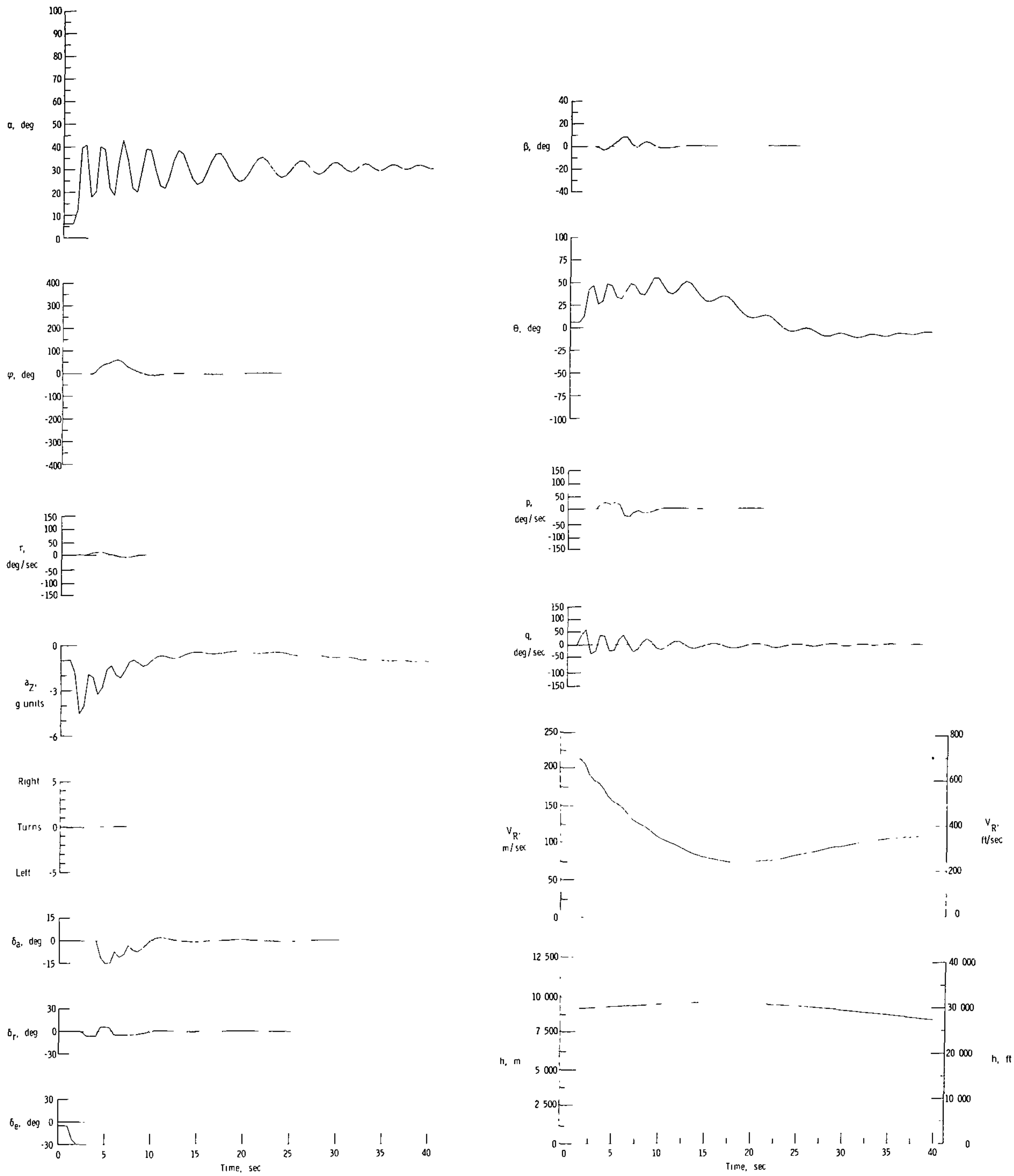
(a) Yaw-rate threshold = 11.5 deg/sec.

Figure 6.- Calculated effect of automatic spin-prevention system for configuration B.



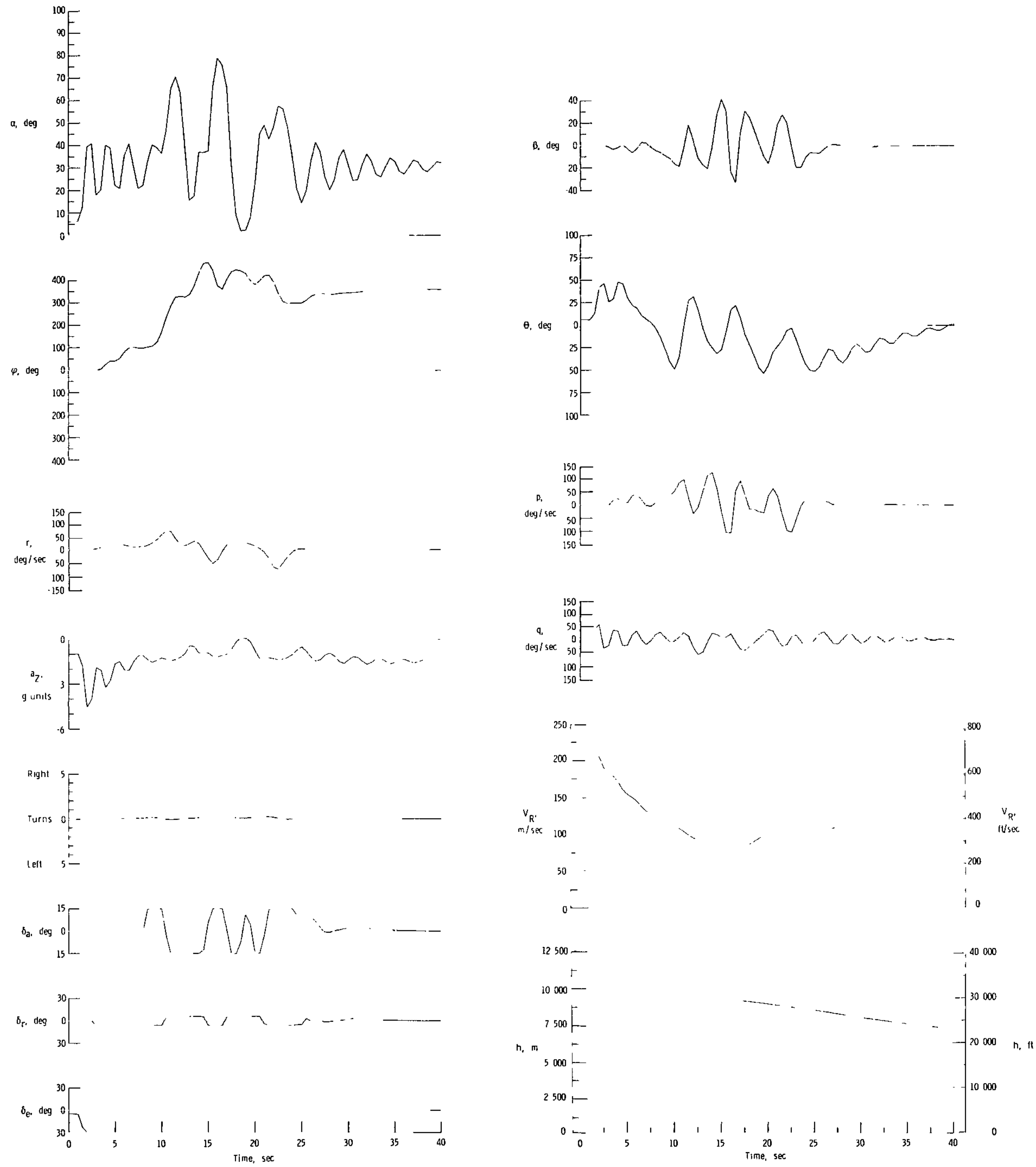
(b) Yaw-rate threshold = 57.3 deg/sec.

Figure 6.- Concluded.



(a) Yaw-rate threshold = 11.5 deg/sec.

Figure 7.- Calculated effect of automatic spin-prevention system for configuration C.



(b) Yaw-rate threshold = 57.3 deg/sec.

Figure 7.- Concluded.

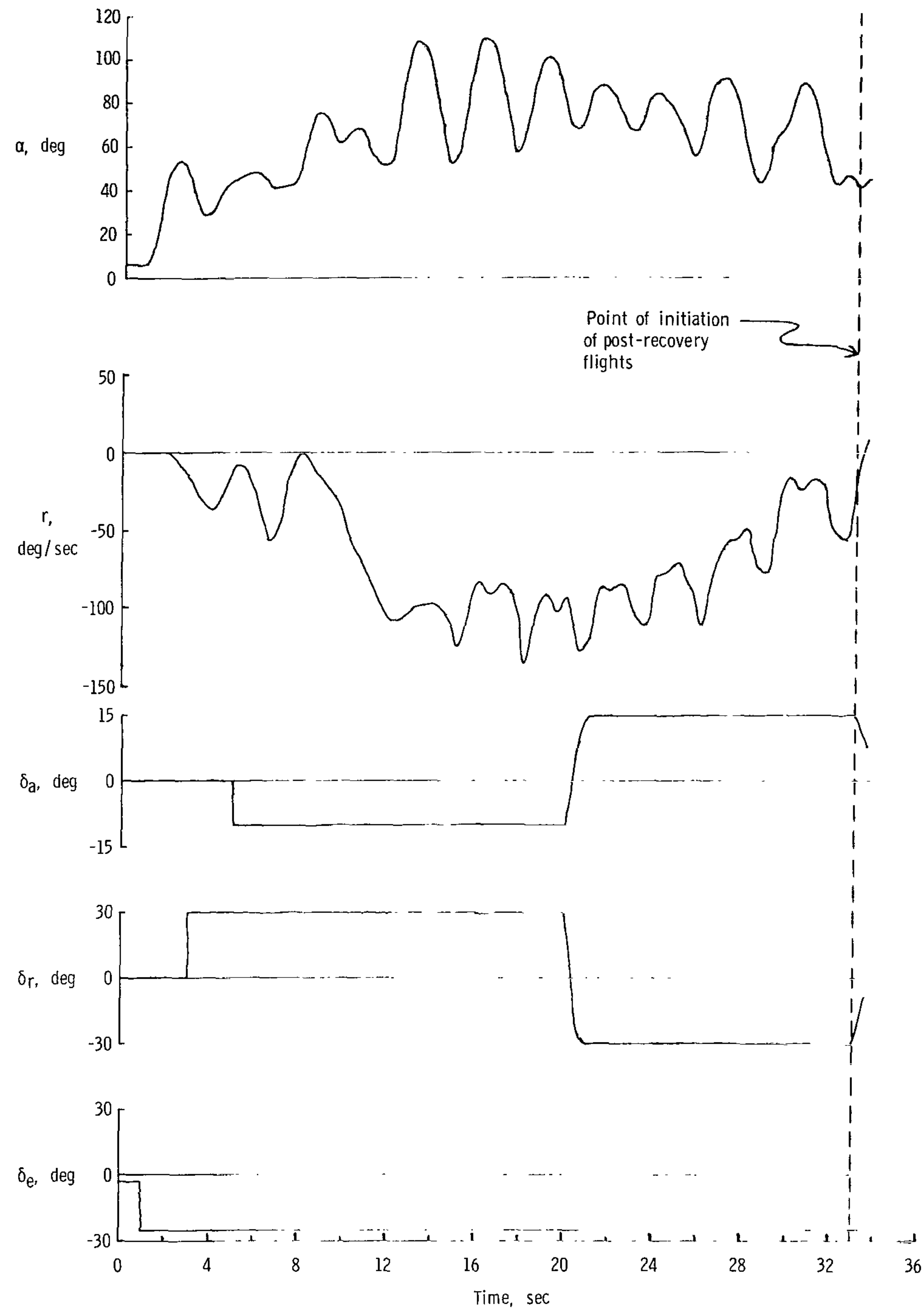
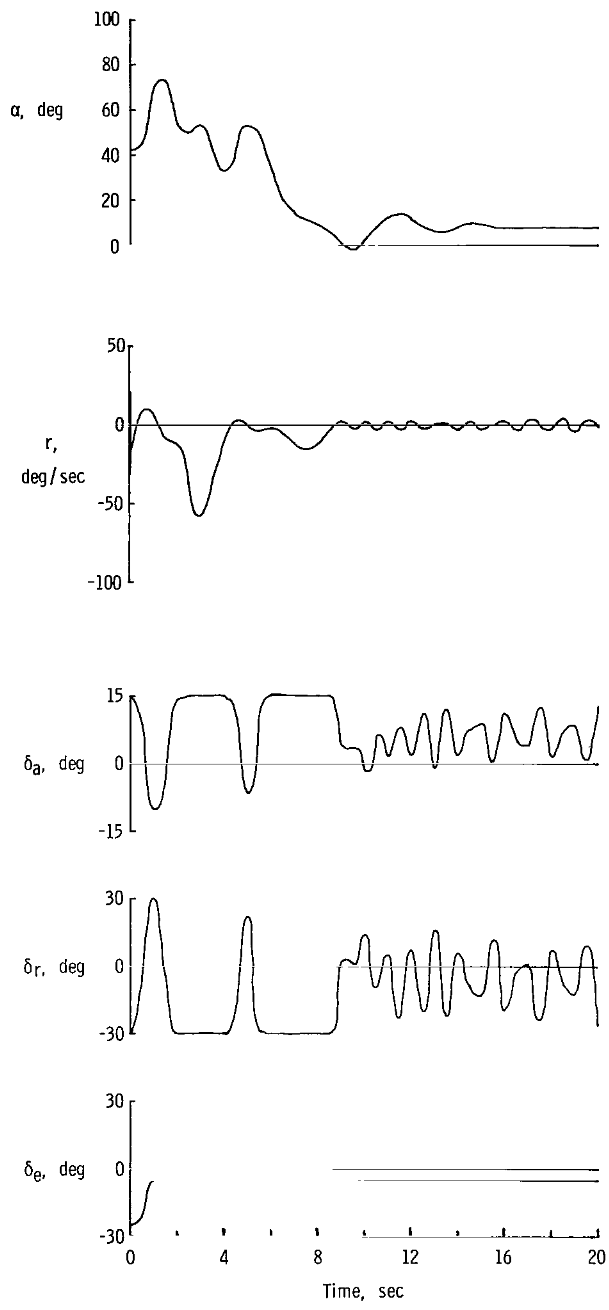
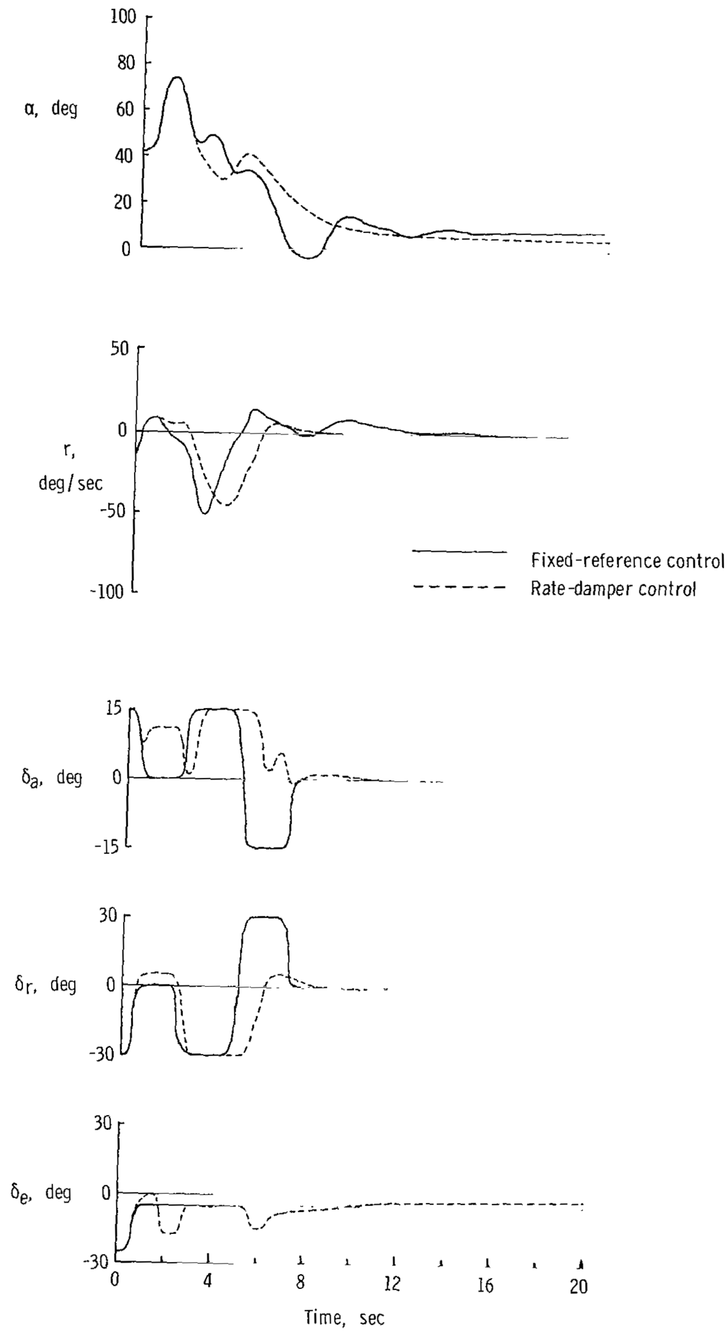


Figure 8.- Flight of configuration A calculated to obtain initial conditions for post-recovery flights of figures 9 and 10.



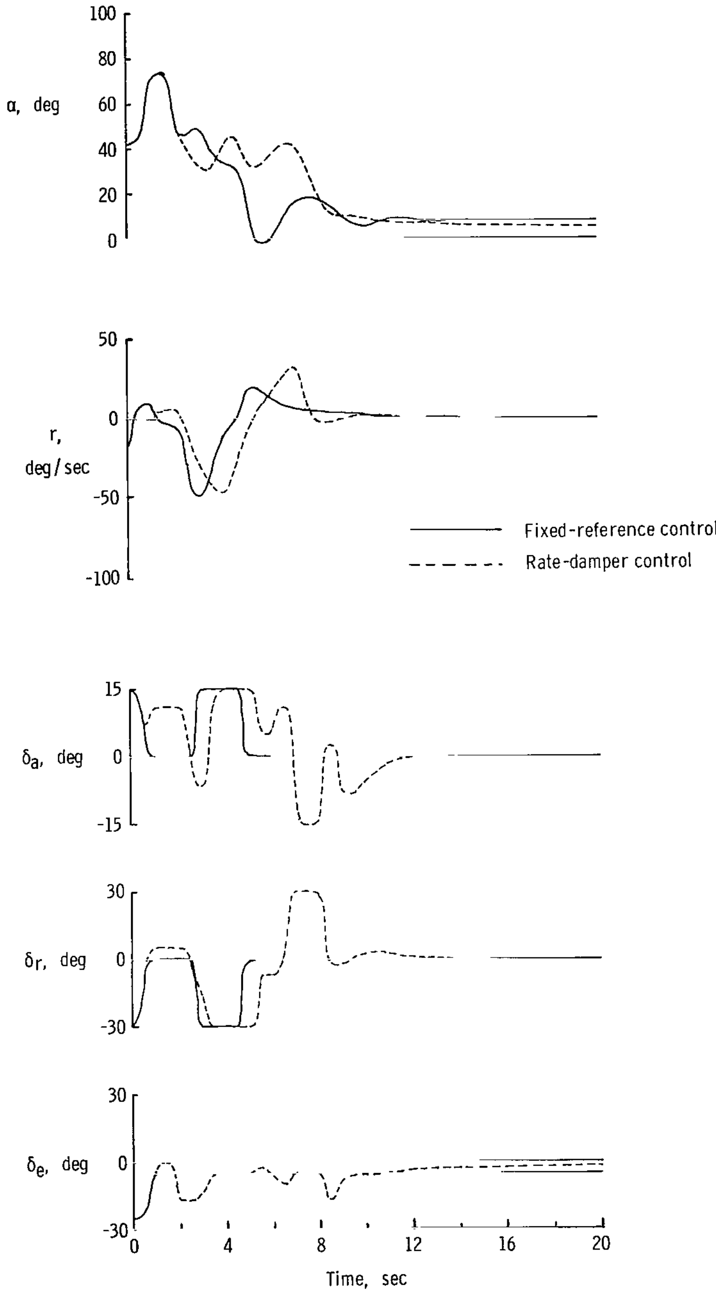
(a) Yaw-rate dead band = 0.0 deg/sec (primary subsystem only).

Figure 9.- Calculated post-recovery flights of configuration A with a horizontal-stabilator reference position at -5°, for various yaw-rate dead bands of the secondary subsystem.



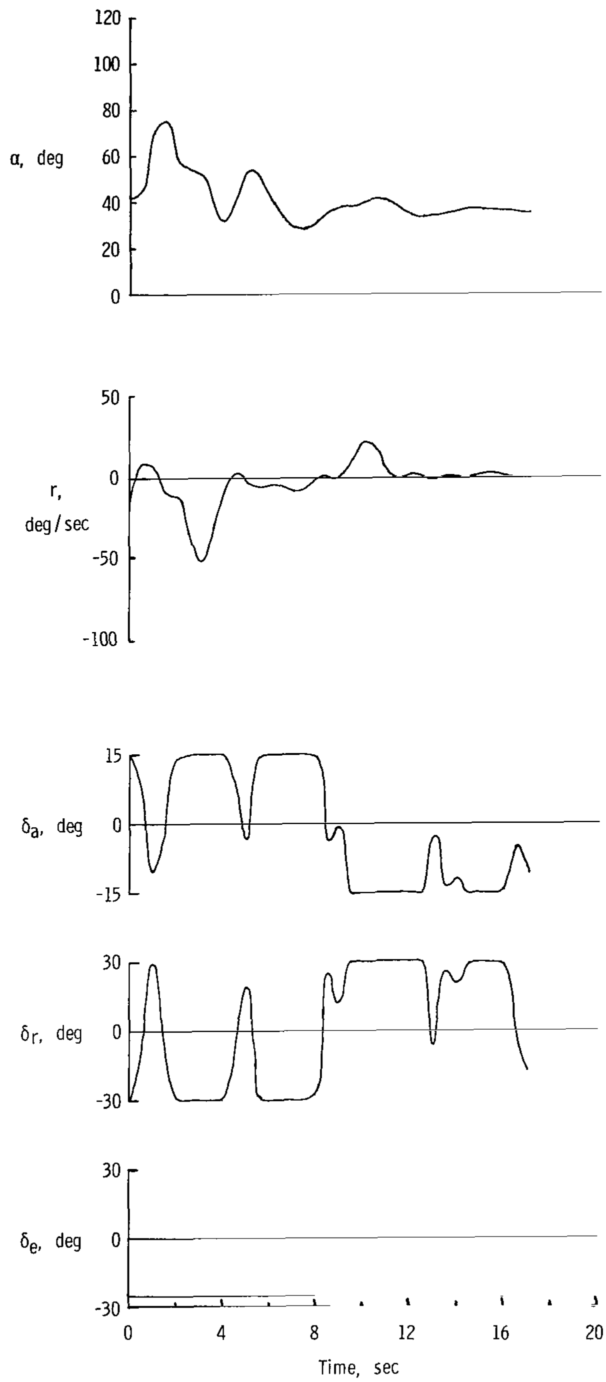
(b) Yaw-rate dead band = ±11.5 deg/sec.

Figure 9.- Continued.



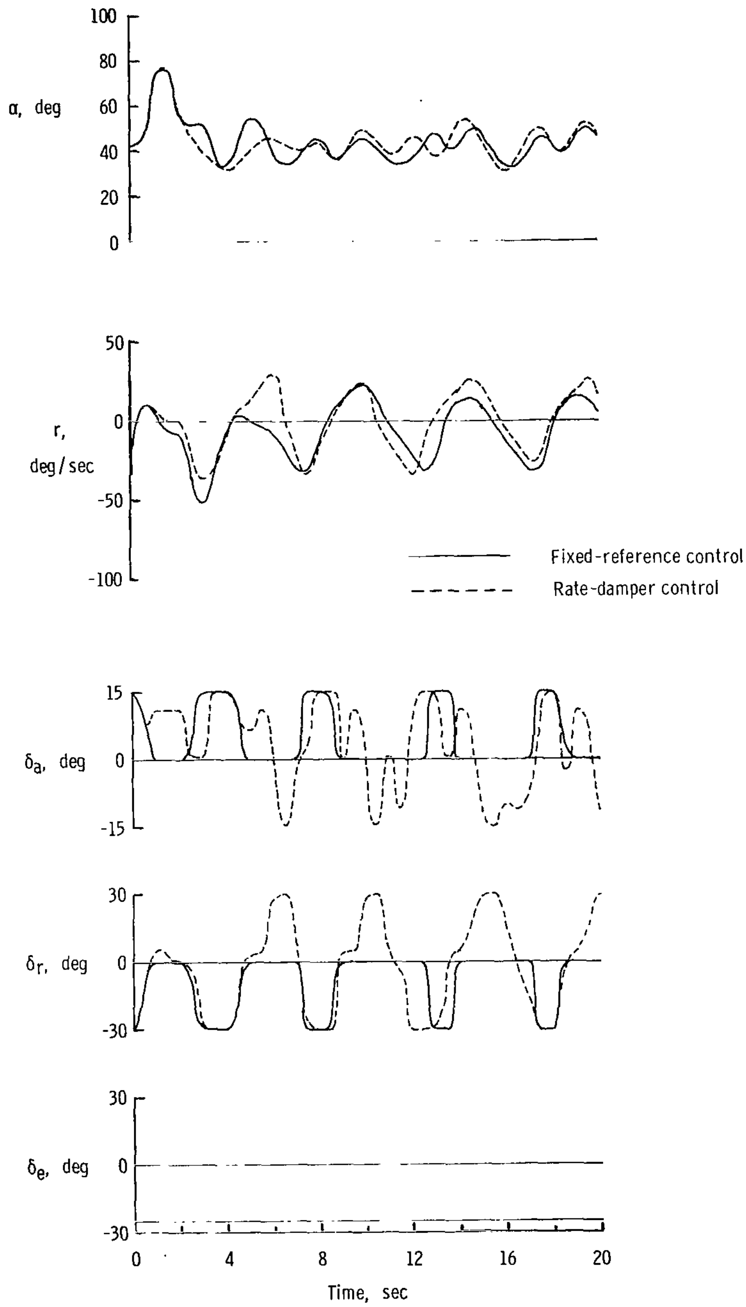
(c) Yaw-rate dead band = ±23.0 deg/sec.

Figure 9.- Concluded.



(a) Yaw-rate dead band = 0.0 deg/sec (primary subsystem only).

Figure 10.- Calculated post-recovery flights of configuration A with horizontal stabilator held fixed in full-trailing-edge-up position (-25°) for various yaw-rate dead bands of the secondary subsystem.



(b) Yaw-rate dead band = ±23.0 deg/sec.

Figure 10.- Concluded.

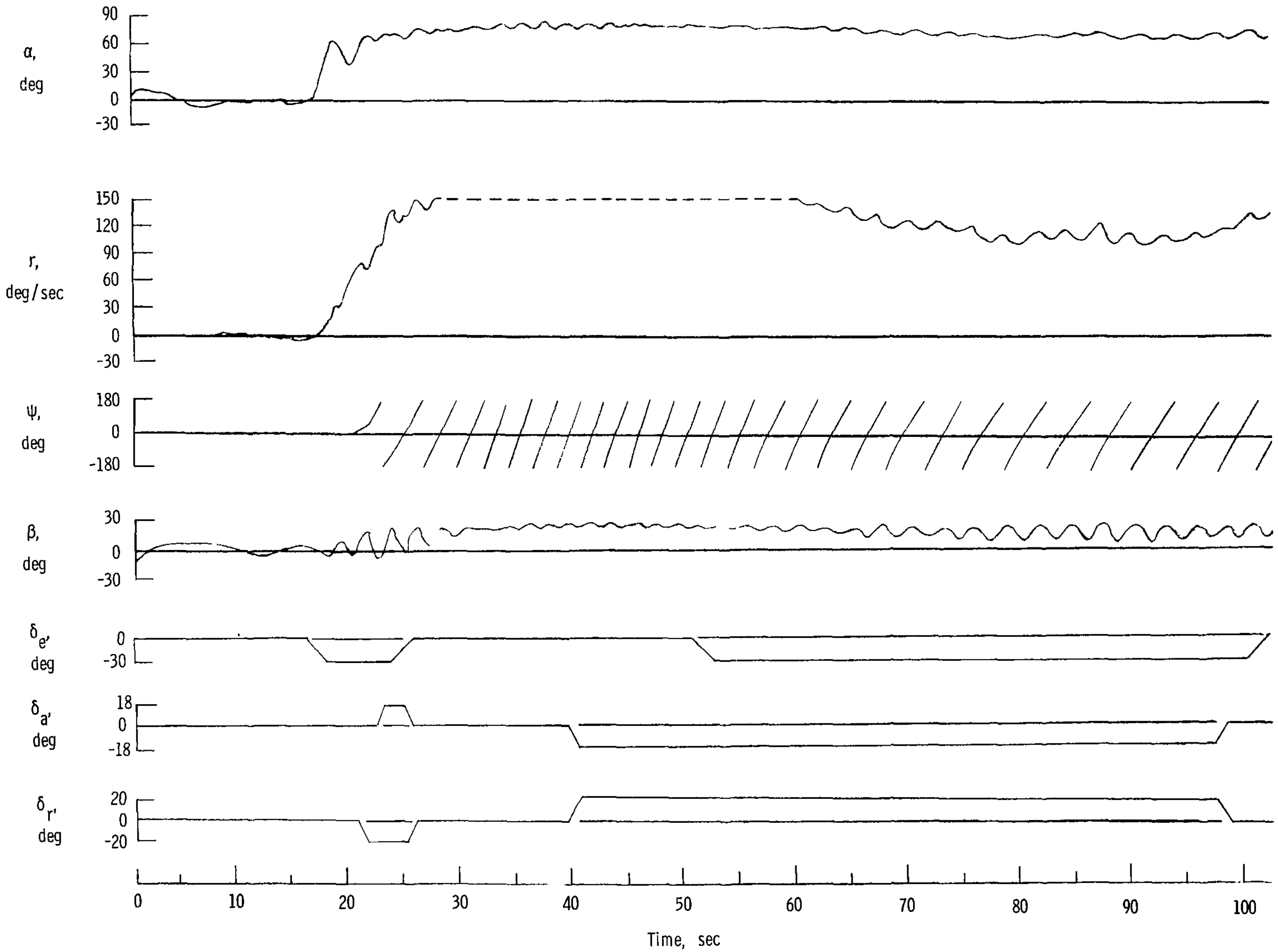


Figure 11.- Representative spin of radio-controlled model of configuration A.

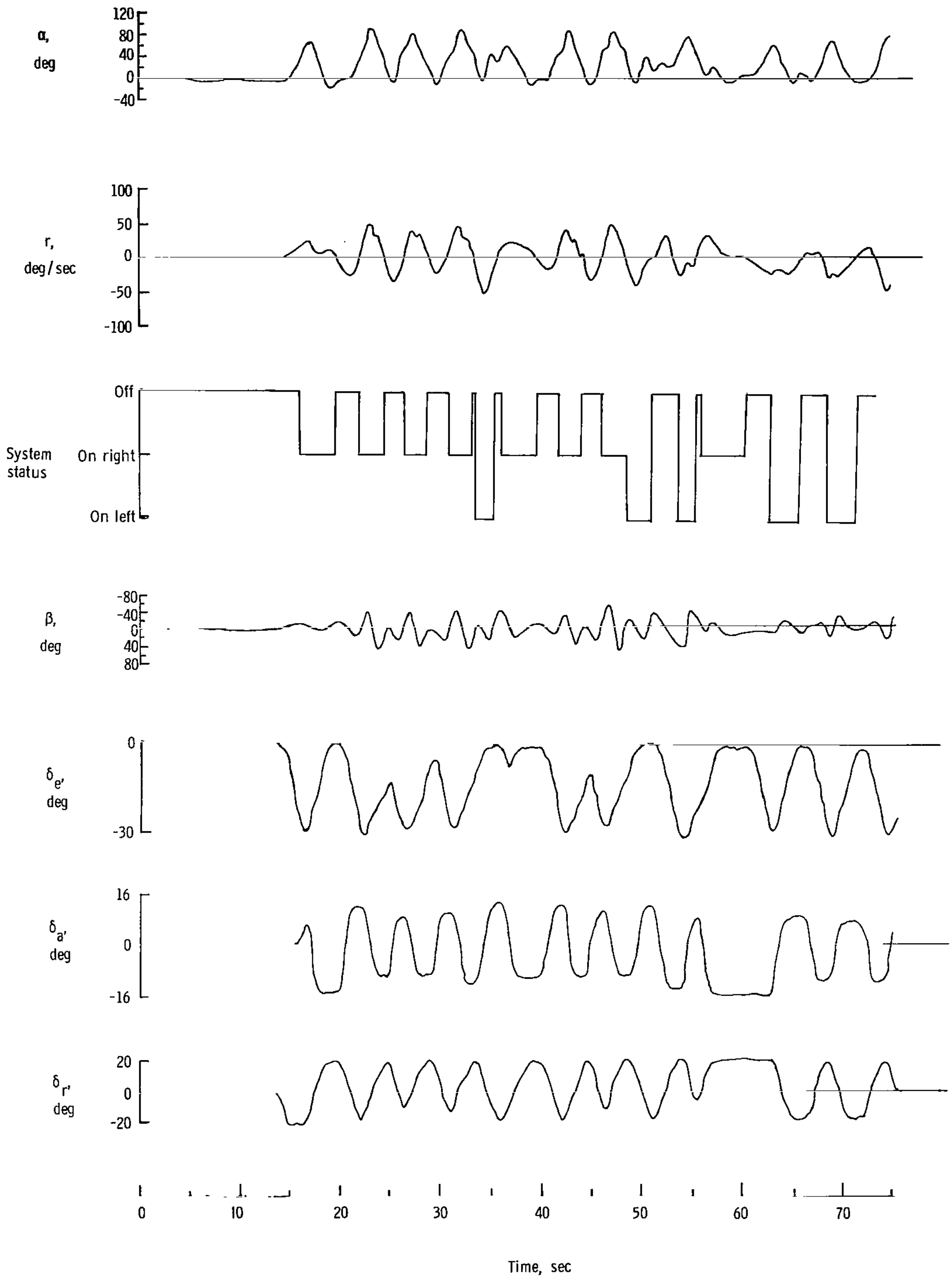
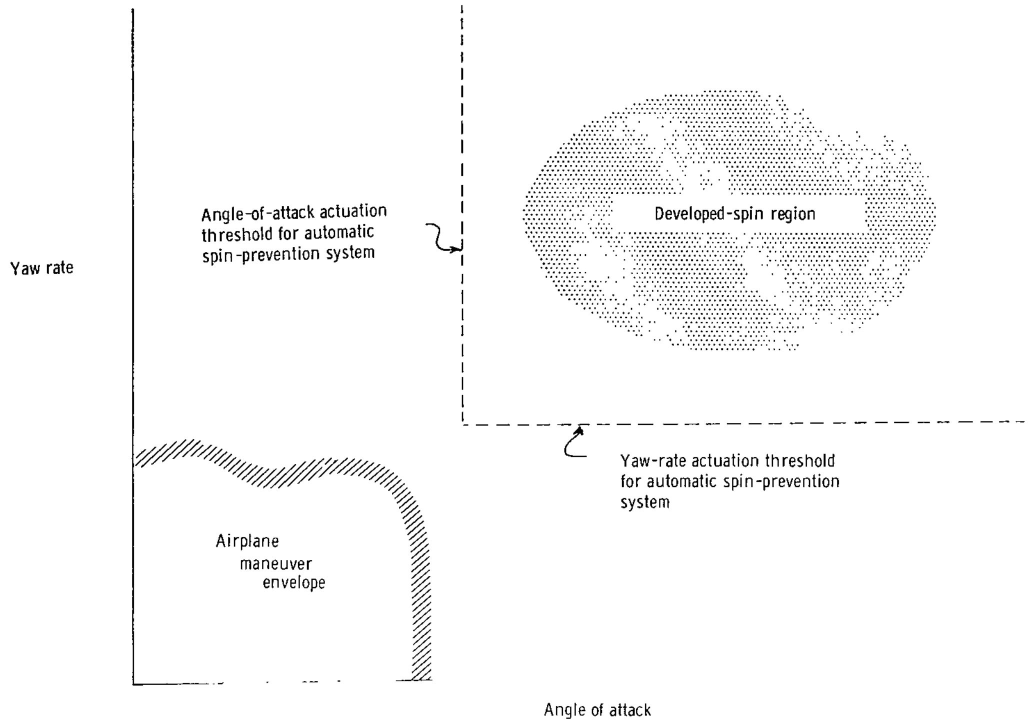
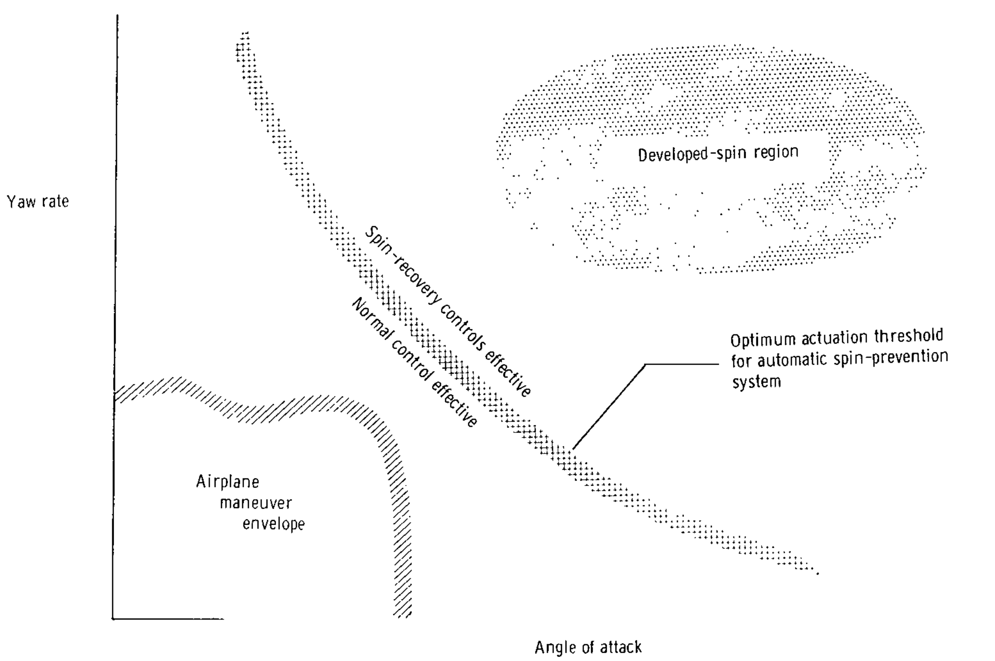


Figure 12.- Effect of automatic spin-prevention system on radio-controlled model of configuration A.



(a) Sketch showing simplified actuation thresholds defined by a constant angle of attack and a constant yaw rate.



(b) Sketch showing optimum actuation threshold for automatic spin-prevention system.

Figure 13.- Sketch showing example of airplane maneuver envelope, developed-spin region, and actuation thresholds in terms of yaw rate and angle of attack.

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