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SUMMARY OF A FLIGHT-TEST EVALUATION OF THE CL-84 TILT-WING V/STOL AIRCRAFT

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16. Abstract

A flight-test evaluation of a second-generation tilt-wing V/STOL aircraft was conducted to ascertain possible problem areas in the flight characteristics. The flying qualities were considered generally good except for a slow arrest of rate of descent at constant power and airspeed that could be of particular significance during instrument flight. This characteristic was documented in flight at an airspeed of about 40 knots.

Included is a bibliography that contains reports concerning much of the work of the NASA in tilt-wing V/STOL research.

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SUMMARY

An abbreviated flight-test evaluation of a second-generation tilt-wing V/STOL aircraft, the Canadair CL-84, was conducted to ascertain possible problem areas in the flight characteristics. The evaluation was concerned primarily with the flying qualities in the hover and transition modes of flight with less attention being given to the cruise mode. Two NASA Langley Research Center pilots, who had previous experience in the operation of tilt-wing V/STOL aircraft, performed the flights at the manufacturer's facility. In addition to quantitative data, pilot opinions of the aircraft characteristics, expressed in terms of Cooper ratings, were obtained.

In general, based on the limited evaluation performed, most of the flying qualities in the hover, transition, and cruise modes of flight were considered good. However, at one conversion angle at least, in transition flight, low normal-velocity damping was experienced at moderate rates of descent which could make glide-path control difficult during instrument flight without augmentation. The low damping was evidenced by an excessive length of time for rate of descent to stabilize after a power reduction. Data presented illustrate this characteristic at an indicated airspeed of about 40 knots and at power settings for indicated rates of descent in excess of about 300 ft/min (1.52 m/sec). Buffeting was not necessarily evident to the pilot until reaching an indicated rate of descent of 700 ft/min (3.56 m/sec) or more. Examination of wind-tunnel data obtained from a model of similar configuration indicates that these characteristics may be related to operation near maximum lift where induced drag is increasing rapidly, and a nearly constant resultant force occurs as angle of attack increases.

INTRODUCTION

The National Aeronautics and Space Administration has been actively engaged in tilt-wing V/STOL research over the past 15 years. Both wind-tunnel and flight studies have been made, and the results of most of this work are covered in the reports listed in the bibliography.

In a continuing effort to broaden the background of tilt-wing technology, a limited flight evaluation was made of a second-generation aircraft, the Canadair CL-84. The flights were conducted at the manufacturer's facility during October 1966 by two NASA Langley Research Center pilots, who had previous tilt-wing flight experience.

This report presents a summary of this abbreviated flight evaluation, the main effort of which was directed toward the stability, control, and handling characteristics during the hovering and transition flight modes. To a lesser degree, these characteristics were investigated in the cruise flight mode. Some of the results presented include initial angular-response characteristics at different stability augmentation levels, height control and response characteristics in hovering flight, maximum-rate level-flight conversion, static stability and oscillatory characteristics, steady-state rate-of-descent characteristics, and pertinent pilot comments. Also included in tabular form are pilot opinions of many of the aircraft characteristics expressed in terms of Cooper ratings.

APPARATUS AND TESTS

Aircraft

General.- The test aircraft was a combination tilt-wing deflected-slipstream V/STOL vehicle with a gross weight of about 11 200 lbf (49 800 N) for VTOL operation. This aircraft was designed for STOL operation at gross weights up to about 14 700 lbf (65 400 N). For the present flight-test evaluation, the VTOL configuration, which included 1000 lbf (4448 N) of fuel and about 1600 lbf (7117 N) of instrumentation, was used. Power was supplied by two gas-turbine engines of the free-turbine type, each engine driving 14-foot-diameter (4.27-m) propellers. The engines, which were linked by cross-shafting, were located in wing-mounted nacelles. Each engine had a maximum output rating of 1400 shaft horsepower (1044 kW). The wing was equipped with Krueger flaps at the leading edge and full-span single-slotted flaps at the trailing edge. The leading- and trailing-edge flaps were deflected automatically with wing incidence and were designed to alleviate stall effects during the transition mode of flight. Figure 1 presents a three-view sketch of the test aircraft and table I lists the physical characteristics and principal dimensions. Figure 2 presents an in-flight photograph of the test aircraft.

Aircraft control.- The pilots operated the control systems through an irreversible hydraulic boost system, and the control-system feel forces were provided by springs. The control force gradients and control breakout forces are shown in table I. The aircraft control system included a stability augmentation system (SAS) about the pitch, roll, and yaw axes, and table II presents the manufacturer's quoted values for the control and stability parameters about these axes. The stability augmentation system included angular-rate feedback about the pitch, roll, and yaw axes and attitude feedback about the pitch axis. The wing-tilt actuation switch was located on top of the power control lever.

Roll-control moments in hovering flight were produced solely by differential propeller-blade pitch. The propeller-blade pitch change for producing roll-control moments was phased out as aileron action of the flaps was phased in with decreasing wing tilt so that the ailerons were the source for roll-control moments in conventional airplane flight. Aileron deflection with full lateral-control deflection as programed with wing incidence is presented in figure 3(a).

Yaw-control moments in hovering flight were provided by differential operation of the trailing-edge flaps (the rudder surface on the center fin moved with the pedals in all modes of flight, however) which changed to a combination of differential flaps, differential propeller-blade pitch, and rudder-surface movement with pedal deflection for the intermediate wing-incidence settings. Aileron deflection with full rudder-pedal deflection as programed with wing incidence is presented in figure 3(b). The rudder and a small amount of differential propeller-blade pitch change provided yaw-control moments in conventional airplane flight. Differential propeller-blade pitch with full lateral-control deflection and full pedal deflection as programed with wing incidence is presented in figure 4.

Pitch-control moments in hovering flight were provided by 7-foot-diameter (2.13-m) dual counter-rotating tail propellers which were stopped and braked in an alined position for conventional airplane flight. The variation of tail propeller-blade angle with full-forward, neutral, and full-rearward longitudinal control-stick position as programed with wing incidence is presented in figure 5(a). The tail propeller and a large horizontal stabilizer with outboard vertical fins were programed with wing incidence to reduce longitudinal trim changes during the transition mode of flight. The program of the horizontal-stabilizer position as it varies with wing incidence is presented in figure 5(b). An elevator control surface provided pitch-control moments for conventional airplane flight.

The program of the trailing-edge flap angle as a function of wing incidence is presented in figure 5(c). The schedule for the Krueger flaps is given in table I. A photograph of the controls mixing unit is presented in figure 6. This unit programs the various controls as a function of wing incidence throughout the hover and transition flight modes.

Engine power control.- Propeller thrust was controlled by an upright throttle-type power lever. At propeller-blade angles used in hovering flight, movement of the power lever commanded a propeller pitch-angle change ("beta" control) and at the same time called for a corresponding change in fuel flow. A propeller governing system modulated the propeller pitch angle during all modes of operation to maintain a constant selected propeller speed.

Test Conditions and Technique

A total of seven flights were made by the two NASA pilots. The winds encountered during these flights were generally high, especially during the flights involving hovering and low-speed modes of operation. The winds encountered on two flights were about 9 knots with gusts to 13 and 17 knots. During the remaining five flights the winds varied from 13 knots to 22 knots with gusts to 35 knots.

The flight evaluation was concentrated primarily on the hovering and transition modes of flight; however, conventional airplane flight was also investigated. Evaluated areas included initial angular response at different stability augmentation levels, height control and response in hovering flight, maximum-rate level-flight conversion, static stability and oscillatory characteristics, and steady-state rates of descent. In general, the piloting and testing techniques were typical of those utilized by the NASA in past flight investigations of hovering and low-speed flight vehicles. No control stop devices were used by the pilots for control step or pulse inputs. Details on the test speed ranges and testing techniques used to investigate each flight characteristic are given in subsequent sections.

Instrumentation

The instrumentation used on the test aircraft was provided by the manufacturer. About 40 flying-quality parameters were measured on a recording oscillograph and included, in general, control-stick positions, control-surface positions, and SAS actuator positions. Also included were aircraft attitudes, angular rates, and angular accelerations about the pitch, roll, and yaw axes; fuselage angle of attack; angle of sideslip; and linear accelerations at the aircraft center of gravity along the three axes. A synchronized photorecorder was used to document other parameters such as airspeed, altitude, instantaneous vertical speed, ambient air temperature, and many pertinent engine, shafting, and gearbox parameters. A flight-path accelerometer readout was mounted on the cockpit instrument panel to provide information to the pilot during conversions.

Pilot opinions, expressed in terms of Cooper ratings for many of the aircraft characteristics discussed herein, are given in table III. The Cooper pilot-opinion rating system is explained in table IV.

HOVERING FLIGHT CHARACTERISTICS

During hover operations below a wheel height of about 15 feet (4.57 m), there was considerable buffeting of the aircraft structure. Also, "suck-down" (negative ground effect) was evident when landing in the winds encountered. It has been the experience that when hovering in very light winds, the ground effect is positive. Buffeting was evident at wheel heights as high as 30 feet (9.14 cm), on occasion, when full power was added to correct for settling. Although, in a previous investigation, wing drop had been reported at 25 knots in accelerating conversions below a wheel height of 15 feet (4.57 m), it was not encountered in these flights at any height when hovering into winds of 9 knots to 35 knots. The aircraft actually exhibited no upset disturbances of appreciable magnitude about any axis during the hover operations, despite the airframe buffeting. However, during vertical landings the aircraft occasionally tended to slide sideways to the right when it was a few feet from the ground. This tendency was corrected readily with a lateral attitude change before ground contact was made. Wing incidence changes were necessary, the fuselage being maintained essentially level, to prevent backward or forward drift of the aircraft as either the vertical take-off or landing progressed. The wind gradients in the first 15 to 20 feet (4.57 to 6.1 m) of altitude were always apparent. Above about a 15-foot (4.57-m) wheel height, the aircraft became very steady with a very low vibration level. The major effect of wind gusts when heading into the wind was a slow drift of the aircraft backward or forward which could be corrected by a short "blip" of the wing-tilt switch. No appreciable accelerations along the longitudinal axis due to the gusts were felt, even though the wind conditions during this evaluation were much more adverse than heretofore experienced by the NASA Langley Research Center pilots during tilt-wing aircraft flights. The operation of this aircraft in winds was considered satisfactory.

Height Control and Response

The piloting evaluation of the height control and response characteristics in the hover mode included take-offs and landings and maneuvers from spot to spot over the ground (longitudinal and lateral translations). Throttle-control step inputs were made to provide a quantitative measure of the height-response characteristics.

A time history of a throttle-control step input and the resulting normal acceleration is presented in figure 7. Although the height-control sensitivity obtained by measurements from this time history was less than the manufacturer's quoted value, 0.13 g/in. (0.05 g/cm) of throttle grip motion compared with 0.20 g/in. (0.08 g/cm), both values fell within the optimum range for visual (VFR) operation as determined by results of a recent height-control investigation with a variable-stability helicopter. (See ref. 1.) It should be noted that the value of height control sensitivity quoted by the manufacturer was based on 100 percent propeller speed, on standard-day conditions, and in still-air hover (88° wing incidence). The value from the time history is based on the steady-state normal-acceleration increment divided by the throttle travel at the center of the pilot's grip. The droop and rise following the initial hump in the normal-acceleration time history in figure 7 is due to the fuel scheduling and propeller governing. Pilot comment indicated that for gross maneuvering flight near hover, the overall available thrust-to-weight ratio of about 1.1 was a minimum for satisfactory operation of this aircraft.

From a hardware standpoint, the pilot commented that the friction in the throttle control was high enough to make operation with finger and wrist action alone difficult. Since no arm rest was provided, a full hand grip on the lever and the use of full arm motions were required; however, satisfactory control was possible after several minutes of practice. The pilot did encounter some mild overcontrolling tendencies (pilot-induced oscillations) while approaching the ground (suck-down region). The latter problem was overcome with a little practice by allowing a positive rate of descent to continue until touchdown.

Force and Stability Characteristics

In lateral translations during hover operations, the aerodynamic side force that developed was high, and the dihedral effect was also high; however, neither of these characteristics seemed unreasonable in degree when considered by itself. The magnitude of the side force was such that when hovering in a 22-knot direct cross wind, the required bank angle was appreciable but at an acceptable level for these wind conditions.

The variation of longitudinal force on the aircraft with speed was very high, resulting in the need for large attitude changes to vary speed so that translations, except for a few yards, were more readily and comfortably accomplished by the use of wing tilt. The stability with speed (stick-position variation) in hover with the wing fixed was also found to be high, but not high enough to be of concern because wing tilt was used for appreciable translations or speed changes.

Lateral Oscillatory Characteristics

A time history indicating the lateral oscillatory characteristics resulting from a lateral-control pulse input in hovering flight with all roll SAS off is presented in figure 8. It can be seen from this figure that the rolling angular velocity expanded at a rapid rate and appeared to the pilot to be almost a divergence on the first swing through the trim attitude. This result was due in large measure to the high dihedral effect and low roll-rate damping. Because of the pilot's apprehension, the oscillation was quickly stopped with control application; in fact, full lateral control was momentarily used at 6.6 seconds to stop the oscillation at a near-level attitude. The time history tends to substantiate pilot comment which indicated that a dangerous pilot-induced oscillation could easily occur if hovering maneuvers involving sideslip velocities were performed without caution and with the roll SAS off. As indicated in table II, the basic aircraft (no stability augmentation) had a roll-rate damping of 0.6 $\frac{\text{rad/sec}^2}{\text{rad/sec}}$.

Longitudinal Oscillatory Characteristics

A time history of a longitudinal-control pulse input in hovering flight with no pitch-stability augmentation is presented in figure 9. The resulting longitudinal oscillation appears slightly divergent, although the character of the pitching angular-velocity trace was affected somewhat by the pilot who did not hold the pitch control at the trim position. The inherent pitch-rate damping of the basic aircraft as given in table II was 0.4 $\frac{\text{rad/sec}^2}{\text{rad/sec}}$. The pilots commented that the SAS-off configuration in pitch did not seem nearly as unstable as the SAS-off configuration in roll and was not of great concern.

A time history of an oscillation resulting from a longitudinal-control pulse input with the pitch-attitude SAS off and with the pitch-rate SAS gain set at 40 percent $\left(\text{net rate damping of about } 1.84 \ \frac{\text{rad/sec}^2}{\text{rad/sec}}\right)$ is presented in figure 10. The resulting pitching angular velocity of the oscillation is shown to be damped.

Stability-Augmentation-System Saturation

Exceeding the angular rates and attitudes at which the stability augmentation systems become saturated (that is, reach maximum actuator authority) could produce a possibly dangerous overshoot of anticipated rates and attitudes in rapid maneuvers. Such an overshoot was experienced by one of the pilots about the roll axis as he attempted to stop a moderately rapid lateral translation wherein the highly stable dihedral effect combined with the roll control used to stop the translation resulted in an unexpectedly high roll rate.

Aircraft Response to Control

The initial angular-response characteristics about the three aircraft axes were investigated in hovering flight by performing control step inputs. The term control power as used herein is the total angular-acceleration capability from trim (rad/sec^2) and the term control sensitivity is the angular-acceleration capability per unit control deflection $\left(\frac{\text{rad/sec}^2}{\text{unit control deflection}}\right)$. Aircraft angular response as used herein is the change in aircraft attitude per unit time following a control input (rad/sec). Time histories, when available, are presented to give quantitative results in conjunction with pilot comment.

Roll.- The SAS-off configuration for the roll axis $\left(\text{roll-rate damping of } 0.6 \ \frac{\text{rad/sec}^2}{\text{rad/sec}}\right)$ was evaluated by the pilots for maneuvering flight. At times this level of damping did result in some lateral wobbling of the aircraft when controlled in hovering. The pilots indicated that the control power and steady-state rolling angular-velocity capability with the SAS off were good for maneuvering with little attitude overshoot when lateral control was recentered if low sideslip velocities were involved. However, the pilots could sense the possibility of a dangerous pilot-induced-oscillation tendency if appreciable sideslip velocities were allowed to develop in rolling maneuvers. With the SAS rate-feedback gain set to yield a roll-rate damping of about 1.6 $\frac{\text{rad/sec}^2}{\text{rad/sec}}$, the pilots commented that some lateral wobbling tendency was still apparent. No lateral wobbling was noted with the maximum level of roll-rate damping $\left(\text{about } 3.0 \ \frac{\text{rad/sec}^2}{\text{rad/sec}}\right)$. The hovering roll rate available with the roll SAS at maximum gain was more sluggish than was desirable for maneuvering according to pilot comment. For example, normal maneuvers required a large portion of the lateral control leaving insufficient margin for rapid or emergency maneuvering. Control for precision hovering was, however, considered very good by the pilots. A time history of a lateral-control step input and the resulting rolling angular velocity with the full roll SAS on is presented in figure 11.

Pitch.- The angular response and steady-state angular velocity in pitch appeared to be quite satisfactory in the nose-down direction with both pitch-rate and pitch-attitude SAS on. In the nose-up direction, however, the initial response was satisfactory but the final pitching angular velocity was considered to be sluggish. Time histories of the aircraft response to a longitudinal-control step input in both the nose-up and nose-down directions with both pitch-attitude and pitch-rate SAS on are presented in figures 12 and 13, respectively. With the pitch-attitude SAS off and only the pitch-rate SAS on, the angular response and the level of steady-state pitching angular velocity appeared to be quite satisfactory with little tendency toward overshoot. Time histories of the aircraft response to a longitudinal-control step input in the nose-up and nose-down directions for this SAS configuration are presented in figures 14 and 15, respectively. With all pitch SAS off, although the level of control power was more than adequate, flight tended to be wobbly in pitch probably because of the low pitch-rate damping; the possibility of a pilot-induced oscillation in pure pitching maneuvers (no airspeed changes) was noted.

Yaw.- Aircraft yawing response with full yaw-rate SAS on was considered unacceptably sluggish for normal operation. Large rudder-pedal deflections were required to exceed SAS saturation and produce acceptable yawing accelerations and angular velocities. Time histories of the aircraft yaw angular response to right and left directional-control step inputs, which were large enough to saturate the SAS system, are presented in figures 16 and 17, respectively. With the yaw SAS off, acceptable yaw control was noted in the maneuvering sense. Both NASA pilots preferred to fly the aircraft with the yaw SAS off. Time histories of the aircraft yaw angular response to directional-control step inputs with the yaw SAS off are presented in figures 18 and 19. Note the greater response of yaw angle in a given time for the SAS-off configuration (figs. 18 and 19) compared with that for the SAS-on configuration (figs. 16 and 17). Although high and gusty winds were encountered during these hover flights, the pilots reported that the external disturbances to the aircraft about the yaw axis were almost nonexistent for all flight conditions encountered.

CONVERSION CHARACTERISTICS

Accelerating Conversions

The accelerating-conversion characteristics of the CL-84 were considered to be outstandingly good. Trim changes were considered minor and satisfactory, and the fuselage attitude could be maintained nearly level until the wing incidence was reduced to 15°.

During the last 15^o of wing movement, the fuselage attitude had to be increased about 10^o, but trim changes were such that the aircraft attitude seemed to increase largely by itself. After take-off on the second full conversion, the pilot determined that it was reasonable to take off vertically to about 20 feet (6.1 m) and, leaving power fixed, hold the wing-tilt switch forward until a wing incidence of 15^o was reached. Because of limited hydraulic-system capacity, the conversion process had to pause temporarily at a 15^o wing incidence so that the landing gear could be retracted. The wing incidence was then reduced to zero, at which time the tail rotor was stopped and alined with the fuselage axis for stowage. Acceleration to cruise or high-speed airplane flight was then continued.

Time histories describing a maximum-performance level-flight accelerating conversion from hovering flight to a transition flight speed of about 100 knots (wing incidence of about 15^o) are presented in figure 20. The time history of the longitudinal stick position indicates that about 50 percent of the control travel from the neutral stick position to full forward and about 30 percent of the control travel from the neutral stick position to full rearward were utilized to maintain trim. The remaining longitudinal-control margin was considered to be satisfactory. Following initiation of wing tilt from an incidence of 84^o, the aircraft climbed slightly, leveled off through the intermediate portion of the conversion, and then climbed so that at a 15^o wing incidence and 100-knot airspeed the rate of climb was about 1500 ft/min (7.62 m/sec). External disturbances to the aircraft about the roll and yaw axes were not apparent at any time during the conversion. The accelerating conversions performed in increments with power readjustments to yield level flight at each increment indicated similarly desirable characteristics.

Decelerating Conversions

During decelerating conversions from cruise flight to hovering flight, no airframe buffeting due to flow separation over the wing was noted within the test power range and magnitudes of deceleration. Deceleration from cruise to about 125 knots was performed by slowly reducing power to flight idle. The initial deceleration of about 0.25g at 85 percent propeller speed seemed satisfactory although a higher value of deceleration would be desirable. At 125 knots and level-flight power, the tail rotor was activated with negligible trim changes. The wing was then unlocked and raised to an incidence of 15^o with continuous wing-tilt switch actuation while power and controls were held fixed. The aircraft ballooned upward and the nose pitched moderately upward. The pilot indicated that the nose-up pitching might have been controlled with a moderate amount of forward longitudinal stick, although it was not controlled for in this case. A continuous actuation of the wing-tilt switch was then made from 15^o to 40^o. Again at constant power and with the controls fixed, the aircraft ballooned upward (about 500 feet (152.4 m)) but showed only minor longitudinal trim changes. About a 0.3g maximum deceleration was noted and no stall buffeting was experienced at these conditions. At higher wing-tilt angles, little ballooning was noted. No specific comparative trials were carried out in which an attempt was made to hold attitude or altitude fixed by power adjustment.

CHARACTERISTICS IN TRANSITION AND CRUISE FLIGHT

Evaluations of control and stability characteristics were made at selected transition and cruise flight airspeeds. Transition airspeeds were obtained by selection of wing-incidence settings of 15°, 30°, and 40°. The aircraft was then trimmed with power for level flight with the fuselage attitude longitudinally level by reference to the gyro-horizon indicator.

Aircraft Response to Control

Time histories of aircraft angular response resulting from control step inputs in roll, pitch, and yaw are presented for trim-level-flight airspeeds of 42 knots (wing incidence of 40°), 100 knots (wing incidence of 15°), and 185 knots (wing locked at 0° incidence). Data are not presented for an airspeed of 50 knots (wing incidence of 30°) since the characteristics were determined to be similar to those at 100 knots. Time histories of lateral-control step inputs and the resulting angular response are presented for all three airspeeds, and time histories of longitudinal- and directional-control step inputs and the resulting angular responses are presented for an airspeed of 42 knots only. Pilot opinions of the angular-response characteristics about the roll, pitch, and yaw axes are presented in table III.

It should be remembered that if selected by the pilot, the roll SAS (rate only) is active in all modes of flight, the yaw SAS (rate only) is active in all modes of flight but operates only through a small pitch range of the main propellers in the cruise mode of flight, and the pitch SAS (rate and attitude) is off when the tail rotor is stopped. Also, the authority of the pitch SAS is reduced as wing incidence is reduced. (See table II.)

Roll.- The aircraft roll response and steady-state rolling angular-velocity capability with the roll SAS off at a trim-level-flight airspeed of 42 knots were considered to be quite satisfactory. A time history of the aircraft response to a lateral-control step input at these conditions is presented in figure 21. A time history showing the aircraft roll-response characteristics following a larger control step input with the SAS off and at the same airspeed is presented in figure 22. With the roll SAS on and at an airspeed of 42 knots, the steady-state rolling angular-velocity capability was considered to be sluggish. A time history showing the results of a lateral-control step input at these conditions is presented in figure 23.

For an airspeed of 100 knots and with the roll SAS off, the aircraft response to a control step input in roll and the steady-state rolling angular velocity were considered very satisfactory with no appreciable overshoot in bank when the lateral control was recentered. With the roll SAS on, the steady-state rolling angular velocity was considered to be too low. A time history showing the rolling response to a lateral-control step input at 100 knots with the SAS on is presented in figure 24.

At trim-level-flight airspeeds ranging to 200 knots, the aircraft rolling response and steady-state rolling angular-velocity capability with the roll SAS off were considered to be very satisfactory with no tendency toward overshoot in bank. The steady-state rolling angular velocity with the roll SAS on was considered to be sluggish. Three time histories showing aircraft response to lateral-control step inputs at a 185-knot airspeed with the roll SAS on are presented in figure 25.

Pitch.- Pitch response and steady-state pitching angular velocity as developed with longitudinal-control step inputs at a trim-level-flight airspeed of 42 knots were considered to be satisfactory when the pitch-rate and pitch-attitude SAS were on. A time history indicating the results of a longitudinal-control step pull-and-hold maneuver at 42 knots with both the pitch-rate and pitch-attitude SAS on is presented in figure 26. When the attitude SAS was off and the rate SAS was on, the angular response and steady-state angular velocity were considered to be very satisfactory with no apparent instability or overshoot tendency when the longitudinal control was recentered. A time history showing the results of a longitudinal-control step pull-and-hold maneuver at 42 knots with the pitch-attitude SAS off and the pitch-rate SAS on is presented in figure 27. In a step pull-and-hold maneuver with all pitch SAS off, the aircraft tended to accelerate in pitch after about a 10° nose-up attitude had been exceeded, and almost immediately the buffet boundary was reached. Recovery was quickly initiated with the longitudinal control. These unstable characteristics were considered to be unsatisfactory.

At a 100-knot airspeed and with the pitch-attitude and pitch-rate SAS on, the pitching angular response to a longitudinal-control step pull-and-hold maneuver was quite satisfactory initially but then slowed to a pitching rate that was considered to be sluggish. With the pitch-attitude SAS off and the pitch-rate SAS on, the pitching response to a step pull-and-hold maneuver and the available steady-state pitching angular velocity were very satisfactory.

In cruise flight at a trim-level-flight airspeed of 200 knots, the aircraft pitching angular response to a step pull-and-hold maneuver was considered quite satisfactory with no noticeable overshoot or oscillatory tendencies when the longitudinal control was recentered.

Yaw.- As in the hovering flight mode, the pilots preferred to fly the aircraft with the yaw SAS off in the transition and cruise flight modes, generally for the same reasons.

A time history indicating the aircraft yaw angular response to a directional-control step input with the yaw SAS off is presented in figure 28 for a transition airspeed of 42 knots. Additional pilot impressions of the aircraft response about the yaw axis are given in table III.

Static Longitudinal Stability

Past studies have indicated that static longitudinal stability with respect to airspeed and in maneuvers should be stable if a V/STOL aircraft is to provide the pilot with the capability of performing precision flight tasks such as the low-speed steep landing approach under instrument flight conditions. Stability characteristics of the CL-84 were investigated and the results are discussed mostly in the form of pilot comment with some quantitative results included when available.

The maneuver stability characteristics were investigated by means of two testing techniques at airspeeds of 42 knots, 50 knots, and 100 knots and in cruise flight at trim-level-flight airspeeds up to 200 knots. The characteristics at 50 knots were not documented and are not discussed because they were similar to those experienced at 100 knots. The first technique was the longitudinal-control step pull-and-hold maneuver wherein the development of aircraft pitching angular velocity or normal acceleration or both (depending on speed) were evaluated for stable characteristics; that is, for an indication of a concave downward trend in the respective time histories within 2 seconds after the start of the maneuver. (See ref. 2.) Thus, the longitudinal-control step pull-and-hold inputs used previously to evaluate response permitted an evaluation of maneuver stability also. The second testing technique was the more familiar windup turn at a constant airspeed.

At an airspeed of 42 knots and with the pitch-rate and pitch-attitude SAS on, the maneuver stability was positive but low in turns with bank angles up to 30° (constant power and airspeed). For the same SAS configuration and airspeed, when power to maintain altitude was added in a turn with a bank angle up to 45°, the longitudinal-stick-position and force changes were again in the stable direction. Previous discussion indicated that with all pitch SAS off, a pull-and-hold maneuver at this airspeed revealed a longitudinal instability in the form of a pitch-up after about a 10° nose-up attitude had been exceeded. Almost immediately, the buffet boundary was reached and recovery was quickly initiated. Also with the SAS off, instability with speed became evident at about 10 knots below the trim speed. The pilot recovered immediately to prevent an apparently imminent loss of forward control. These unstable characteristics were considered unsatisfactory. The need for the attitude SAS in pitch thus became apparent.

At an airspeed of 100 knots, the longitudinal-stick-position and force changes in turns with bank angles up to 35° (power and airspeed constant) were satisfactorily stable with the pitch-attitude SAS on or off. The result of a windup turn at this airspeed with both the rate and attitude SAS on is shown in figure 29. Stable characteristics with respect to speed were also apparent for this SAS configuration.

In the cruise flight mode at trim-level-flight airspeeds up to 200 knots, the longitudinal stick force per g unit was low but because of the 17 percent static margin, the aircraft was satisfactorily stable and had large stick-fixed maneuver gradients. The result of a windup turn at 175 knots is presented in figure 30. The static stability with respect to airspeed in the 200-knot speed range was judged by the pilots to be satisfactory.

Static Lateral-Directional Stability and Side-Force Characteristics

The static lateral-directional stability and side-force characteristics were investigated at trim-level-flight airspeeds of 42 knots, 100 knots, and 175 knots. The test technique used by the pilots was to slowly increase sideslip (1^{o} sideslip per second or less) from trim out to the maximum feasible sideslip in one direction, then from trim out to the maximum feasible sideslip in the opposite direction. Rudder-pedal releases from the sideslips were performed in some of the tests.

Static directional stability.- Static directional stability is indicated for airspeeds of 42 knots, 100 knots, and 175 knots in figures 31, 32, and 33, respectively. Rudder-pedal releases from sideslip were made at each of the three airspeeds with the yaw SAS off. When the aircraft was released from about a 15^{o} sideslip angle at 42 knots, it returned to near-zero sideslip (1/2 ball width by the sideslip indicator) in a definite but not a rapid manner (that is, in about 3 seconds) according to the pilots. Data for this test, however, are not shown. Rudder-pedal releases at 100 knots from right and left sideslips are presented in figures 34 and 35, respectively, and rudder-pedal releases at 175 knots from right and left sideslips are presented in figures 36 and 37, respectively. For these airspeeds, the pilots commented that the aircraft returned to within 1/2 to 1 ball width of trim sideslip in a definite manner but the aircraft could not be considered directionally "stiff" on the basis of these maneuvers. The rate of return to zero sideslip in these maneuvers tended to be independent of airspeed.

Effective dihedral.- The effective dihedral characteristics are presented for trim-level-flight airspeeds of 42 knots, 100 knots, and 175 knots in figures 38, 39, and 40, respectively. At 42 knots, the data in figure 38 indicate stable dihedral effect out to about 10^{o} of right sideslip and out to about 6^{o} of left sideslip; however, the data 2^{o} to 4^{o} beyond these points indicate that the dihedral effect tends to decrease at larger sideslip angles. At 100 knots, the data in figure 39 indicate that the effective dihedral was about neutral. At 175 knots, the data in figure 40 indicate that the dihedral effect was stable for the test range of sideslip angles. Pilot comment indicated that the dihedral effect at airspeeds of 42 knots, 100 knots, and 175 knots was satisfactory.

Side force.- The side-force characteristics in terms of bank angle as a function of sideslip angle are indicated in figures 41, 42, and 43 for airspeeds of 42 knots, 100 knots, and 175 knots, respectively. Pilot comment indicated that the side-force characteristics were satisfactory. In fact, for all test airspeeds, the pilots indicated that the directional stability, dihedral effect, and side-force characteristics were satisfactory and in good harmony.

Aerodynamic Coupling With Control Usage

At an airspeed of 42 knots and with the roll SAS on and the yaw SAS off, the aerodynamic coupling was not significant; that is, the adverse yaw due to a lateral-control step input and the adverse roll due to a directional-control step input, as indicated in figures 23 and 28, respectively, were satisfactorily low. With the roll SAS off (more rolling angular-velocity capability), the adverse yaw characteristics were still considered satisfactorily low as shown in figures 21 and 22.

At an airspeed of 100 knots with the yaw SAS off and roll SAS on, the direct roll-due-to-yaw and yaw-due-to-roll angular-velocity coupling with the use of controls was considered insignificant. Although little adverse yaw or sideslip developed in roll maneuvers (see fig. 24), it was found that when attempting to maintain zero sideslip, it was easy to overcontrol with the rudder pedals. The pedal forces were light, which is desirable in itself, but yaw control power and sensitivity seemed low and there was a tendency to overshoot sideslip for trim. With the yaw-rate SAS on, coarse use of the rudder pedals and large leg motions were required in establishing turns because of the initially high rate damping and the nonlinearity in control at the point of SAS saturation $\left(\frac{5^{\circ}}{\text{sec}}\text{ yaw rate}\right)$. The saturation rate was often exceeded in turns. Furthermore, an appreciable amount of continuous rudder-pedal displacement was required in steady turns.

At an airspeed of 175 knots, a pedals-fixed roll reversal was performed to evaluate the aerodynamic coupling characteristics with the yaw SAS off. A time history of this maneuver is presented in figure 44. The adverse yaw characteristics were considered satisfactorily low by the pilots. The lateral maneuvering characteristics were considered good by the pilots in terms of rudder-pedal displacement required for turn coordination. However, as for an airspeed of 100 knots, when attempting to achieve minimum sideslip in maneuvers, the pilot tended to apply too much rudder pedal, thus leading to mild overcontrolling which seemed to be caused by low yaw-control sensitivity, light rudder-pedal forces, and an apparently low degree of static directional stability. With the yaw-rate SAS on at 175 knots, coarse use of the rudder pedals and large leg motions were required in establishing turns because of the initially high yaw-rate damping and the nonlinearity in the yaw control produced at the point of SAS saturation. The saturation rate was often exceeded in turns at this airspeed and lower airspeeds. Furthermore, an appreciable amount of continuous rudder-pedal displacement was required in steady turns.

NOISE AND VIBRATION

Other tilt-wing aircraft have had higher than desirable noise and vibration levels. The noise level produced by the tilt-wing CL-84 in a hovering take-off and in hovering flight was judged by the NASA pilots to be acceptable from outside the aircraft and was comparable to the noise level produced by a C-47 airplane during take-off. The operating propeller speeds for hover, transition, and cruise flight were 1167 rpm (95 percent of design), 1043 rpm (85 percent of design), and 982 rpm (80 percent of design), respectively. The propeller tip speed was, accordingly, 855 ft/sec (260.6 m/sec) or a Mach number of 0.76 for a hovering take-off. In the cockpit during hover flight, the propeller noise was considered comfortably low with the major noise coming from inverters located behind the pilot compartment. Main-propeller-blade buzz occurred at low pitch and low power operation with the wing in the vertical position prior to lift-off. This buzz stopped when the power was increased for lift-off. Buzz was also encountered in flight at wing incidence angles between 15° and 40° at power for level flight and at a sideslip angle of 10° or more. In transition flight and in cruise flight, the noise levels were considered to be at satisfactorily low levels. The vibration levels in all modes of flight were also considered to be satisfactorily low.

RATE-OF-DESCENT CHARACTERISTICS

The purpose of the rate-of-descent investigation was to determine the usable descent rates for airspeeds typical of those that are used during a final landing approach. Experience from previous investigations of helicopters and test-bed V/STOL aircraft has indicated that a usable descent rate of about 1000 ft/min (5.08 m/sec) below an airspeed of 60 knots is a desirable minimum goal to provide the pilot with a 500-ft/min (2.54-m/sec) rate of descent for the intended glide path and a 500-ft/min (2.54-m/sec) rate-of-descent margin for capture and corrections to the glide path. For a steady 500-ft/min (2.54-m/sec) rate of descent, airspeeds between 40 knots and 60 knots result in glide-slope angles in still air conditions between about 7.5° and 4.5°.

The rate-of-descent characteristics of the CL-84 were investigated by starting at a longitudinally level fuselage attitude at trim-level-flight airspeeds of 100 knots, 50 knots, and 42 knots. The piloting technique used to investigate the descent included the establishment of steady trimmed level flight with a fuselage-level attitude and then the addition of power over that for level flight to alleviate possible stall hysteresis effects from previous flight conditions. Next, a slow reduction in power was initiated to produce a slowly increasing rate of descent, the initial trim speed being maintained. The objective was to determine limiting aerodynamic or stability and control characteristics under practically static descent conditions. The various limiting characteristics (for example, buffet onset, limit buffet, trim changes, the sudden onset of external rolling, yawing, or pitching motion, and static instabilities), if encountered in the descent, were noted by the pilot.

Rate-of-Descent Limits

100 knots.- The limiting indicated rate of descent at an airspeed of 100 knots was reached at about 1500 ft/min (7.62 m/sec). The pilot noted that at this rate of descent, the aircraft was experiencing mild buffeting and a well-defined nose-down trim change and roll-off to the right. These characteristics were not violent and possibly could have been controlled by coarse control usage. Since an indicated rate of descent of over 1000 ft/min (5.08 m/sec) was determined to be operationally usable, the descent characteristics were considered satisfactory for this airspeed and wing incidence.

50 knots.- At an airspeed of 50 knots, the limiting indicated rate of descent was reached at 1000 ft/min (5.08 m/sec). At this rate of descent, general airframe buffeting and a well-defined nose-down trim change and a roll-off to the right were noted. The indicated 1000-ft/min (5.08-m/sec) stall boundary limit established with this piloting technique for this airspeed was thought to result in a glide path that was too shallow. Steeper paths could, of course, be flown at the same wing incidence (30°) by accepting a nose-down attitude and a resulting increase in airspeed.

42 knots.- At an airspeed of 42 knots, very light sporadic buffeting was detected at an indicated 300-ft/min (1.52-m/sec) descent rate; at an indicated 500 ft/min (2.54 m/sec) descent rate, a light high-frequency continuous buffeting began; and at the limiting indicated rate of descent of about 700 ft/min (3.56 m/sec), the aircraft nosed down and rolled right in a moderate but definite manner with an accompanying moderate increase in buffeting and rate of descent. About 1000-ft/min (5.08-m/sec) maximum descent rate was indicated as power was applied for recovery. Although these longitudinal and lateral trim changes could have been controlled, continuous flight in this condition was not considered feasible. This indicated 700-ft/min (3.56-m/sec) rate-of-descent limit at a typical STOL airspeed of 42 knots does not appear to provide enough margin for operational use.

Low Normal-Velocity Damping in Descent

Flight results.- During a descent to a landing at a 42-knot airspeed, an attempt was made to establish a steady-state indicated rate of descent of 500 ft/min (2.54 m/sec) so as to allow a reasonable margin from the previously determined indicated 700-ft/min (3.56-m/sec) limit boundary. After a few seconds during which attention was on other matters in the cockpit and in checking position in the landing pattern it was noted that the aircraft was nosing over and rolling off with mild buffeting and had attained an indicated rate of descent which was much higher than was initially established. No buffeting as an indication of stall had been apparent to the pilot prior to the nosing over and rolling off. During recovery with power, the altitude tended to return to its initial value, thus negating the attempt at descent. After several successive similar attempts to establish an indicated 500-ft/min (2.54-m/sec) descent rate at a constant power setting, it was finally determined that the indicated rate of descent could not be allowed to exceed about 300 ft/min (1.52 m/sec) if the tendency toward excessive settling was to be avoided. This indicated 300-ft/min (1.52-m/sec) limitation may well be related to the light sporadic buffeting encountered at this rate of descent in trials at altitude. This sporadic buffeting, as insignificant as it seemed, may be associated with flight near maximum lift, and the increased settling may indicate flight beyond the peak of the lift curve. It is probable that small maneuvers or rough air may help precipitate the settling. An indicated rate of descent could be maintained between 300 and 700 ft/min (1.52 and 3.56 m/sec) if frequent adjustments to the power control lever were made.

A time history which illustrates this flight characteristic is presented in figure 45. The descent maneuver was preceded by establishing trim with power for level flight at a 42-knot airspeed. The airspeed for this trim condition was thereafter held constant. As discussed previously, the maneuver was begun with power increased over that for level flight (thus producing a climb) as a precaution to eliminate possible stall hysteresis effects from prior flight conditions. Then a slow decrease in power was initiated to produce an increase in rate of descent, the object being to approximate static conditions for any one power condition. The pilot apparently was concentrating on maintaining a slow increase in rate of descent since the power was found to have been held fixed following attainment of a 300-ft/min (1.52-m/sec) indicated rate of descent. Although the power was held constant for the next 7 to 8 seconds, the indicated rate of descent did not stabilize and continued to increase until buffeting and nose and wing drop occurred. Power was then added to recover from the run. At the time of recovery, an indicated rate of descent of 850 ft/min (4.32 m/sec) had been reached. In figure 45, the normal acceleration time history, occurring within the same time interval in which the power lever remained fixed $\left(9\frac{3}{4}\right.$ seconds to about 16 seconds$\left.\right)$, indicates that the aircraft was slowly returning to 1g flight. This slow stabilization of rate of descent indicates a low value of normal-velocity damping. This characteristic, which occurred at moderate indicated descent rates, could make glide-path control difficult during instrument flight, and augmentation may be required to attain a satisfactory level of normal-velocity damping. Instrument approach studies with V/STOL aircraft have indicated generally that the time constant for normal-velocity response to a power change should be 3 seconds or less to be satisfactory. The aircraft fuselage angle of attack indicated in the time history is thought to be high because of the upwash induced by the propellers and wing. Flight-path angles calculated from the airspeed and indicated rates of descent recorded seem to agree roughly with pilot visual impressions when near the ground.

Discussion.- Pertinent data are presented in reference 3 for a wing-propeller model configuration similar to this aircraft. Examination of these data indicates that a portion of the descent envelope for this model is characterized by negative values of lift-curve slope and rapidly increasing induced drag which result in a nearly constant resultant force. It is thought that these characteristics can lead to low or even negative normal-velocity damping.

STOL OPERATIONS

In a limited number of STOL approaches and landings, the final approaches were flown at an airspeed of 42 knots to a preselected touchdown spot. The descent angles were limited to an indicated descent rate of 300 ft/min (1.52 m/sec), thought necessary for accuracy of control, and were judged to be less than 5° into about a 13-knot wind. While the actual value of descent rate may have been appreciably different from the indicated value, due to instrument lag, it was the pilot's impression that the available descent limits were not adequate for an operational aircraft, particularly for steep gradient instrument flight. Within the 300-ft/min (1.52-m/sec) indicated rate-of-descent limit, thought necessary for accuracy, the flight path could be very accurately controlled. Within the region of suck-down below a 20-foot (6.1-m) altitude, there was a nose-down trim change which could be readily controlled. The aircraft also seemed to accelerate forward in this region. As a result, there was a strong tendency to pull the nose up above level.

During the STOL landings, the aircraft could be easily held in the level attitude through touchdown. On the first landing, the throttle was moved forward at a rate thought to compensate for the suck-down. However, a surge of power occurred that caused the aircraft to rebound. Later, the records showed that the bleed band on one engine had closed at this point causing a 7-percent step increase in power. On the second landing a small step increase in power was made as suck-down was entered and the aircraft made ground contact in a positive but very satisfactory manner in level attitude with minor controlling. The power lever was immediately pulled to ground idle to provide strong braking. Combined with wheel brakes, this action led to a landing roll which was no more than 50 feet (15.2 m). These STOL landing characteristics were judged to be good. During the STOL approaches and landings, no lateral or directional excursions occurred.

The STOL take-off was very easy and the take-off distance was short. With wing incidence set at about 40°, the power was increased until brake slippage was imminent and then the remaining power was added as the brakes were released. The aircraft became airborne quickly with little controlling required.

The landing-gear characteristics of the aircraft were judged to be very good although nose-wheel steering would be desirable. The gear was very stable during ground roll, yet the aircraft could be steered readily with brakes. Shock absorption was good, and gear flexibility was adequate to check the functioning of the controls on the ground and to trim the aircraft laterally to some extent for side winds (for example, during take-off).

CONCLUDING REMARKS

An abbreviated flight-test evaluation of a second-generation tilt-wing V/STOL aircraft, the Canadair CL-84, was conducted to ascertain possible problem areas. In general, based on the limited evaluation possible, most of the flying qualities in the hover, transition, and cruise modes of flight were considered good. However, an indicated rate-of-descent limit of 700 ft/min (3.56 m/sec), defined by loss of control due to stalling, at a typical STOL airspeed of 42 knots did not appear to provide enough margin for ultimate operational use. Furthermore, low normal-velocity damping was encountered at about 40 knots airspeed at indicated rates of descent desirable for operational use. This characteristic appeared as a prolonged increase in rate of descent following a small power reduction, and is thought to be significant for instrument flight. According to pilot observations and the time histories, this characteristic occurred with power settings for initial indicated rates of descent as low as 300 ft/min (1.52 m/sec). Buffeting was not always apparent to the pilot as excessive sink rates developed and, in several descents at altitude, the first indications of approach to limiting stalling were pitch-down and roll-off that occurred at an indicated rate of descent of about 700 ft/min (3.56 m/sec). This behavior may be related to aerodynamic characteristics at angles of attack near maximum lift.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., August 15, 1969.

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TABLE I.- PHYSICAL CHARACTERISTICS OF TEST AIRCRAFT

Main propellers:	
Diameter, ft (m)	14 (4.27)
Number of blades (each propeller)	4
100 percent design operating speed, rpm	1228
Distance between rotor axes, ft (m)	20.67 (6.3)
Blade-angle travel (at 0.75 radius), deg	5 to 45
Wing:	
Span, ft (m)	33.33 (10.16)
Chord, ft (m)	7.0 (2.13)
Airfoil section	Modified NACA 63_3-418
Taper ratio	1
Sweep, deg	0
Dihedral, deg	0
Tilt range, deg	0 to 100
Tilt rates, deg/sec –	
High rate up	17 5
Normal rate up (max)*	6
Normal rate down (max)*	12
Pivot, percent chord	46.0
Ailerons (flaps):	
Chord, ft (m)	2.1 (0.64)
Type (flaps)	Full-span, single-slotted
Differential travel (for hover yaw control), deg –	
Up	20
Down	20
Travel in airplane flight (for roll control), deg –	
Up	12
Down	12
Travel as flaps, deg	0 to 25
Leading-edge flaps	
Type	Krueger
Wing incidence for outer leading-edge flap extension, deg –	
Wing moving upward	12
Wing moving downward	70
Wing incidence for outer leading-edge flap retraction, deg –	
Wing moving upward	75
Wing moving downward	10
Wing incidence for center leading-edge flap extension, deg	23 to 100
Longitudinal-control propellers:	
Type	Coaxial, counter-rotating
Number of blades (each propeller)	2
Diameter, ft (m)	7 (2.13)
100 percent design operating speed, rpm	2125
Moment arm about wing pivot, ft (m)	21 7 (6.62)
Blade-angle travel (at 0.70 radius), deg	-7 to 23

*The normal wing-up rate of 6°/sec and wing-down rate of 12°/sec are programed to vary with wing position; that is, the wing-up rate increases at a constant rate from 2.36°/sec to 6°/sec between the wing positions of 5° and 45°, and the wing-down rate decreases at a constant rate from 12°/sec to 2.36°/sec between the wing positions of 45° and 5°

TABLE I.- PHYSICAL CHARACTERISTICS OF TEST AIRCRAFT - Concluded

Power plants	
Type	Lycoming LTC1K-4A (free turbine)
Number of engines	2
Maximum output power (shaft horsepower), hp (kW)	1400 (1044)
Normal rated power (shaft horsepower), hp (kW)	1150 (858)
Control travel	
Rudder pedals, in. (cm) -	
Right	3 (7.62)
Left	3 (7.62)
Longitudinal stick, in. (cm) -	
Forward	3 (7.62)
Rearward	5 (12.7)
Lateral stick (approximate), in. (cm) -	
Right	5 (12.7)
Left	5 (12.7)
Power lever, in. (cm)	6.5 (16.5)
Control force characteristics	
Gradients, lbf/in. (N/cm) -	
Rudder pedals	7 (12.25)
Longitudinal stick	2 (3.50)
Lateral stick	2 (3.50)
Breakout, lbf (N) -	
Rudder pedals	3 (13.34)
Longitudinal stick	0.5 (2.22)
Lateral stick	0.5 (2.22)
General airframe	
Gross weight, lbf (N) -	
VTOL	11 200 (49 800)
STOL	14 700 (65 400)
Span, ft (m) -	
Wing	33.33 (10.16)
Horizontal tail	16.66 (5.08)
Maximum width over propeller tips, ft (m)	34.66 (10.56)
Overall length (tip of nose probe to tip of tail propeller), ft (m)	47.29 (14.4)
Height over propeller spinners (wing tilted 90°), ft (m)	17.13 (5.22)
Control-surface travel (those not given previously):	
Rudder, deg -	
Left	25
Right	25
Elevator, deg -	
Up	25
Down	25
Horizontal stabilizer, deg	0 to 45

TABLE II.- AIRCRAFT CONTROL AND STABILITY PARAMETERS IN HOVER

[a][Information provided by manufacturer]

	Yaw	Roll	Pitch	Height
Inherent rate damping	$0.4\ \frac{rad/sec^2}{rad/sec}$	$0.6\ \frac{rad/sec^2}{rad/sec}$	$0.4\ \frac{rad/sec^2}{rad/sec}$	$0.12\ \frac{ft/sec^2}{ft/sec}$ $\left(0.12\ \frac{m/sec^2}{m/sec}\right)$
Artificial rate damping	[b]$1.8\ \frac{rad/sec^2}{rad/sec}$	[c]$2.4\ \frac{rad/sec^2}{rad/sec}$	[d]$3.6\ \frac{rad/sec^2}{rad/sec}$	------------
Total rate damping	$2.2\ \frac{rad/sec^2}{rad/sec}$	$3.0\ \frac{rad/sec^2}{rad/sec}$	$4.0\ \frac{rad/sec^2}{rad/sec}$	$0.12\ \frac{ft/sec^2}{ft/sec}$ $\left(0.12\ \frac{m/sec^2}{m/sec}\right)$
Artificial attitude stiffness	--------------	--------------	[d]$1.8\ \frac{rad/sec^2}{rad}$	------------
SAS saturation level	5^o/sec	15^o/sec	11^o/sec and 13^o attitude	------------
SAS authority, average	33%	32%	51%	------------
Primary control power	$\pm 0.47\ \frac{rad}{sec^2}$	$\pm 1.80\ \frac{rad}{sec^2}$	$\pm 1.35\ \frac{rad}{sec^2}$	Up to 1.2g
Control sensitivity	[e]$0.21\ \frac{rad/sec^2}{in.}$ $\left(\pm 0.06\ \frac{rad/sec^2}{cm}\right)$	$\pm 0.36\ \frac{rad/sec^2}{in.}$ $\left(\pm 0.14\ \frac{rad/sec^2}{cm}\right)$	$\pm 0.41\ \frac{rad/sec^2}{in.}$ $\left(\pm 0.16\ \frac{rad/sec^2}{cm}\right)$	±0.2 g/in (±0.08 g/cm)

[a]Parameters based on 100% propeller speed.

[b]Yaw SAS operates through propellers only (small pitch range) in cruise flight mode

[c]Roll SAS is fully active throughout transition flight mode

[d]Pitch SAS is off when the tail rotor is stopped. Pitch SAS has a single attitude channel, but dual rate channels If one rate channel should fail, the remaining one doubles its gain so that full rate authority is retained. The authority reduces as wing incidence is reduced.

[e]The yaw control sensitivity is nonlinear, with the last 35 percent of the pedal travel providing essentially no additional control power

TABLE III.- PILOT RATINGS AND COMMENTS

(a) Detailed aircraft characteristics

Flight mode	Factor	Cooper rating	Basis for rating
Hover	Height control	3	Mechanical characteristics and response
	Thrust/weight = 1.1	4	Gross maneuvering flight near hover
	Hover above 15 ft (4.57 m)	2	Maintains steady position in gusts; low vibration level
	Lateral oscillation, SAS off	5	Rapid divergence; possible pilot-induced-oscillation coupling with sideslip
	Roll SAS saturation	5	Violent roll recovery from translation
	Longitudinal oscillation, SAS off	4	Moderate divergence
	Roll maneuver:		
	SAS on	4	Sluggish for maneuvers
	SAS off	2	Good; little overshoot, detectable lag
	Pitch maneuver:		
	SAS on (attitude and rate)	2 (nose-down) 4 (nose-up)	Initially good, then sluggish nose-up
	SAS rate on (attitude off)	2	Good with no overshoot
	SAS off	5	Wobbly; tendency to get out of phase (pilot-induced oscillation)
	Yaw maneuver:		
	SAS on	5	Coarse leg motion required
	SAS off	4	
	Yaw disturbances	$1\frac{1}{2}$	Nearly nonexistent from gusts or recirculation
	Yaw trim capability	4	10% control remaining at 50° to 60° heading out of winds of 22 knots with gusts to 31 knots
	Wing-tilt rate:		
	Downward	2	
	Upward	4	Slow for use as primary control near hover
Accelerating conversion	Longitudinal trim changes	$1\frac{1}{2}$	Minor corrections required by pilot
	Performance	$1\frac{1}{2}$	Quick; easy to perform; altitude gained
Airplane flight	Overall	$2\frac{1}{2}$	
	Longitudinal response	2	Good with no overshoot
	Rolling response:		
	SAS on	4	Sluggish
	SAS off	1	Excellent; no overshoot
	Turns and reversals:		
	Yaw SAS on	5	Large leg motions required
	Yaw SAS off	2	Little adverse sideslip
	Rudder in steady turns, SAS on	4	Large pedal displacements
Decelerating conversion	Trim changes	$1\frac{1}{2}$	Minor
	Ballooning, 0° to 40° wing incidence	4	Cannot do at maximum rate and maintain altitude

TABLE III.- PILOT RATINGS AND COMMENTS - Continued

(a) Detailed aircraft characteristics - Concluded

Flight mode	Factor	Cooper rating	Basis for rating
Transition flight (15° and 30° wing incidence)	Longitudinal response:		
	SAS on (attitude and rate)	4	Good initial response, then sluggish
	SAS rate on (attitude off)	$1\frac{1}{2}$	
	Longitudinal stability in turns	3	Full SAS or rate only on
	Rolling response:		
	SAS on	4	Sluggish
	SAS off	$1\frac{1}{2}$	Very good; little overshoot
	Turns and reversals:		
	Yaw SAS on	5	Large adverse sideslip
	Yaw SAS off	2	Low adverse sideslip
	Roll due to yaw	$1\frac{1}{2}$	Very little
	Longitudinal trim change with power	$1\frac{1}{2}$	Small and in correct direction (nose-down with reduced power)
	Descent boundary:		
	At 15°	3	Stall limit not restrictive
	At 30°	4	Rate of descent at stall boundary restrictive for initial approach descent
Transition flight (40° wing incidence)	Longitudinal response:		
	SAS on	3	
	SAS rate on (attitude off)	2	
	All SAS off	$4\frac{1}{2}$	Longitudinal instability after about 10° nose-up attitude
	Longitudinal stability in turns	$3\frac{1}{2}$	Positive but low up to 30° bank angle
	Longitudinal stability with speed, SAS off	6	Imminent loss of forward pitch control below trim speed
	Rolling response:		
	SAS on	4	Sluggish
	SAS off	2	Very good
	Turns and reversals, yaw SAS off	2	Little adverse sideslip
	Roll due to yaw roll SAS on	2	Little direct coupling
	Longitudinal trim change with power	$1\frac{1}{2}$	Small and in correct direction (nose-down with reduced power)
	Descent stall boundary	5	Not sufficient operationally for STOL mode, particularly instrument flight
	Slow arrest of descent rate (Rate of descent ≧ 300 ft/min (1.52 m/sec))	6	Poor for glide-path control in STOL mode, particularly instrument flight
STOL operations	Landing (Rate of descent ≦ 300 ft/min (1.52 m/sec))	3	
	Take-off	2	
	Landing-gear characteristics	2	

TABLE III.- PILOT RATINGS AND COMMENTS – Concluded

(b) Overall aircraft characteristics

Factor	Cooper rating
Noise:	
VTOL, 95% propeller speed (outside)	[a]$3\frac{1}{2}$
VTOL, 95% propeller speed (inside)	3
Airplane, 80% to 85% propeller speed	2
STOL, 85% propeller speed	$2\frac{1}{2}$
Vibration:	
VTOL	2
Airplane	2
STOL	2
Control forces (hover and low speed)	2
Control sensitivity (initial acceleration per unit of displacement):	
Roll and pitch	2
Yaw	4
Height	3

[a]Level of C-47 on take-off.

TABLE IV.- COOPER PILOT-OPINION RATING SYSTEM

Operating conditions	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[a]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[a]	No	Doubtful
		8	Unacceptable – dangerous	No	No
		9	Unacceptable – uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

[a]Failure of a stability augmenter.

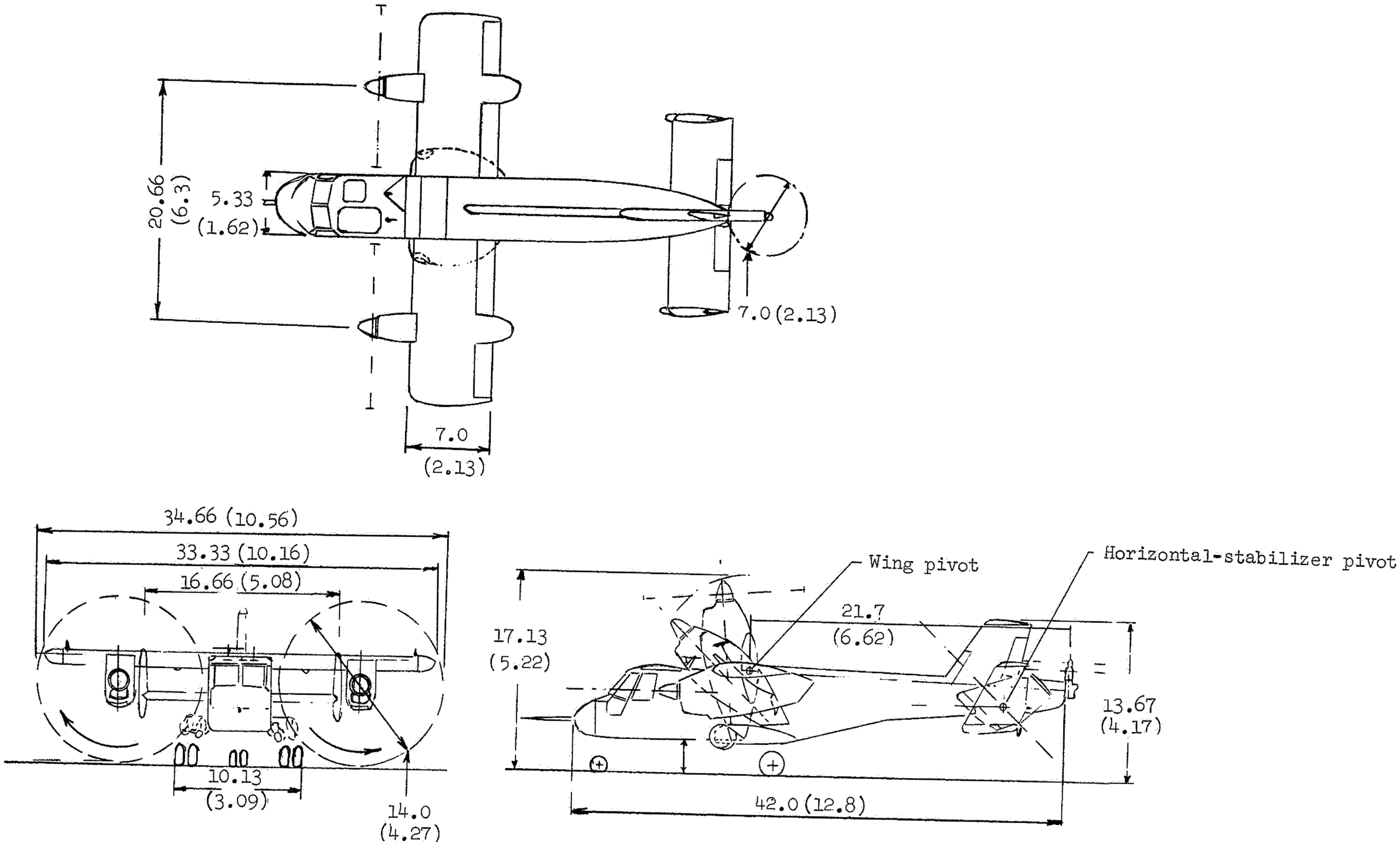

Figure 1.- Three-view sketch of tilt-wing V/STOL test aircraft. Dimensions are given in feet and parenthetically in meters.

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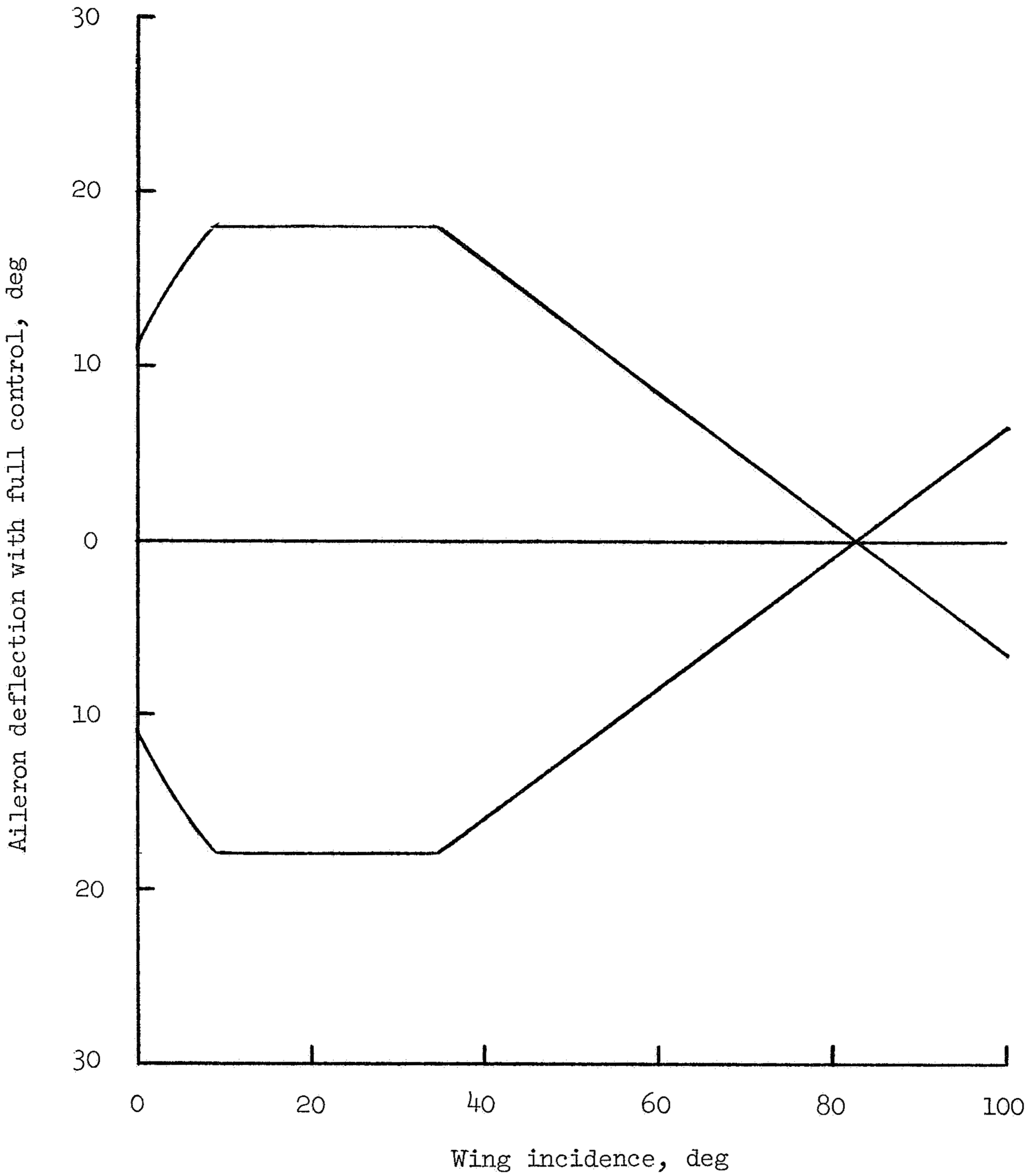
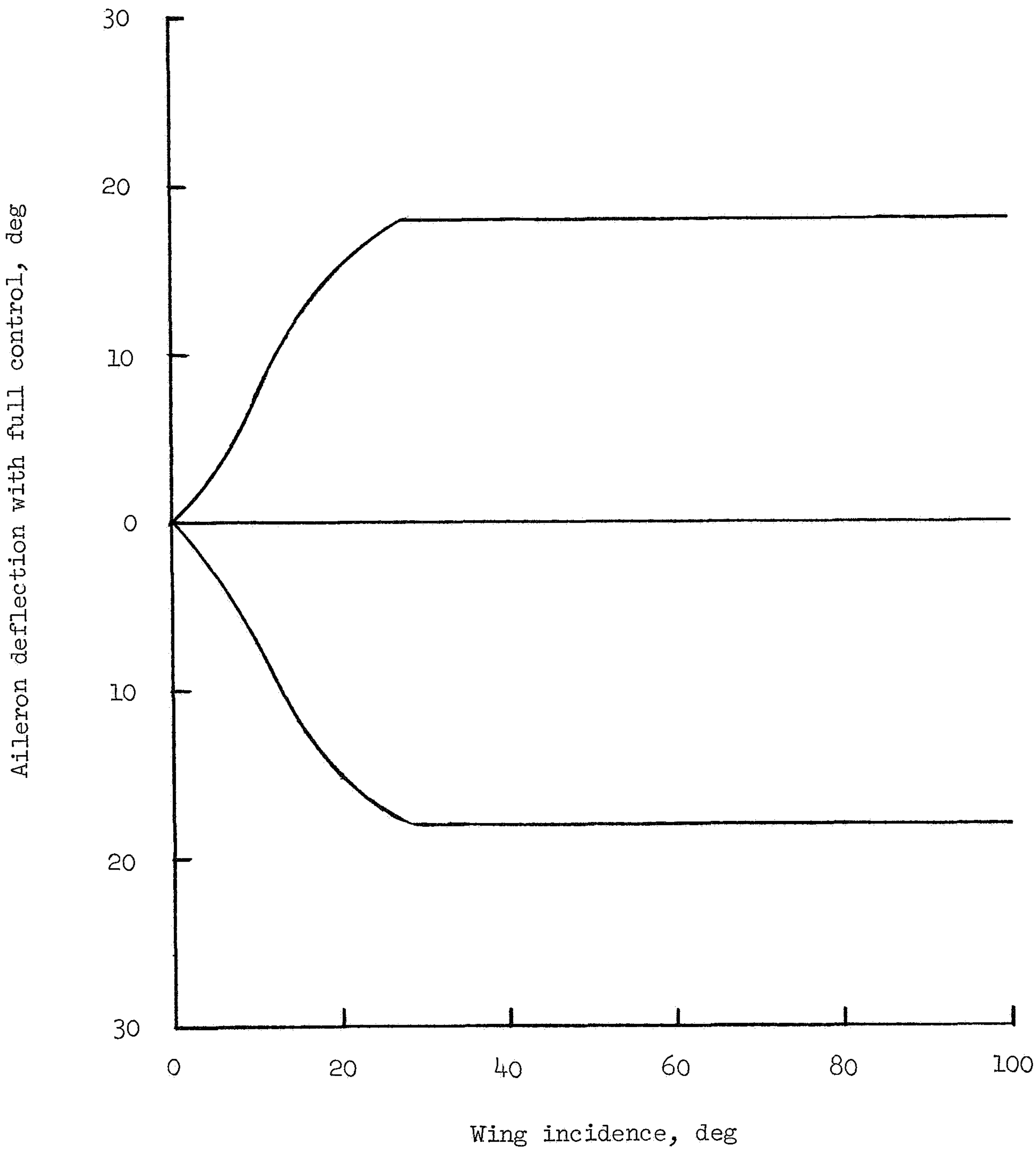
Figure 2. In-flight photograph of test aircraft in transition flight mode.



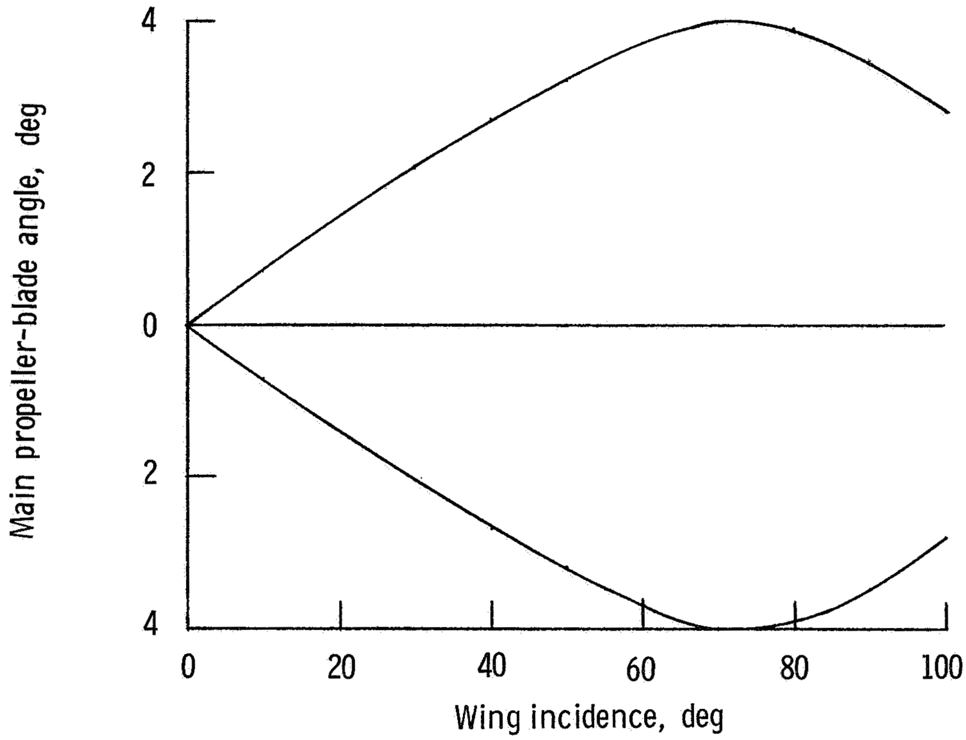
(a) Aileron deflection with full lateral stick.

Figure 3.- Program of aileron with wing incidence.

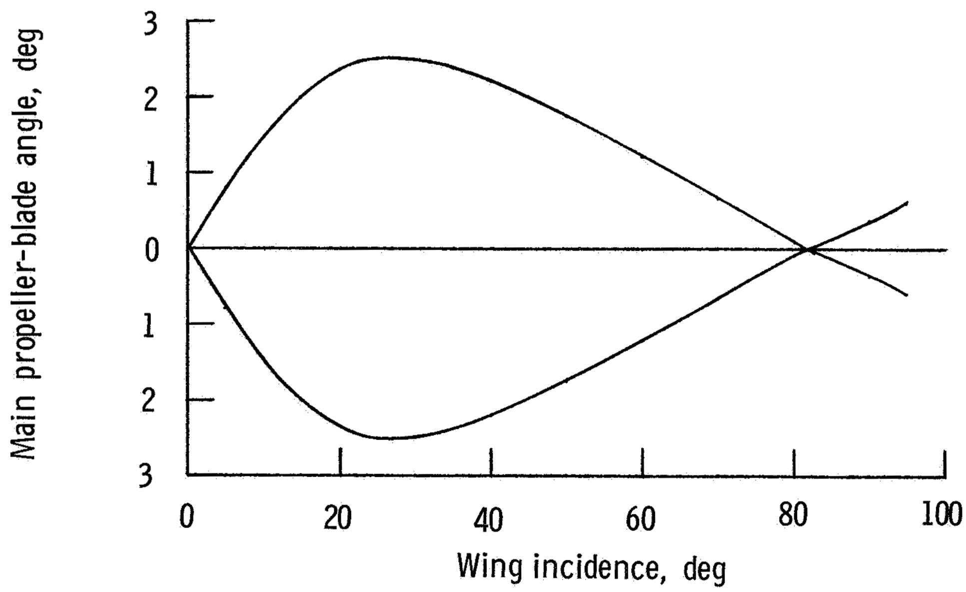


(b) Aileron deflection with full rudder pedal.

Figure 3.- Concluded.

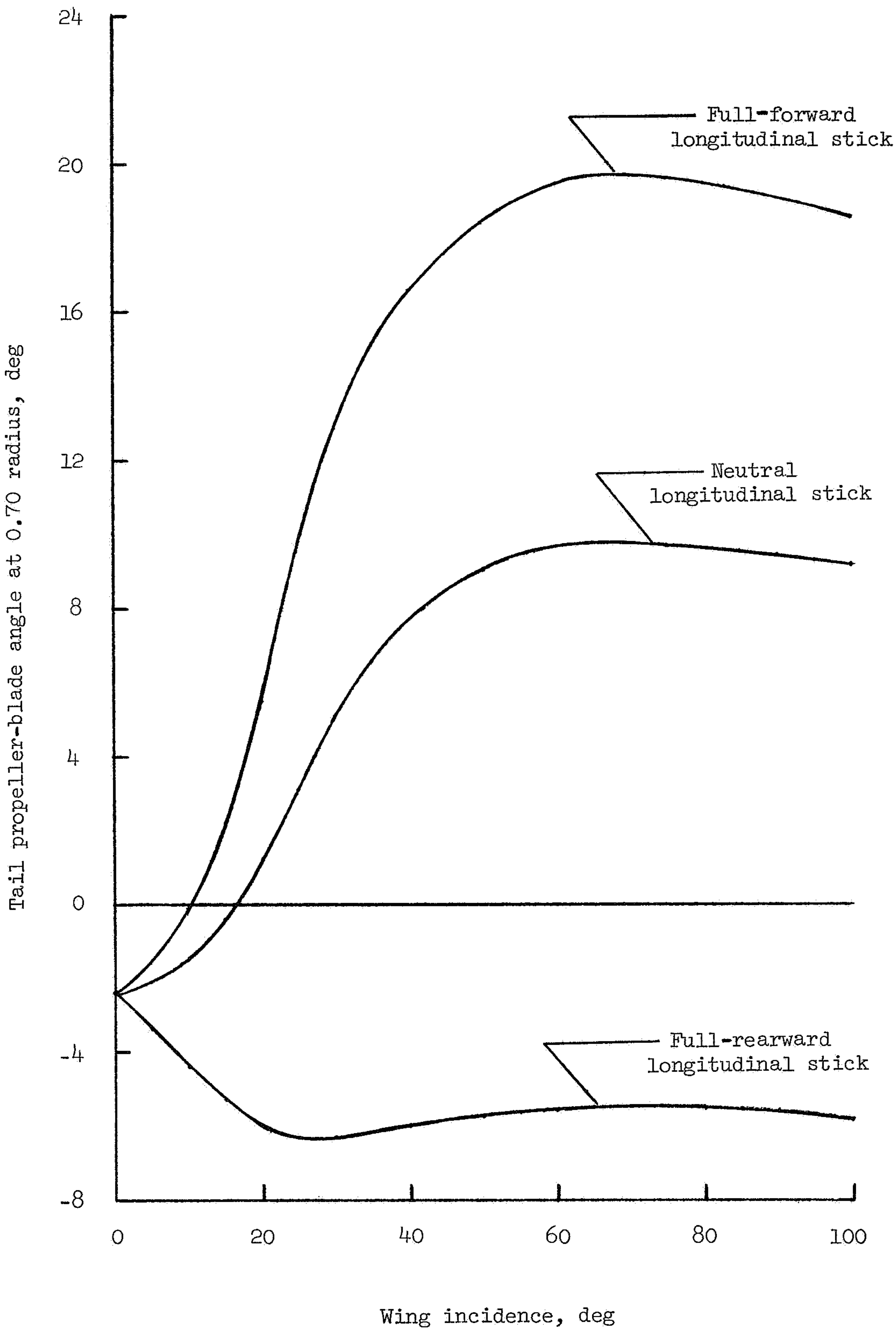


(a) Differential blade angle with full lateral stick.



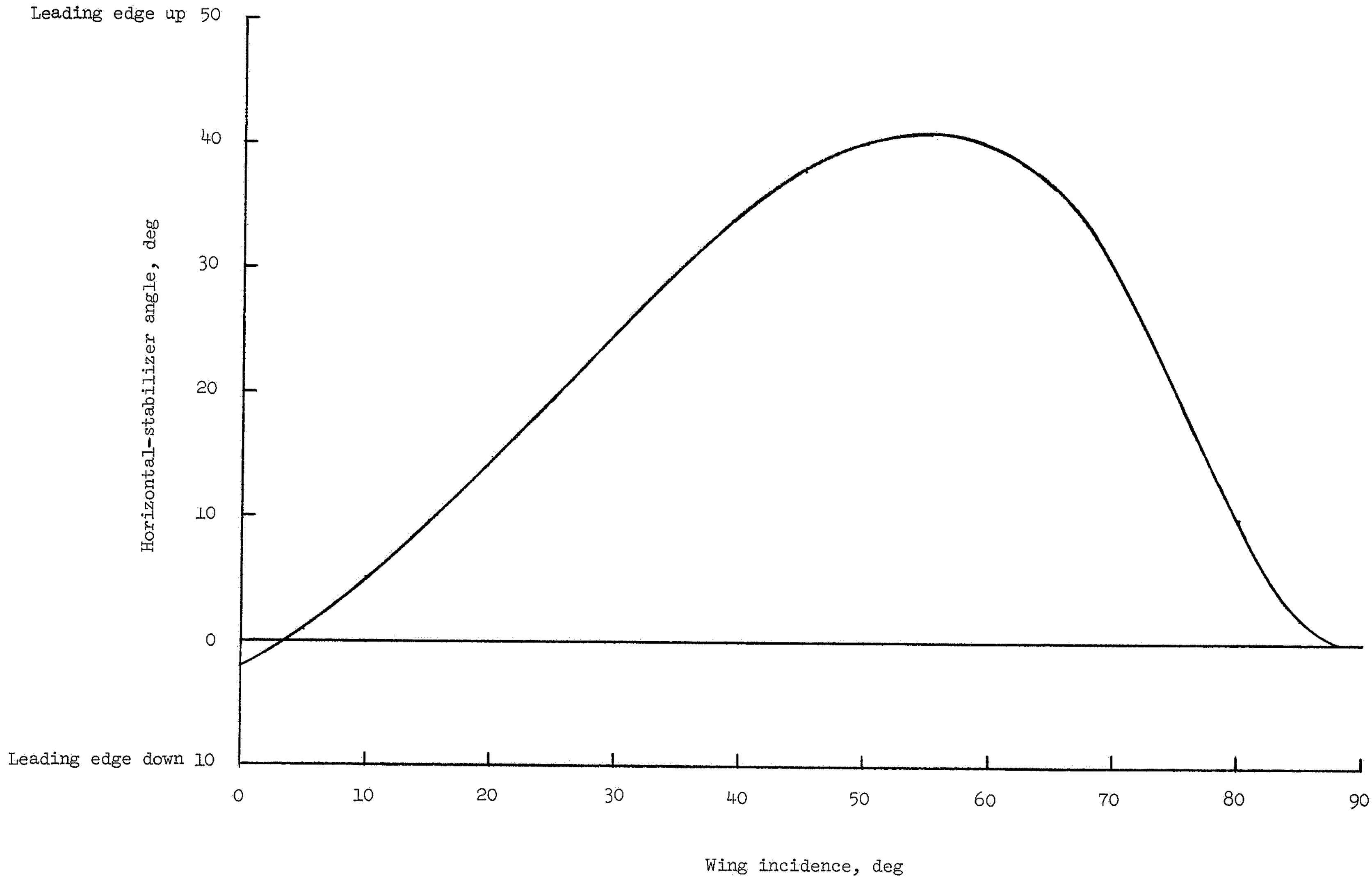
(b) Differential blade angle with full rudder pedal.

Figure 4.- Program of differential propeller-blade angle with wing incidence.



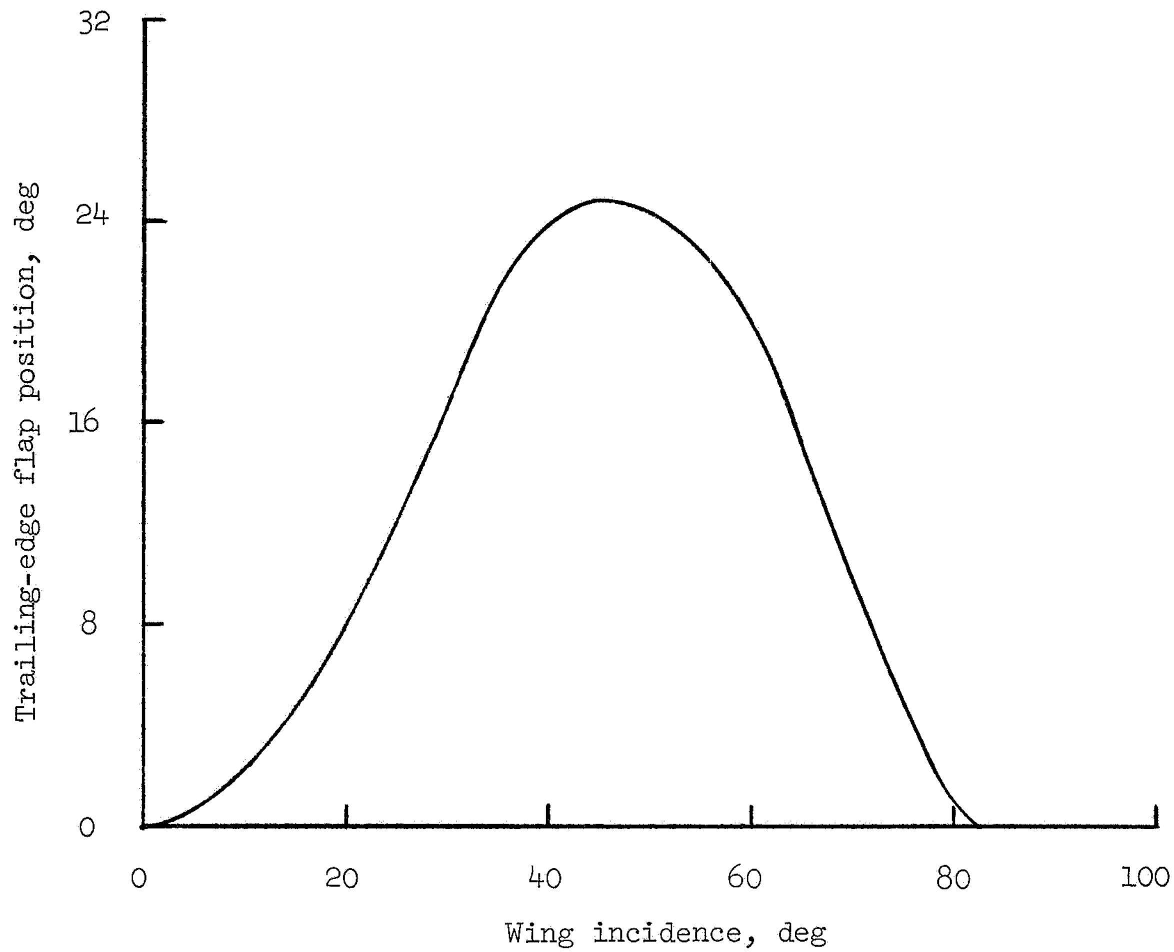
(a) Propeller-blade angle.

Figure 5.- Program of tail propeller-blade angle, horizontal stabilizer, and trailing-edge flap with wing incidence.



(b) Horizontal stabilizer

Figure 5.- Continued.



(c) Trailing-edge flap.

Figure 5.- Concluded.

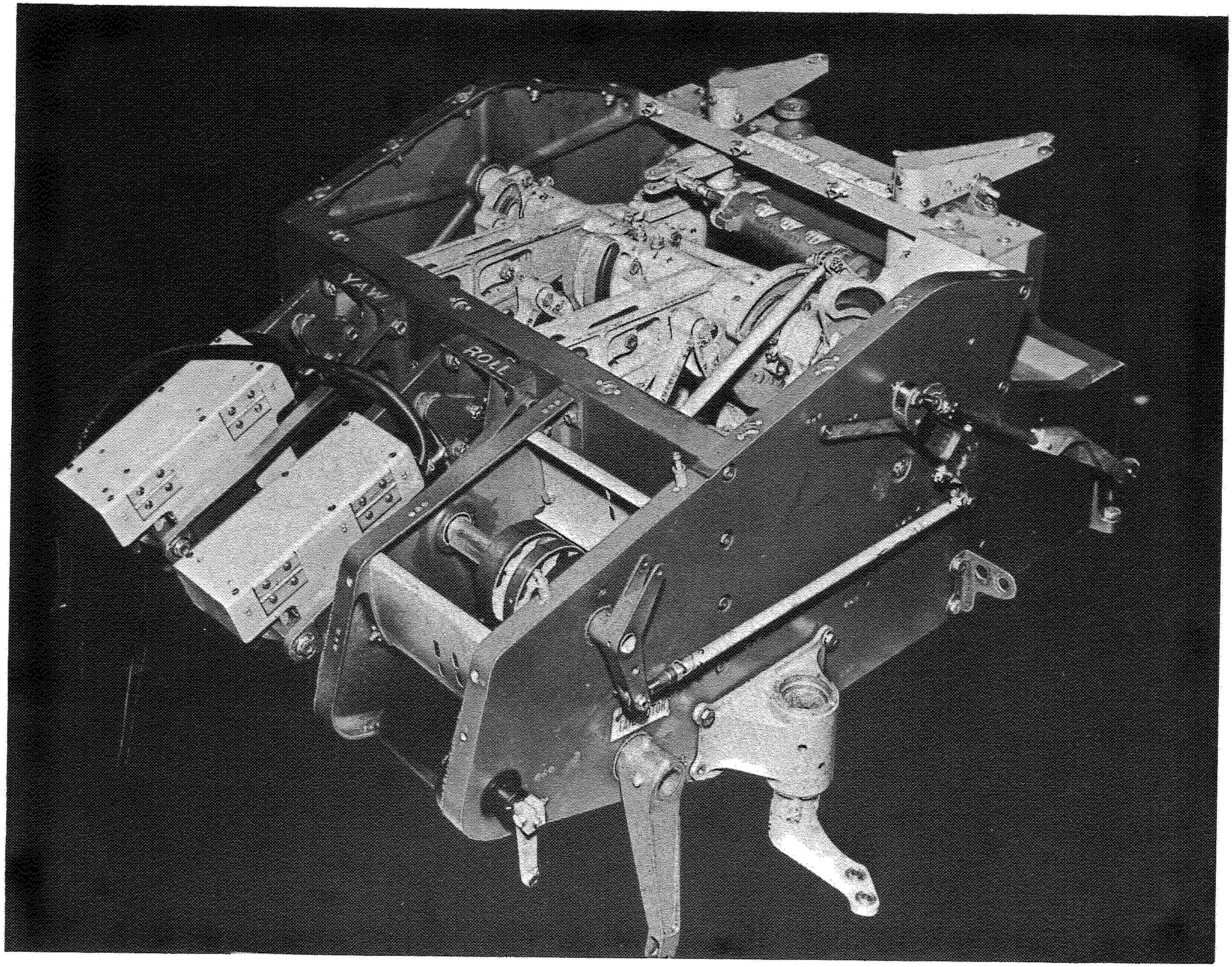


Figure 6.- Photograph of controls mixing unit.

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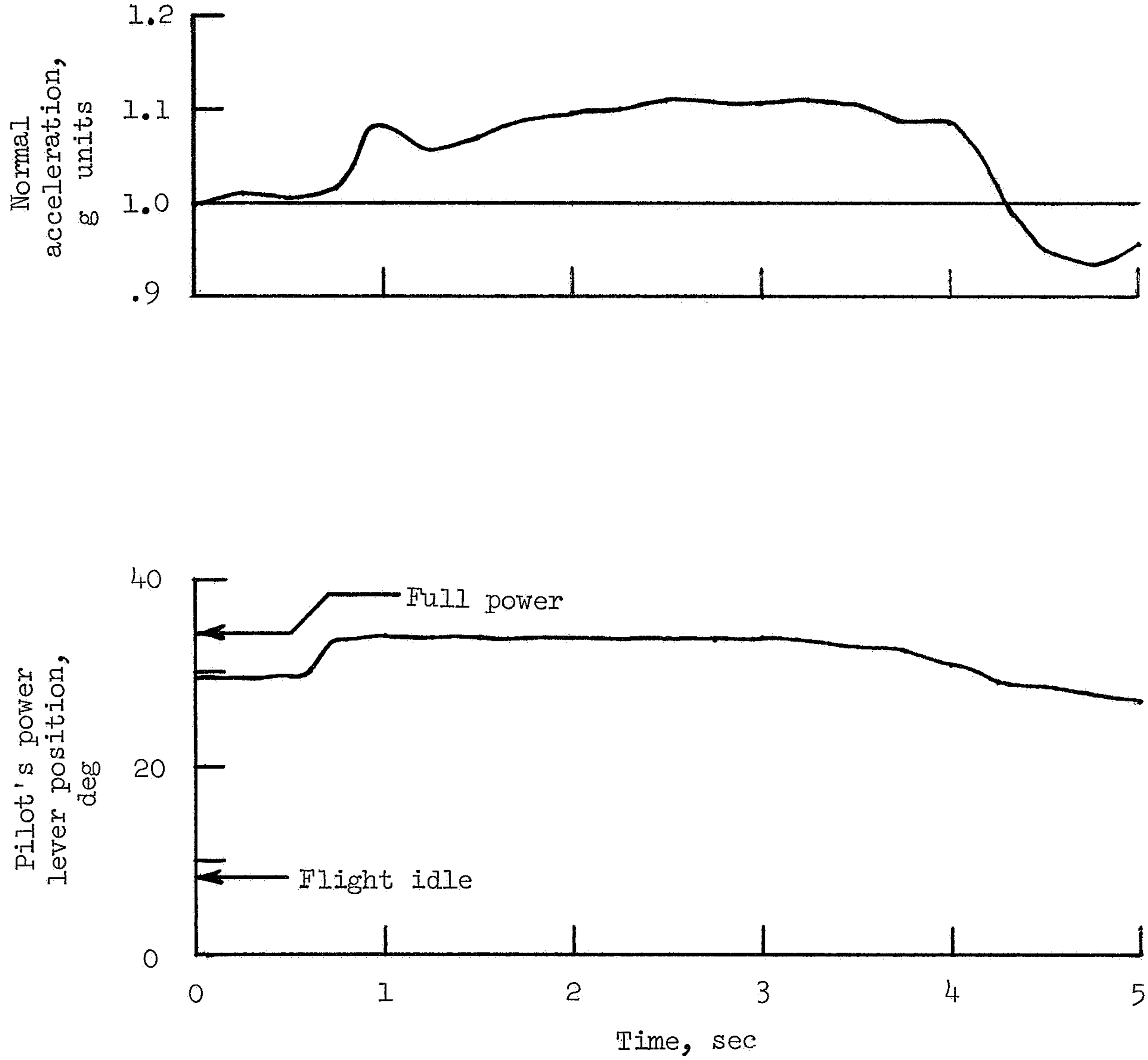

Figure 7.- Time history of throttle-control step input in hovering flight. Wing incidence of 79.4°

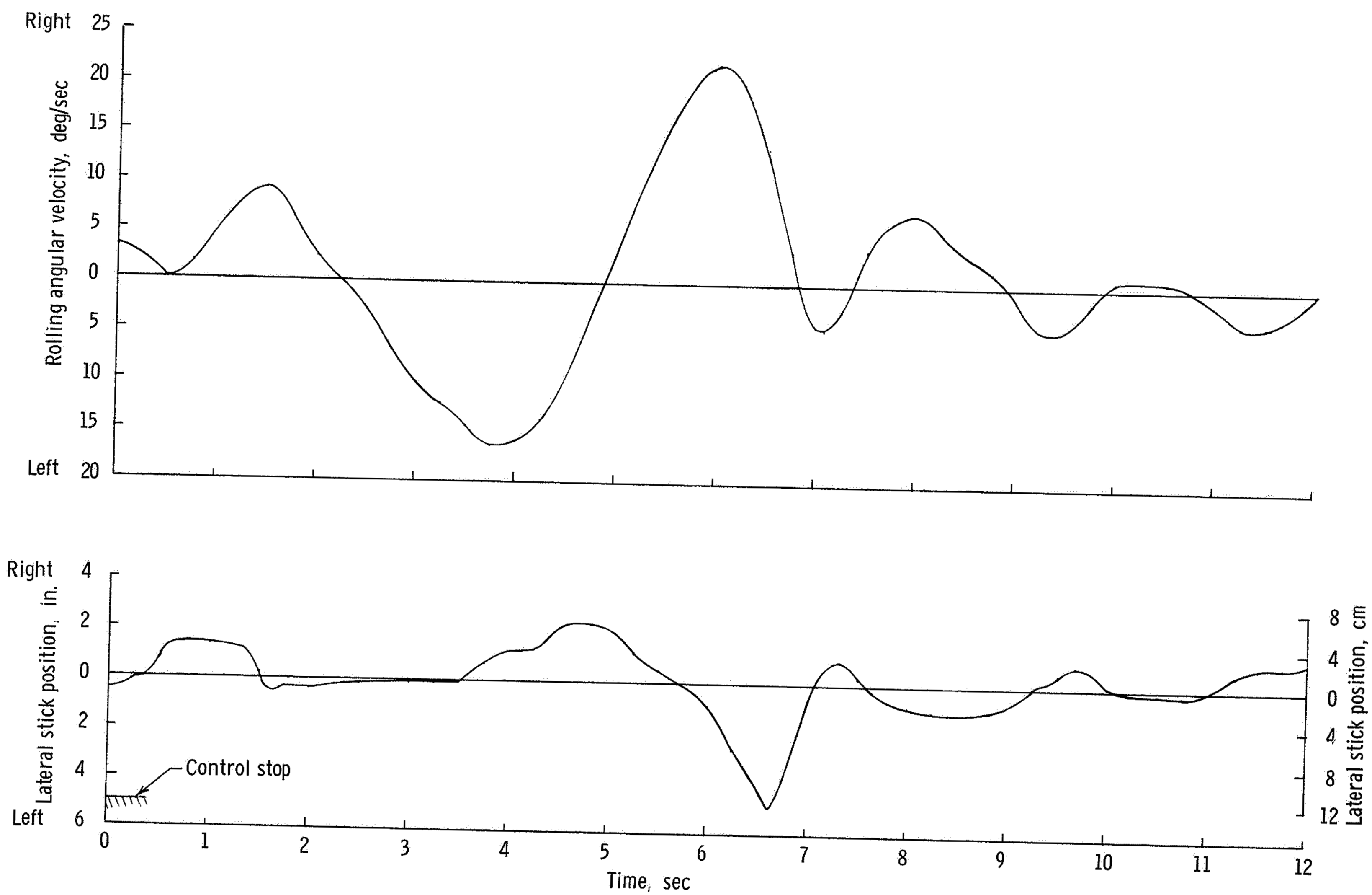

Figure 8.- Time history of lateral-control pulse input in hovering flight with roll SAS off. Wing incidence of 79.4°

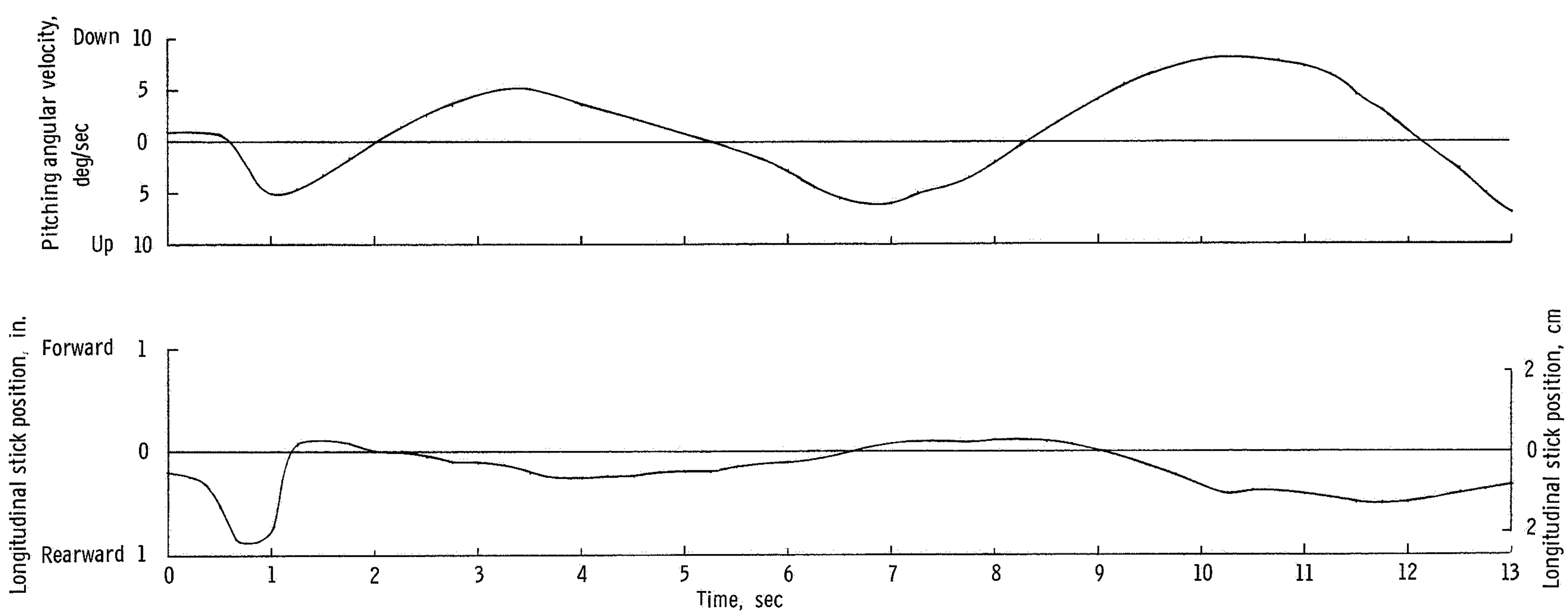

Figure 9.- Time history of longitudinal-control pulse input in hovering flight with pitch SAS off. Wing incidence of 79.4°

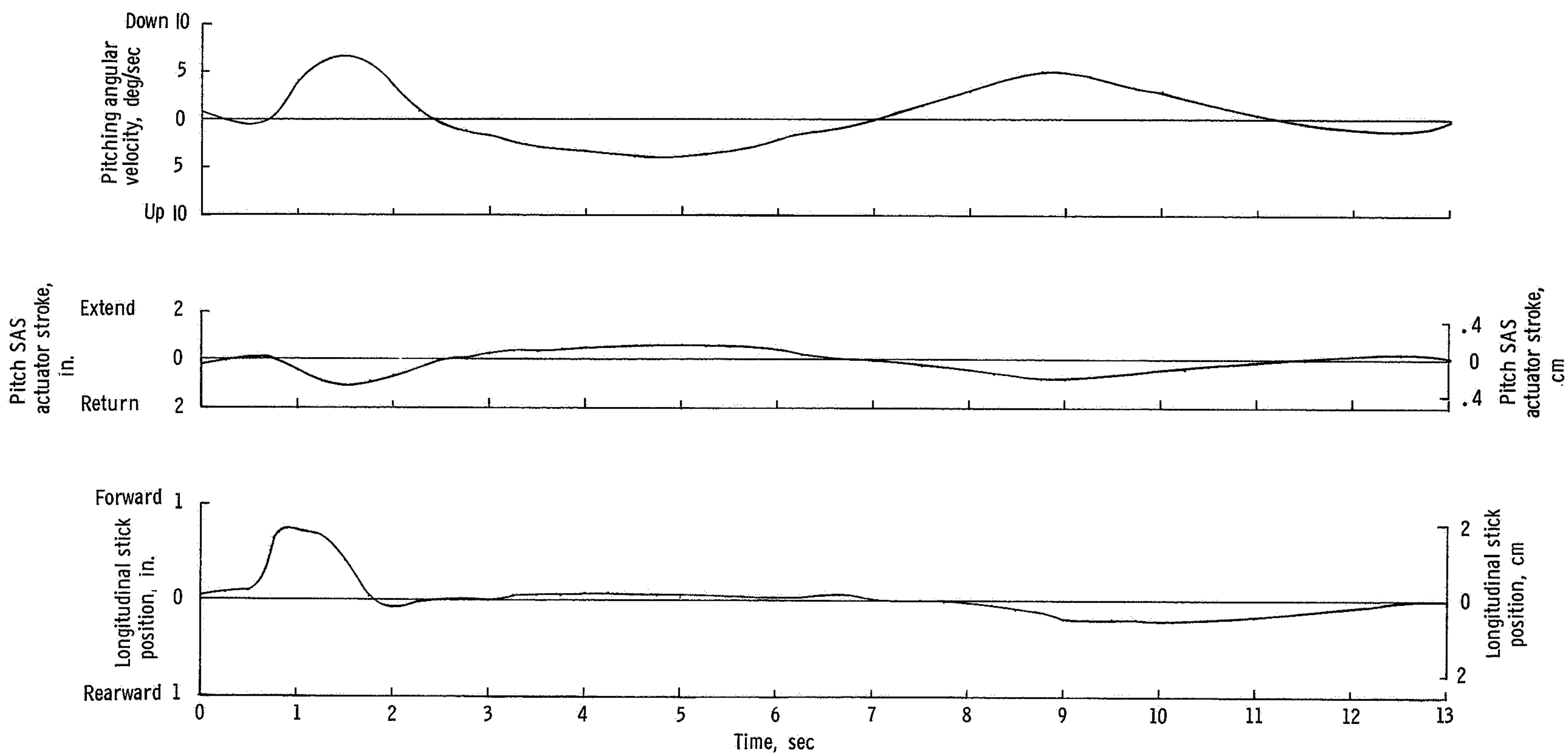

Figure 10.- Time history of longitudinal-control pulse input in hovering flight with 40 percent rate damping and attitude SAS off Wing incidence of 79.4°

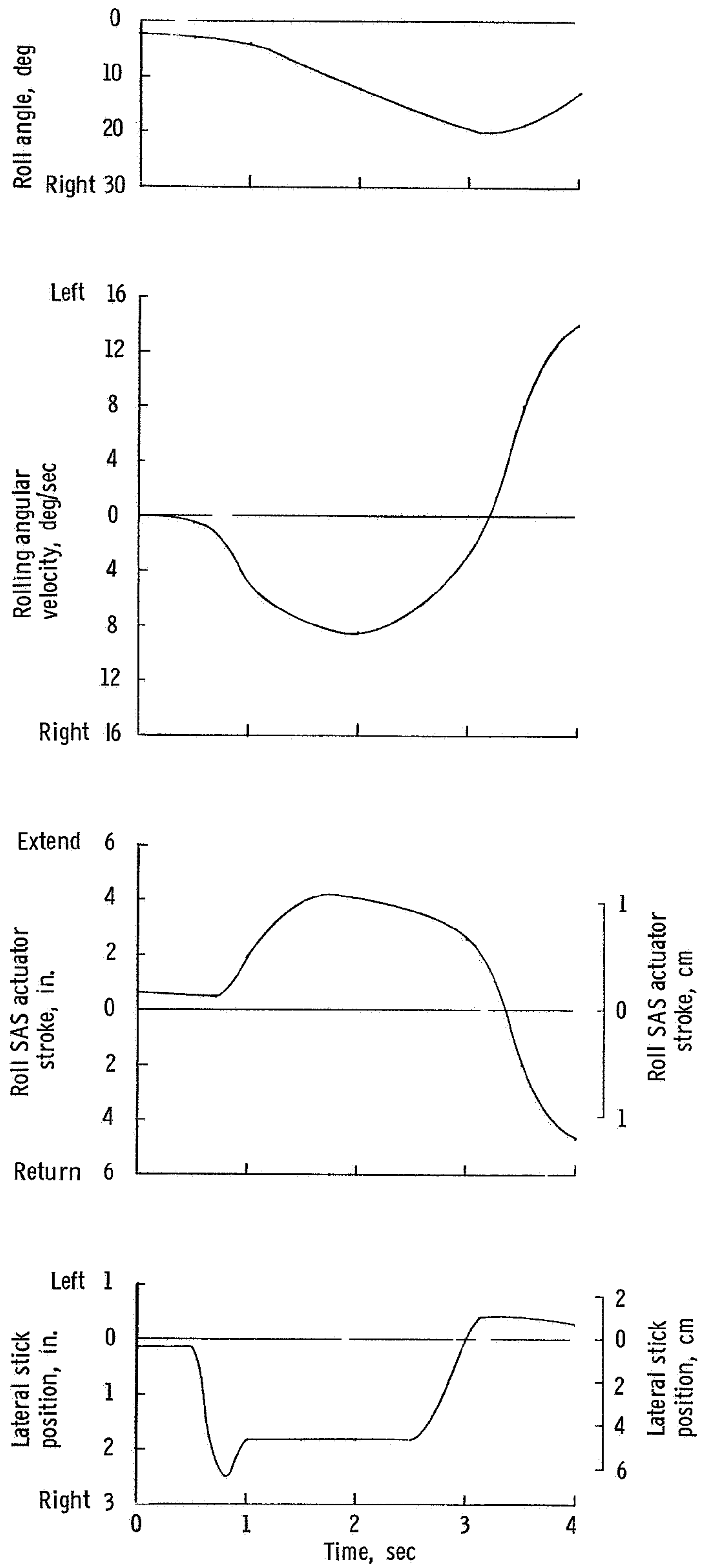

Figure 11.- Time history of lateral-control step input in hovering flight with SAS on. Aircraft roll-rate damping of about 3.0 $\frac{\text{rad/sec}^2}{\text{rad/sec}}$.

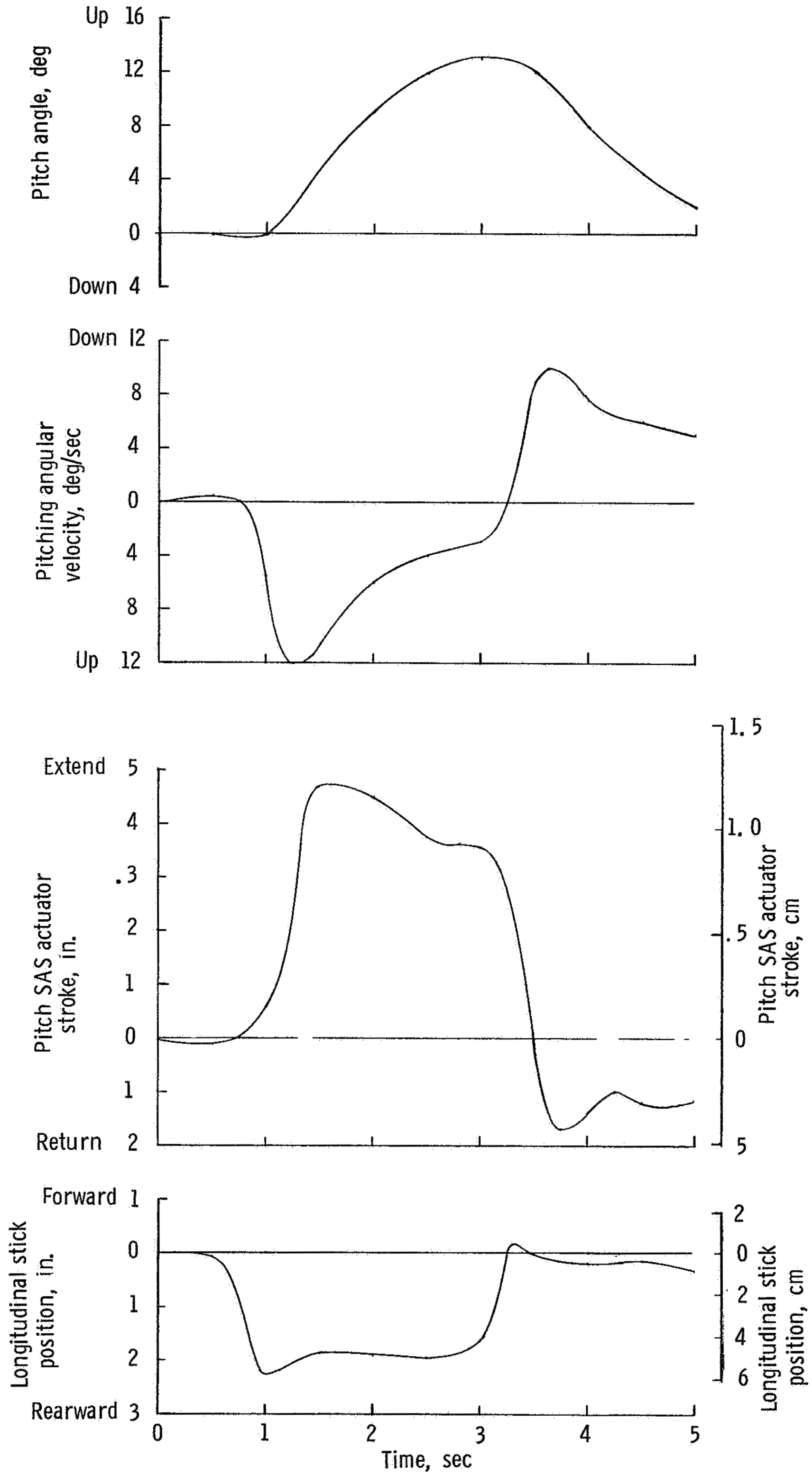

Figure 12.- Time history of rearward longitudinal-control step input in hovering flight with attitude and rate SAS on. Aircraft pitch-rate damping of about 4.0 $\frac{\text{rad/sec}^2}{\text{rad/sec}}$; artificial pitch-attitude stiffness of about 1.8 $\frac{\text{rad/sec}^2}{\text{rad}}$.

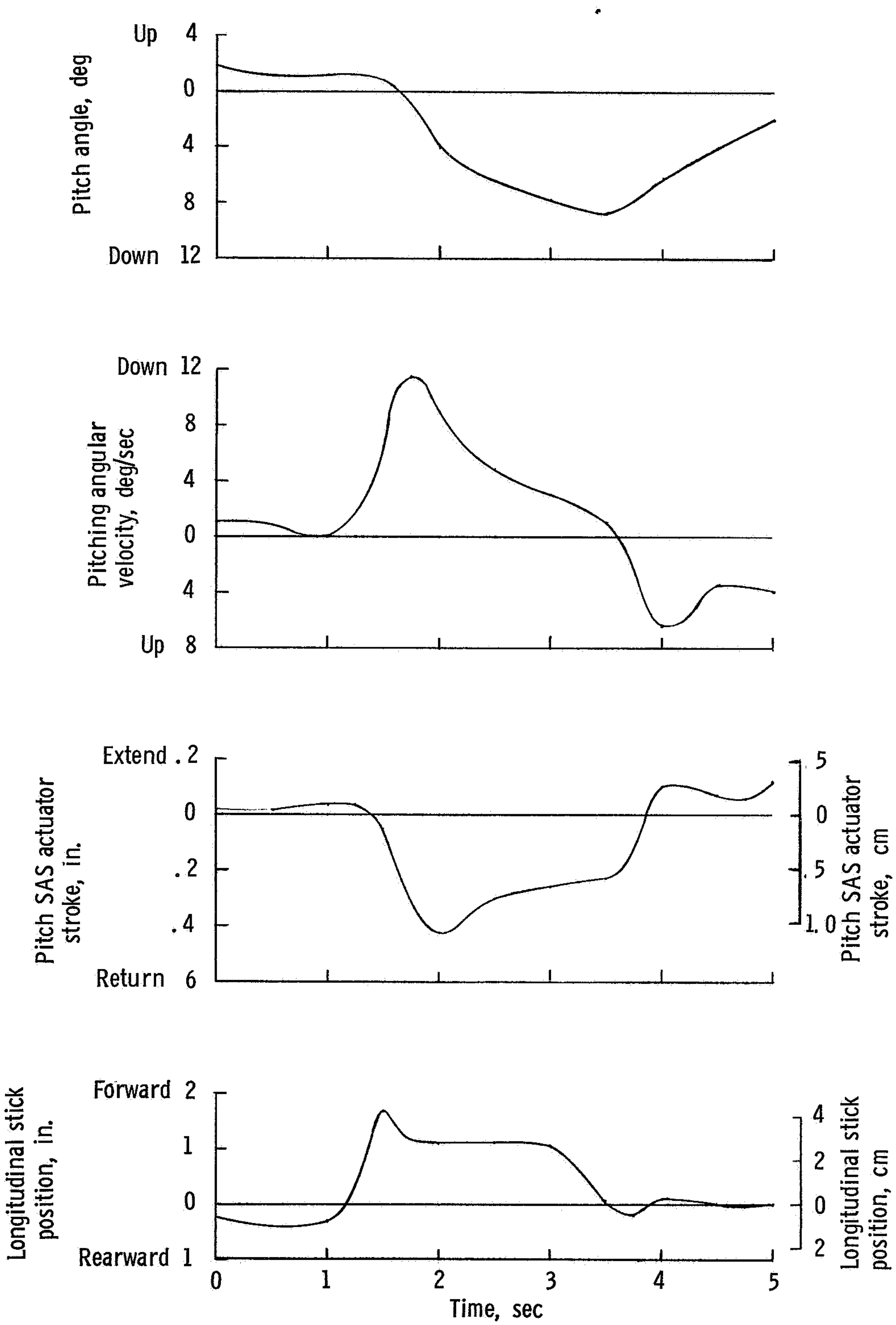

Figure 13.- Time history of forward longitudinal-control step input in hovering flight with attitude and rate SAS on. Aircraft pitch-rate damping of about 4.0 $\frac{\text{rad/sec}^2}{\text{rad/sec}}$; artificial pitch-attitude stiffness of about 1.8 $\frac{\text{rad/sec}^2}{\text{rad}}$

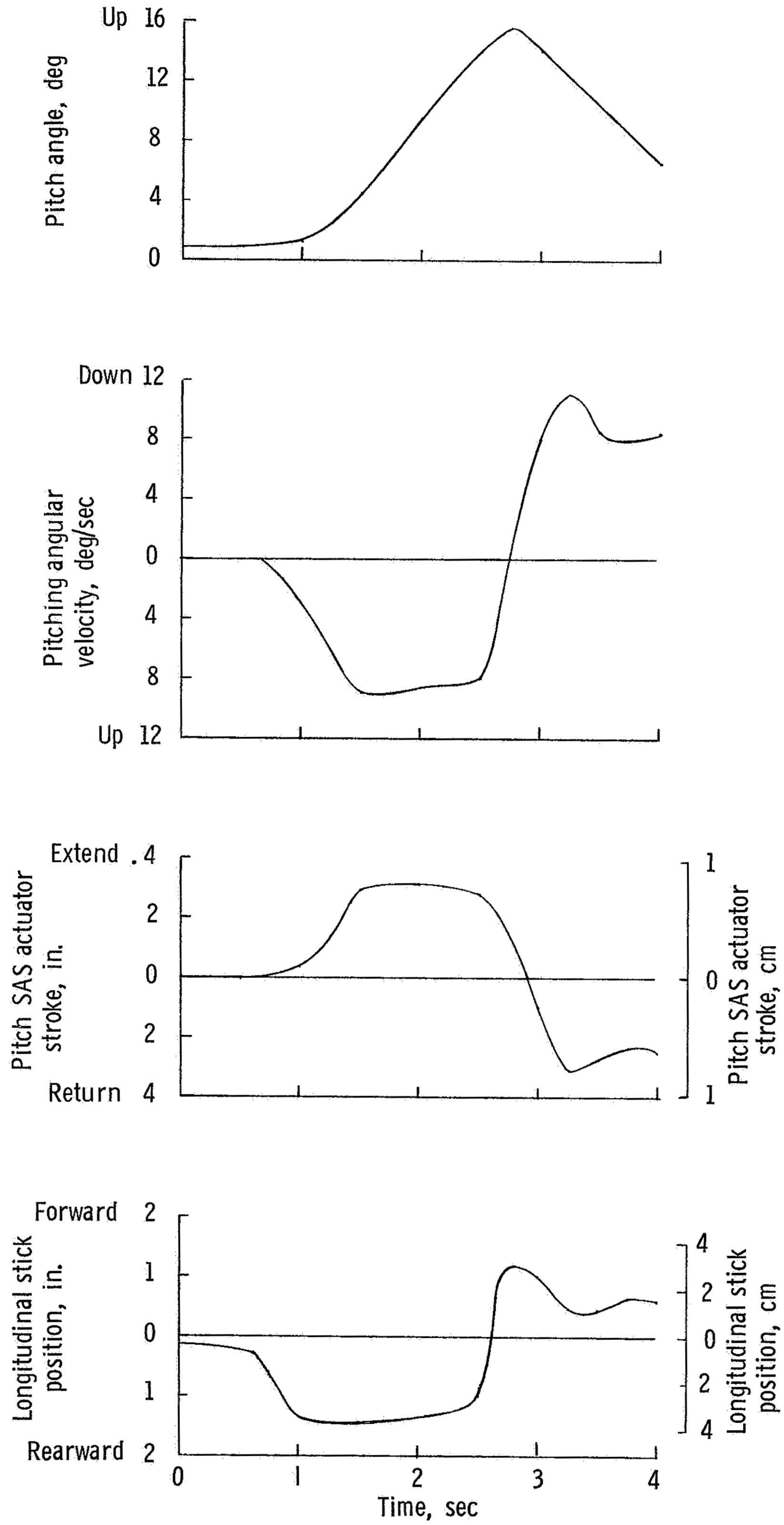

Figure 14.- Time history of rearward longitudinal-control step input in hovering flight with rate SAS only. Aircraft pitch-rate damping of about 4.0 $\frac{\text{rad/sec}^2}{\text{rad/sec}}$

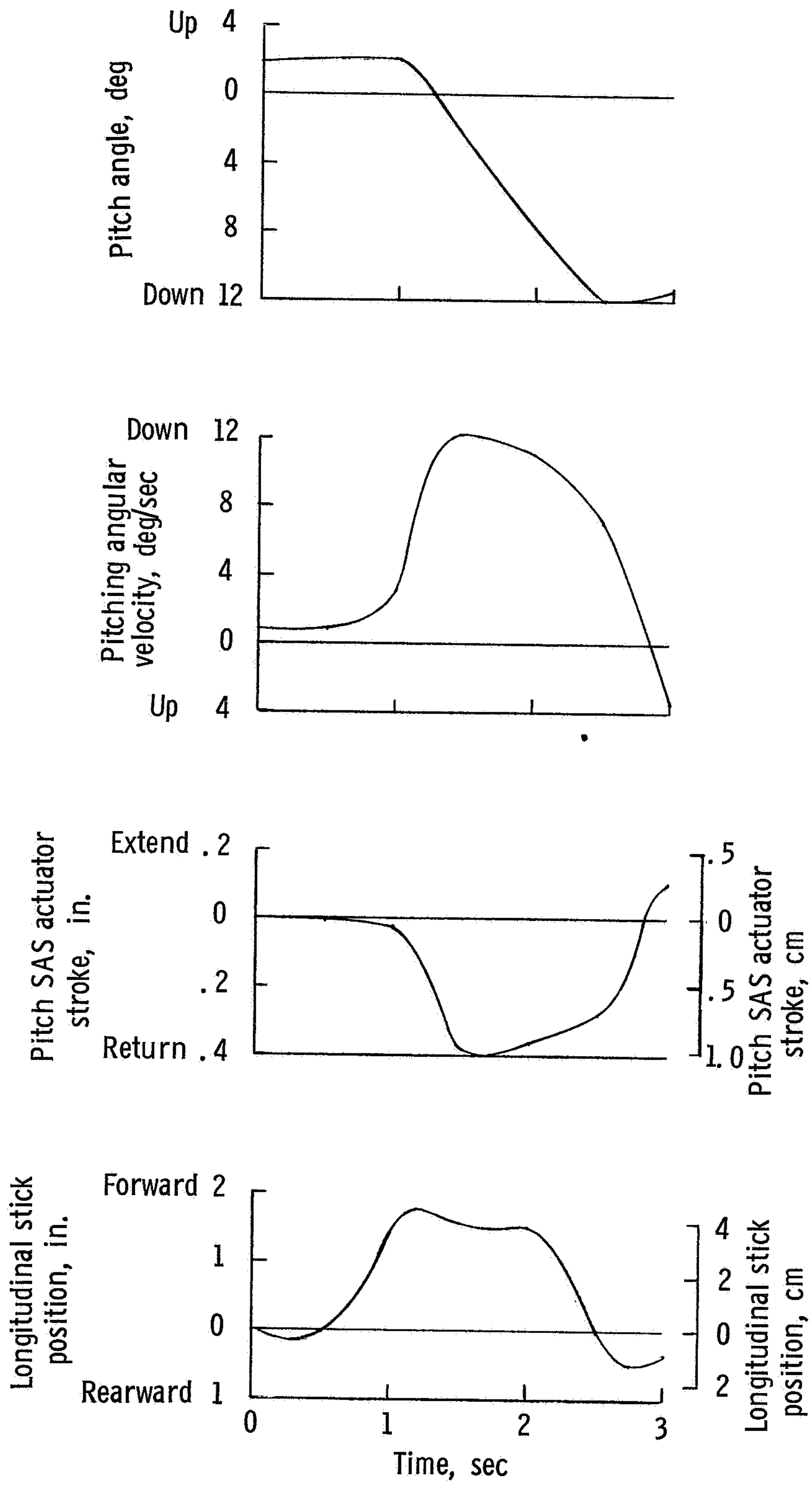

Figure 15.- Time history of forward longitudinal-control step input in hovering flight with rate SAS only. Aircraft pitch-rate damping of about 4.0 $\frac{\text{rad/sec}^2}{\text{rad/sec}}$.

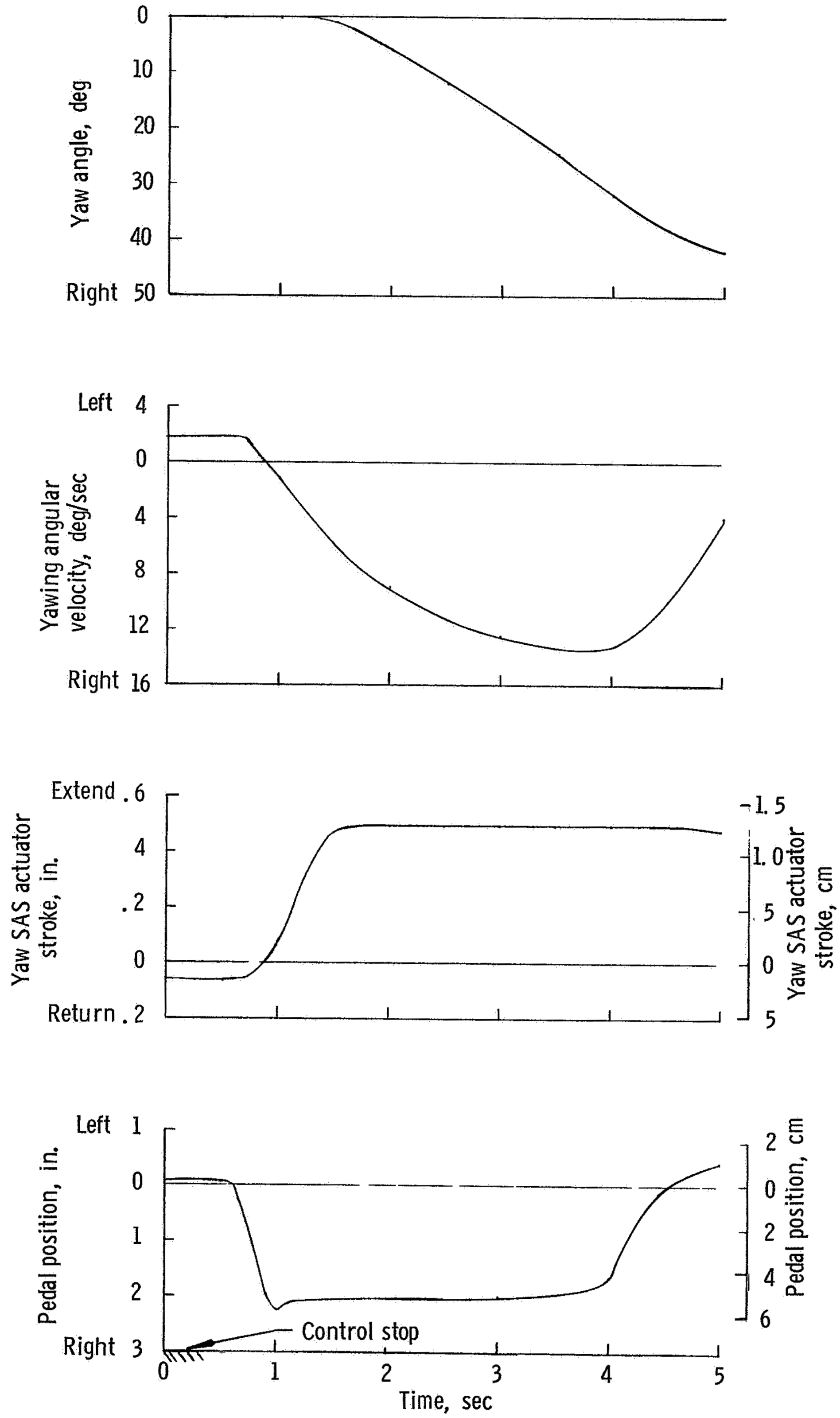

Figure 16.- Time history of right directional-control step input in hovering flight with SAS on. Aircraft yaw-rate damping of about 2.2 $\frac{\text{rad/sec}^2}{\text{rad/sec}}$

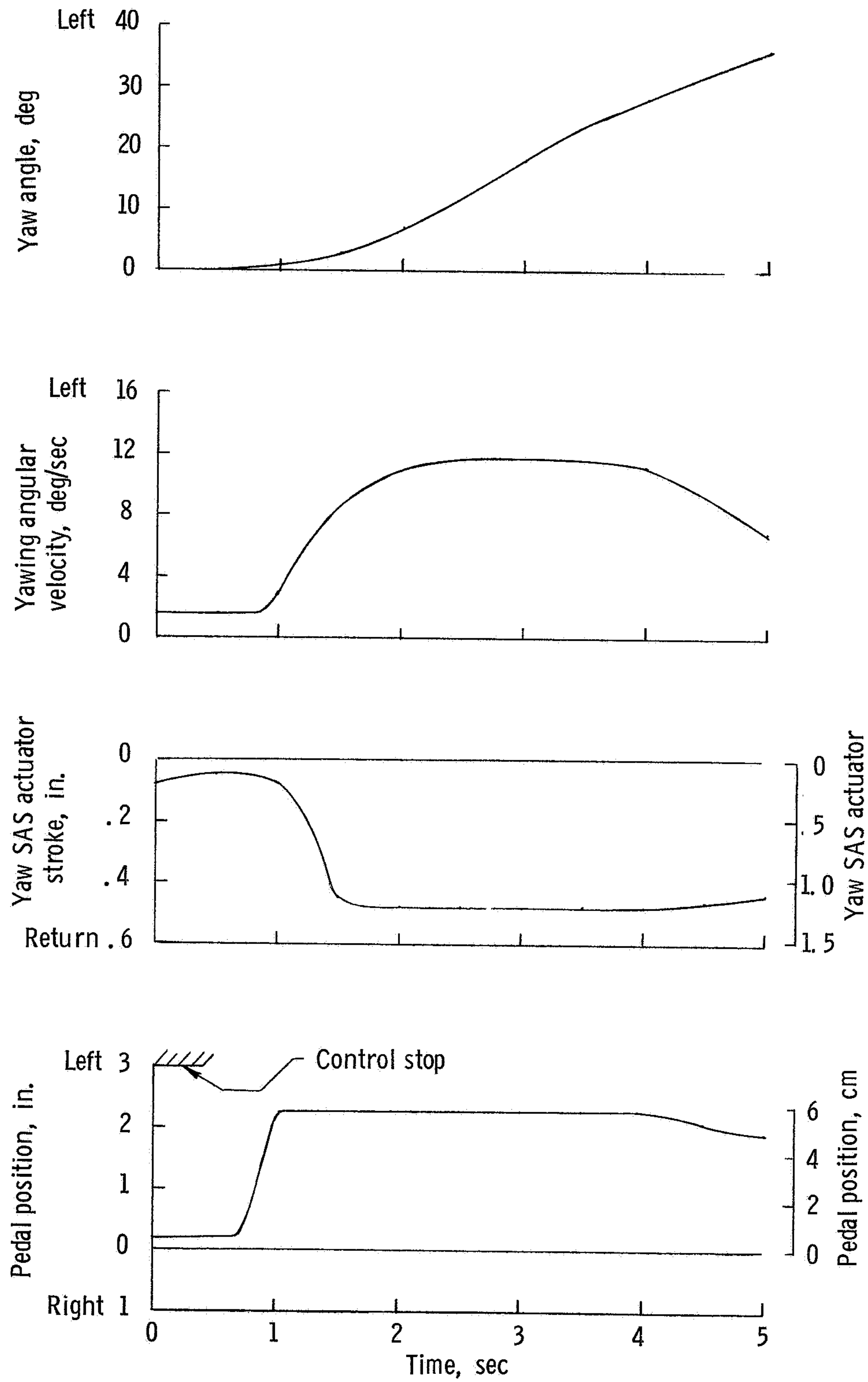

Figure 17 Time history of left directional-control step input in hovering flight with SAS on. Aircraft yaw-rate damping of about 2.2 $\frac{\text{rad/sec}^2}{\text{rad/sec}}$

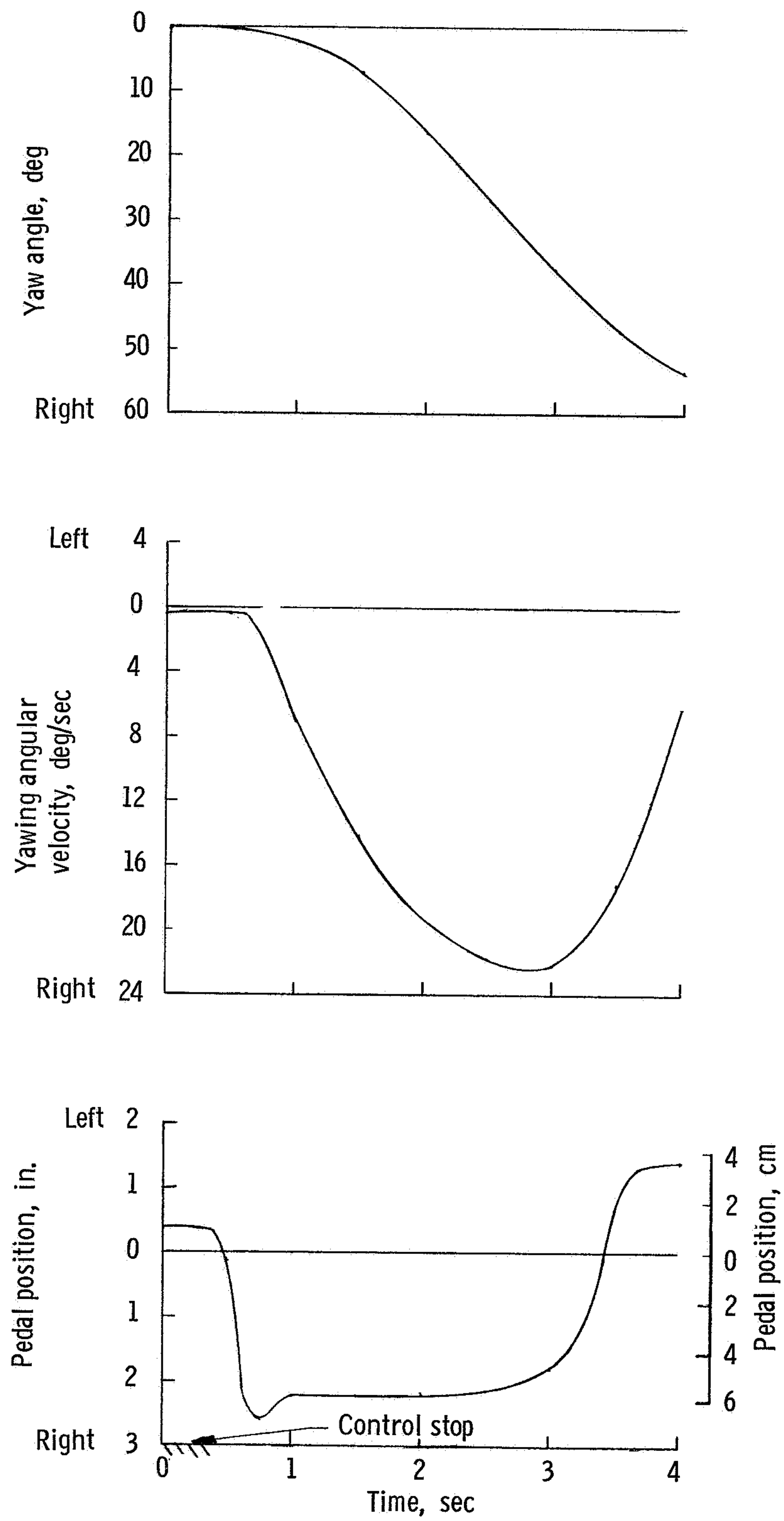

Figure 18.- Time history of right directional-control step input in hovering flight with SAS off. Aircraft yaw-rate damping of about 0.4 $\frac{\text{rad/sec}^2}{\text{rad/sec}}$

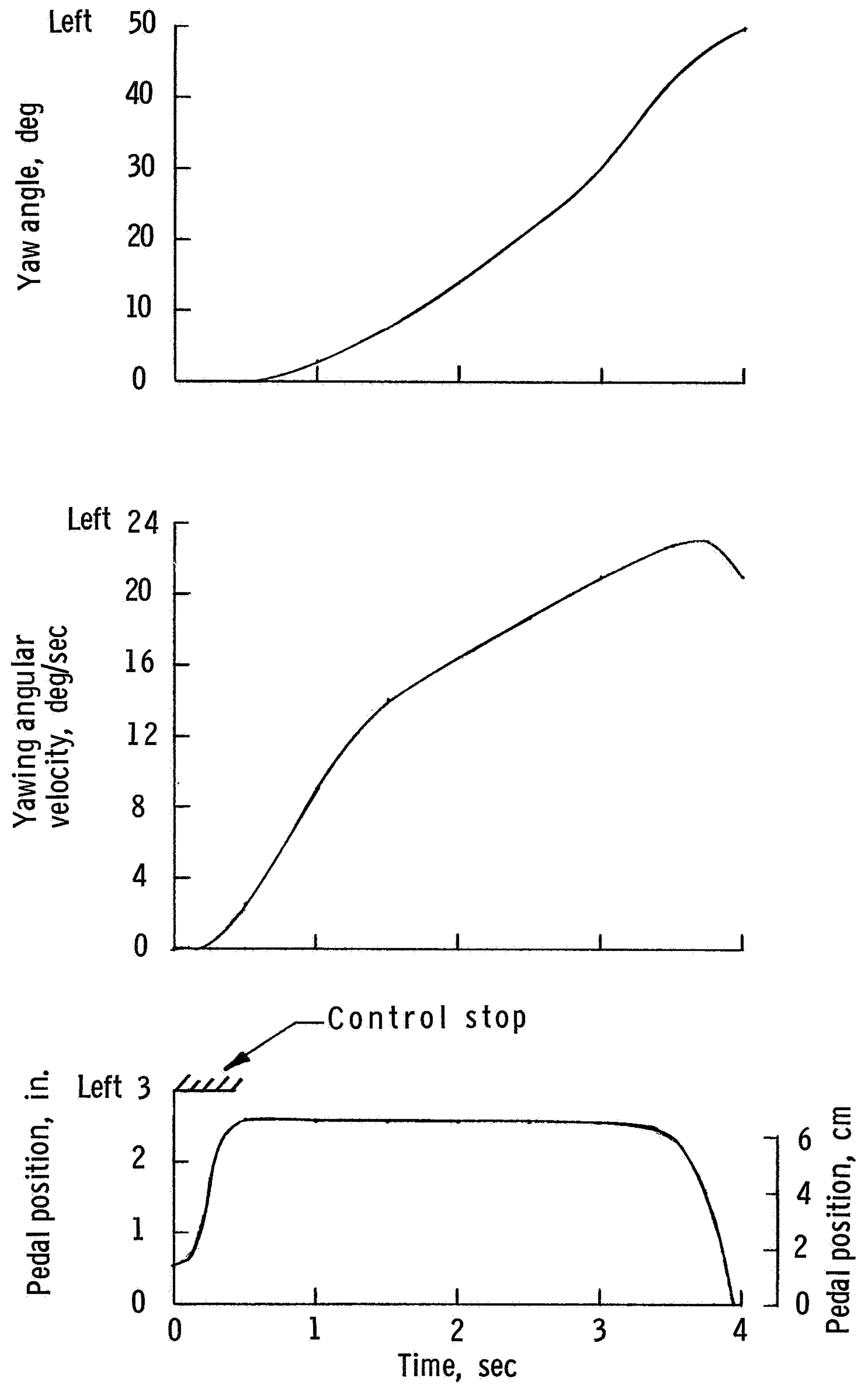

Figure 19.- Time history of left directional-control step input in hovering flight with SAS off. Aircraft yaw-rate damping of about 0.4 $\frac{\text{rad/sec}^2}{\text{rad/sec}}$.

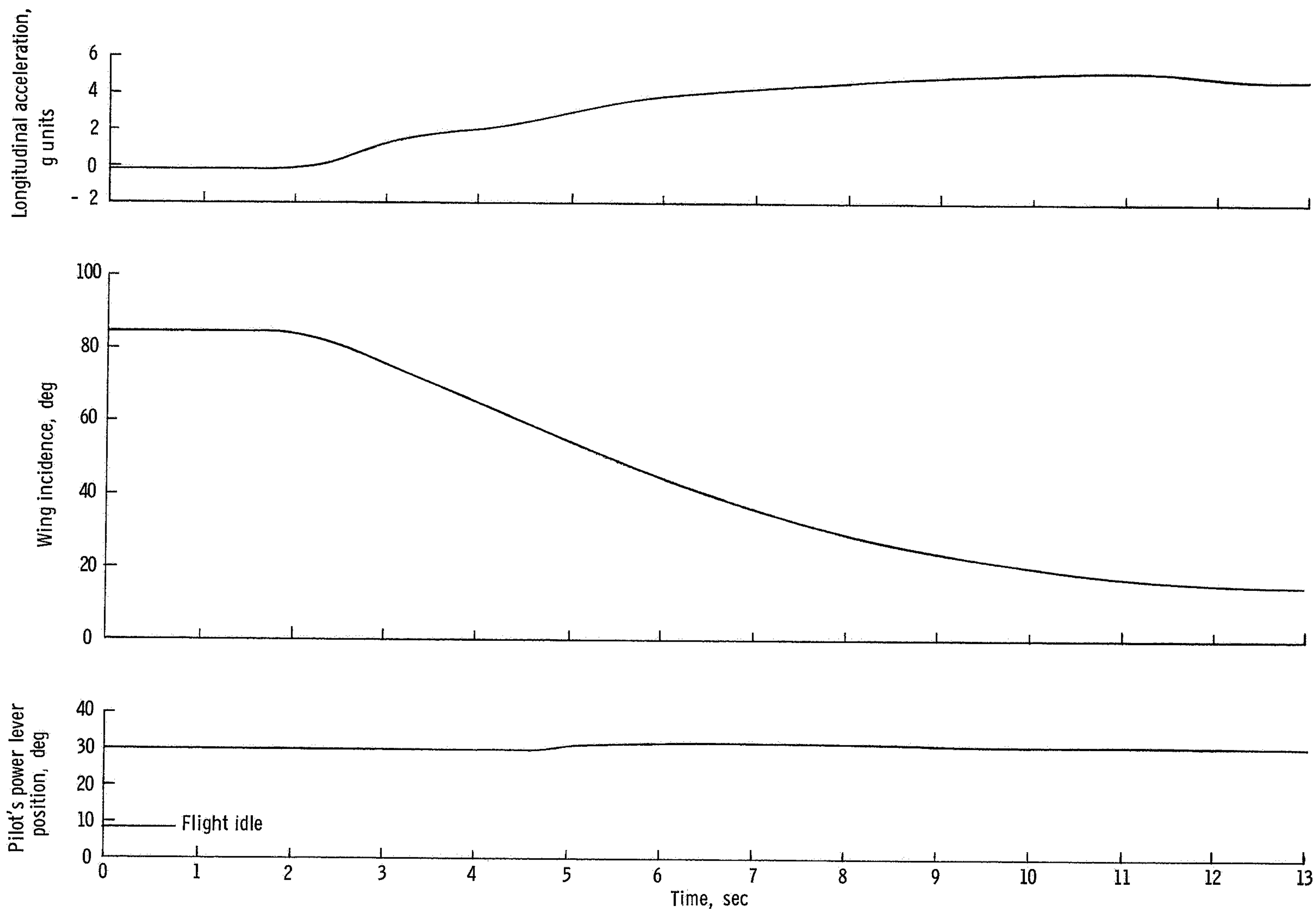

Figure 20.- Time histories for maximum-performance level-flight accelerating conversion.

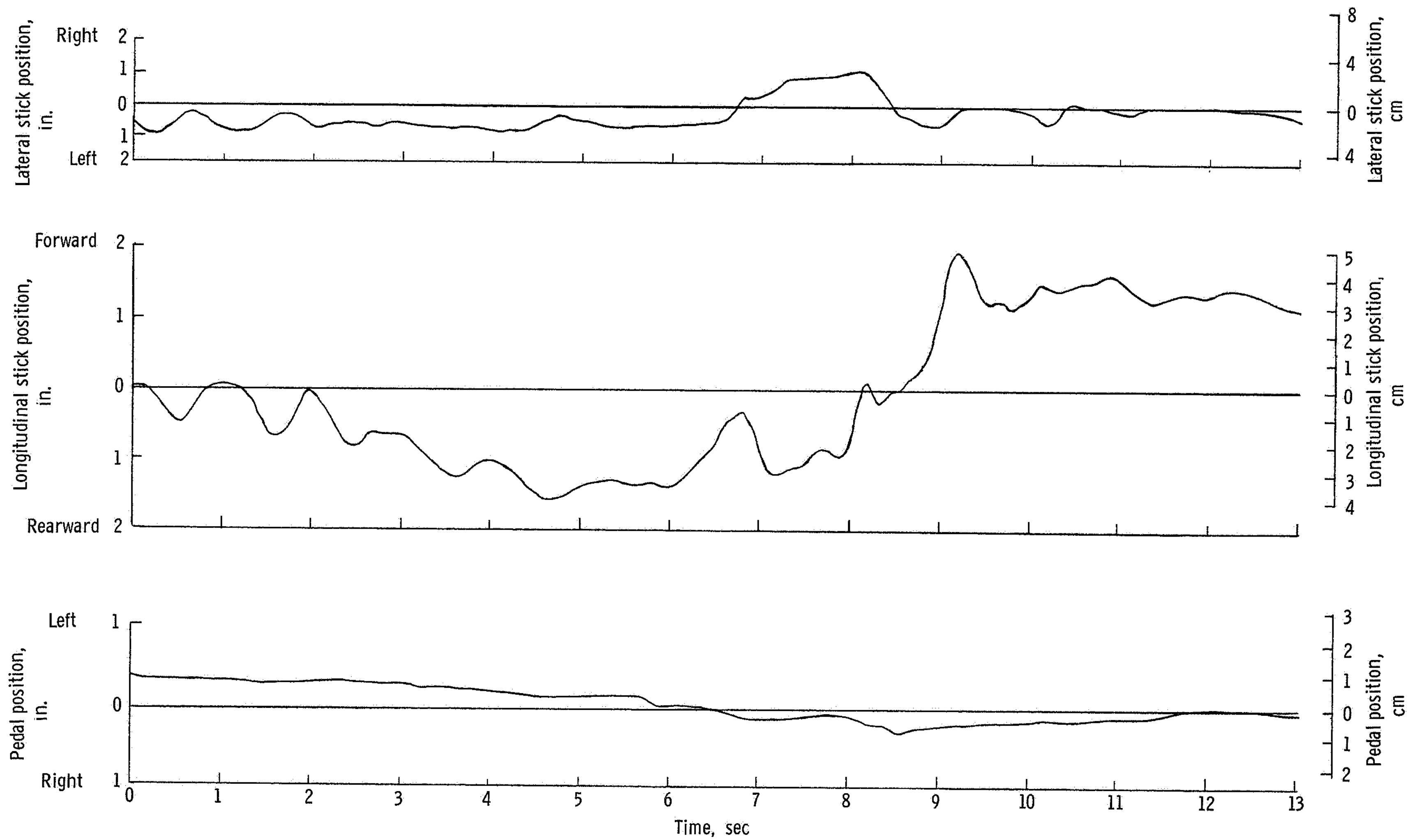

Figure 20.- Continued.

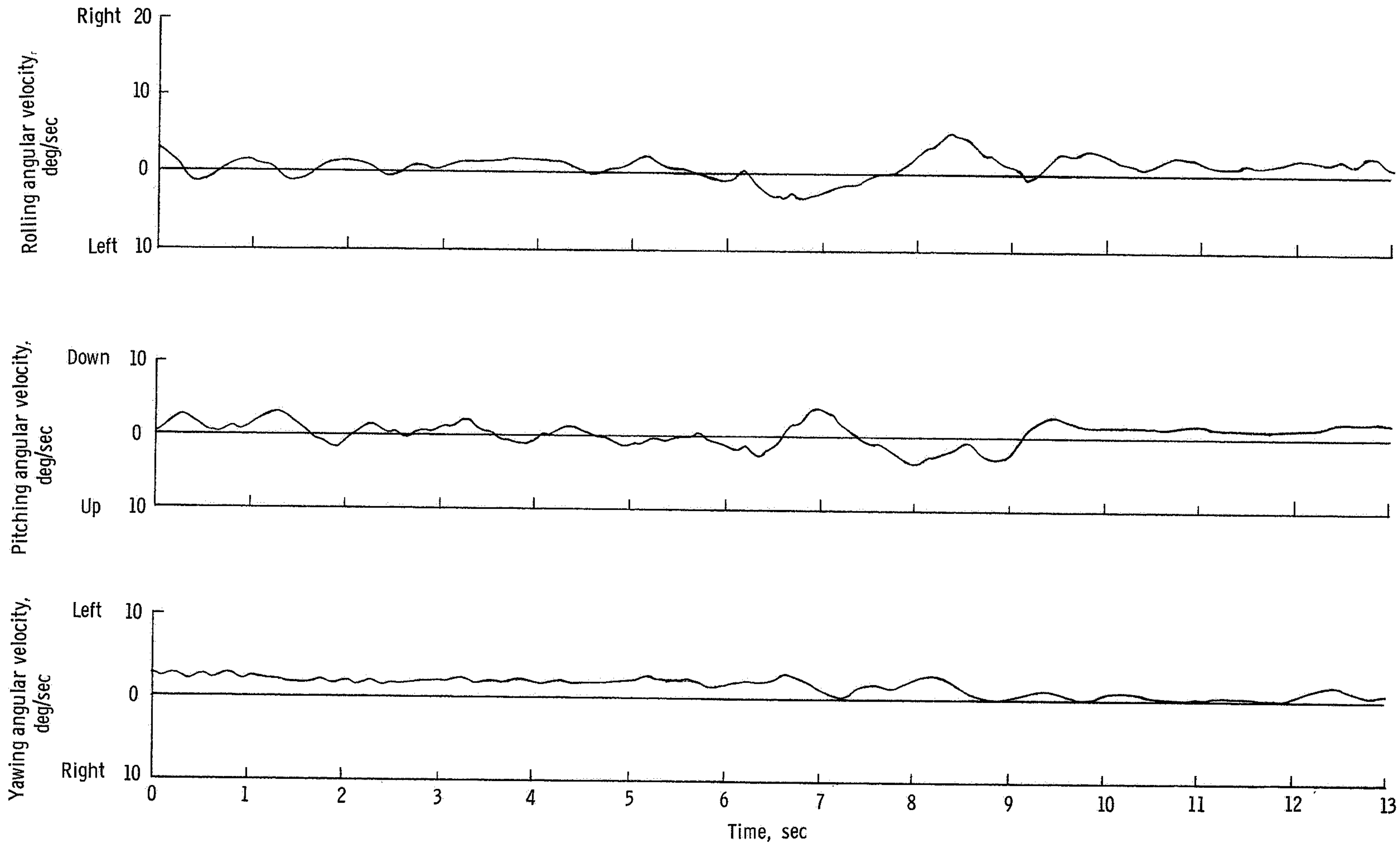

Figure 20.- Concluded.

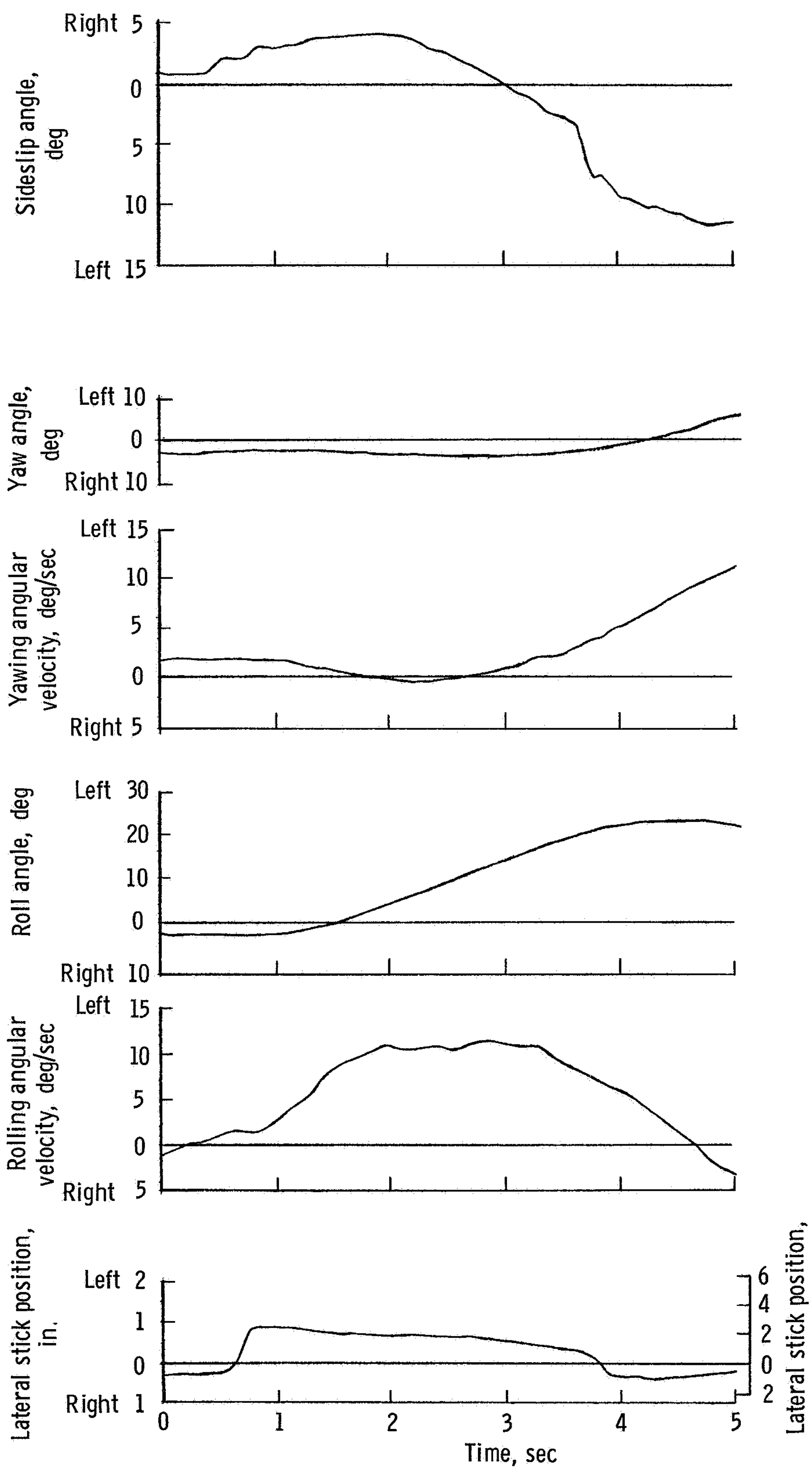

Figure 21.- Time history of lateral-control step input with roll SAS off. Airspeed of 42 knots; wing incidence of 40°, flap incidence of 24°

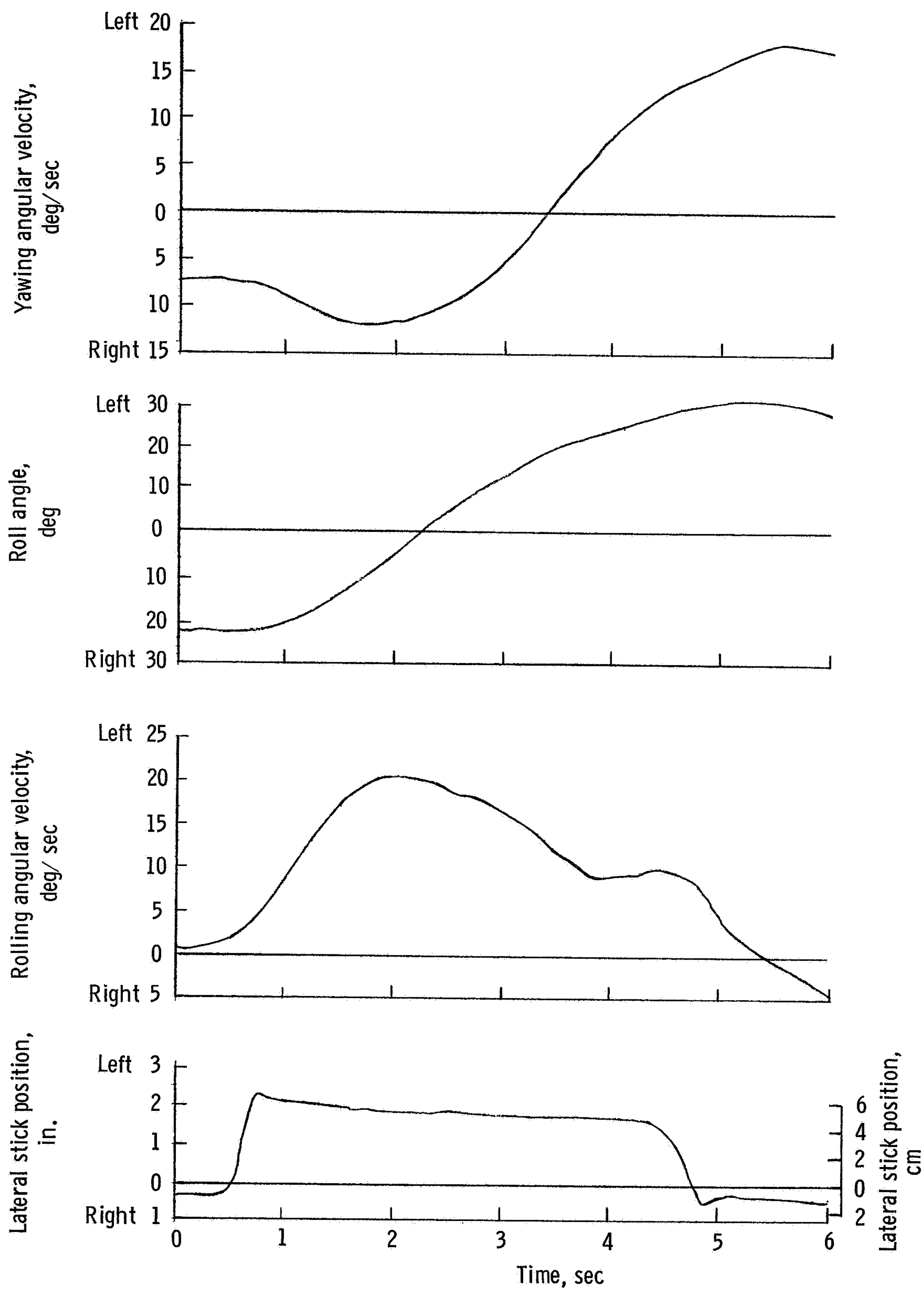

Figure 22.- Time history of lateral-control step input from a 23° banked turn with roll SAS off. Airspeed of 42 knots; wing incidence of 40°: flap incidence of 24°

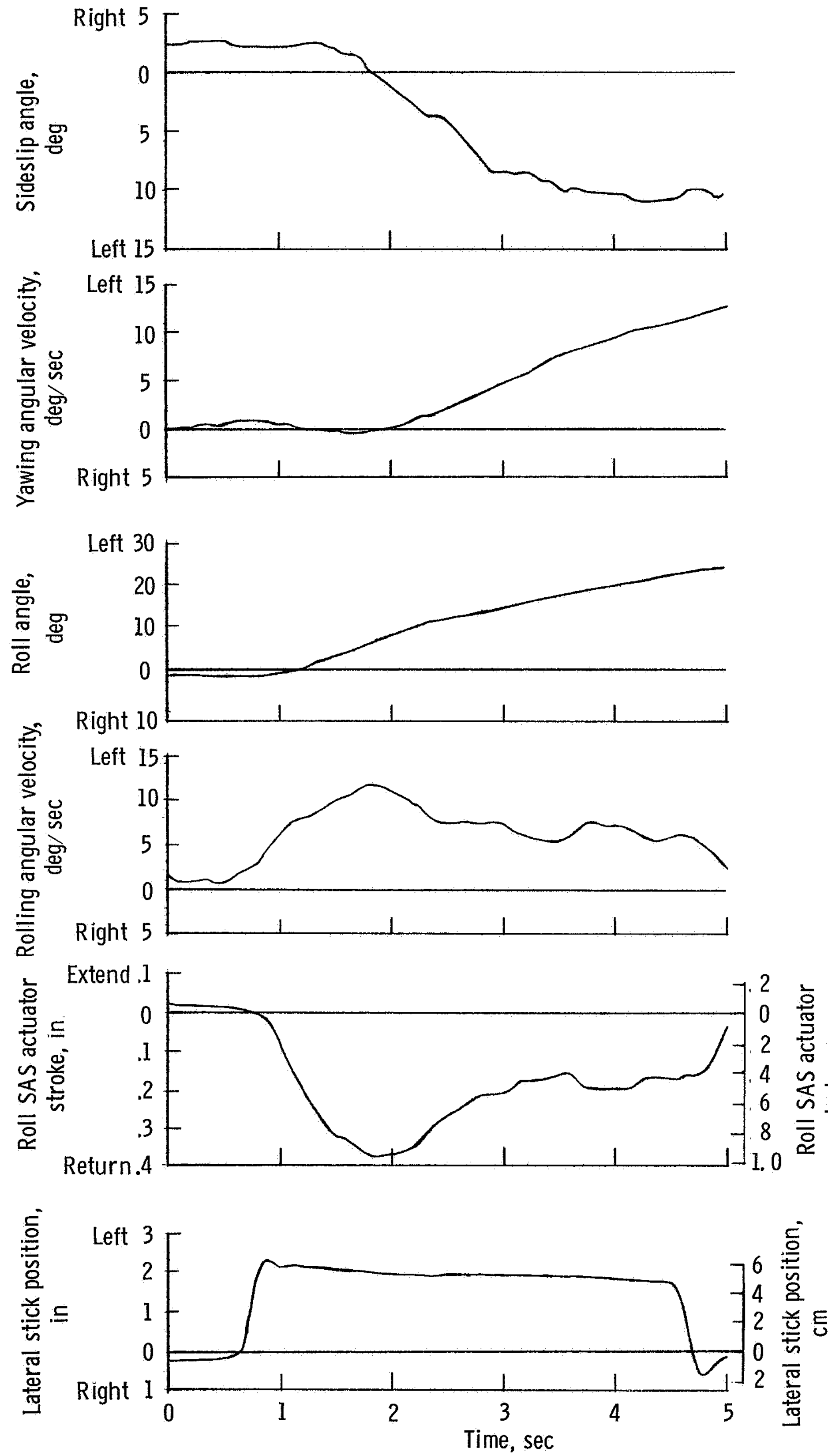

Figure 23.- Time history of lateral-control step input with roll SAS on. Airspeed of 42 knots; wing incidence of 40°; flap incidence of 24°

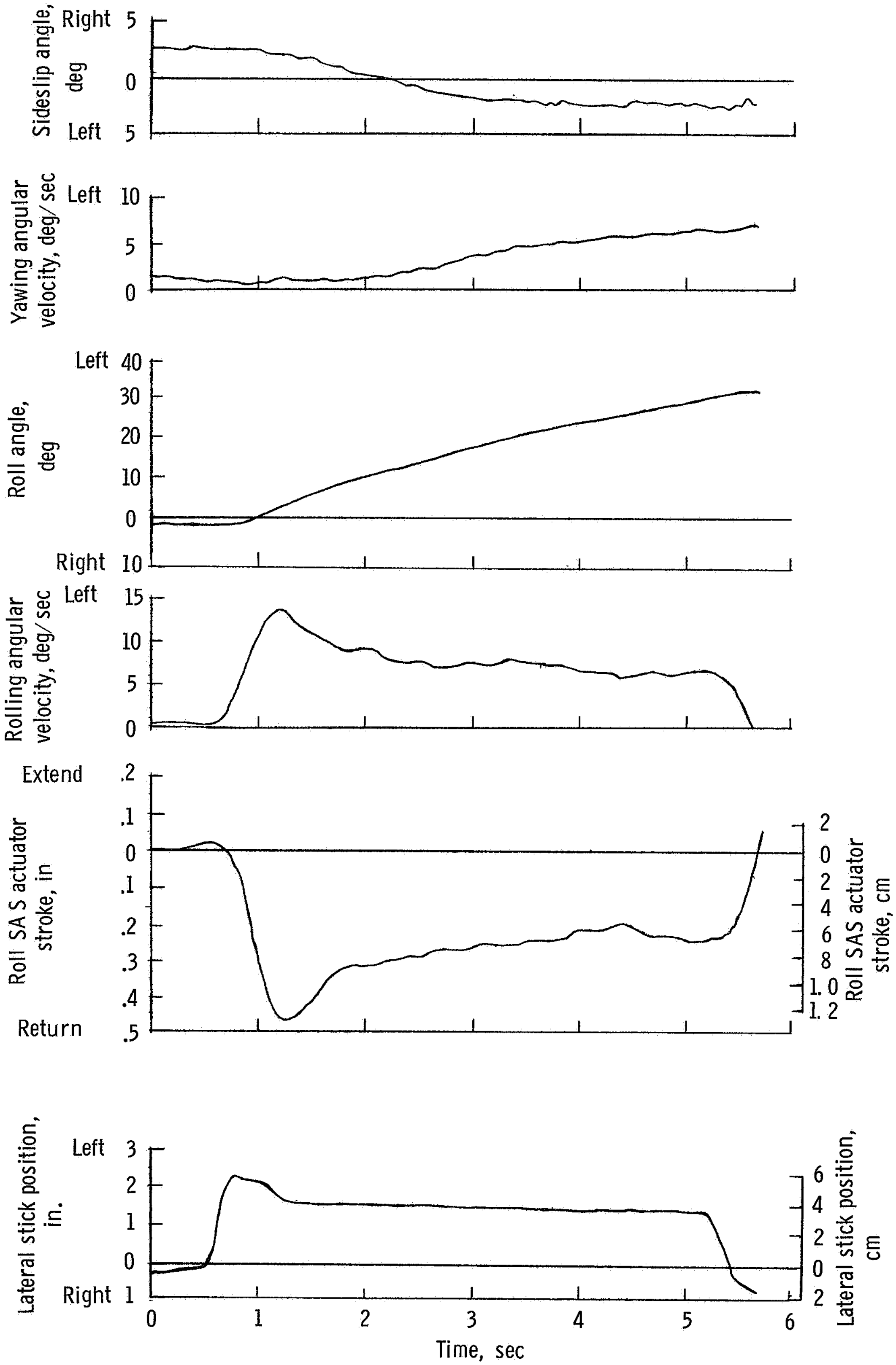

Figure 24.- Time history of lateral-control step input with roll SAS on. Airspeed of 100 knots; wing incidence of 15°; flap incidence of 5°

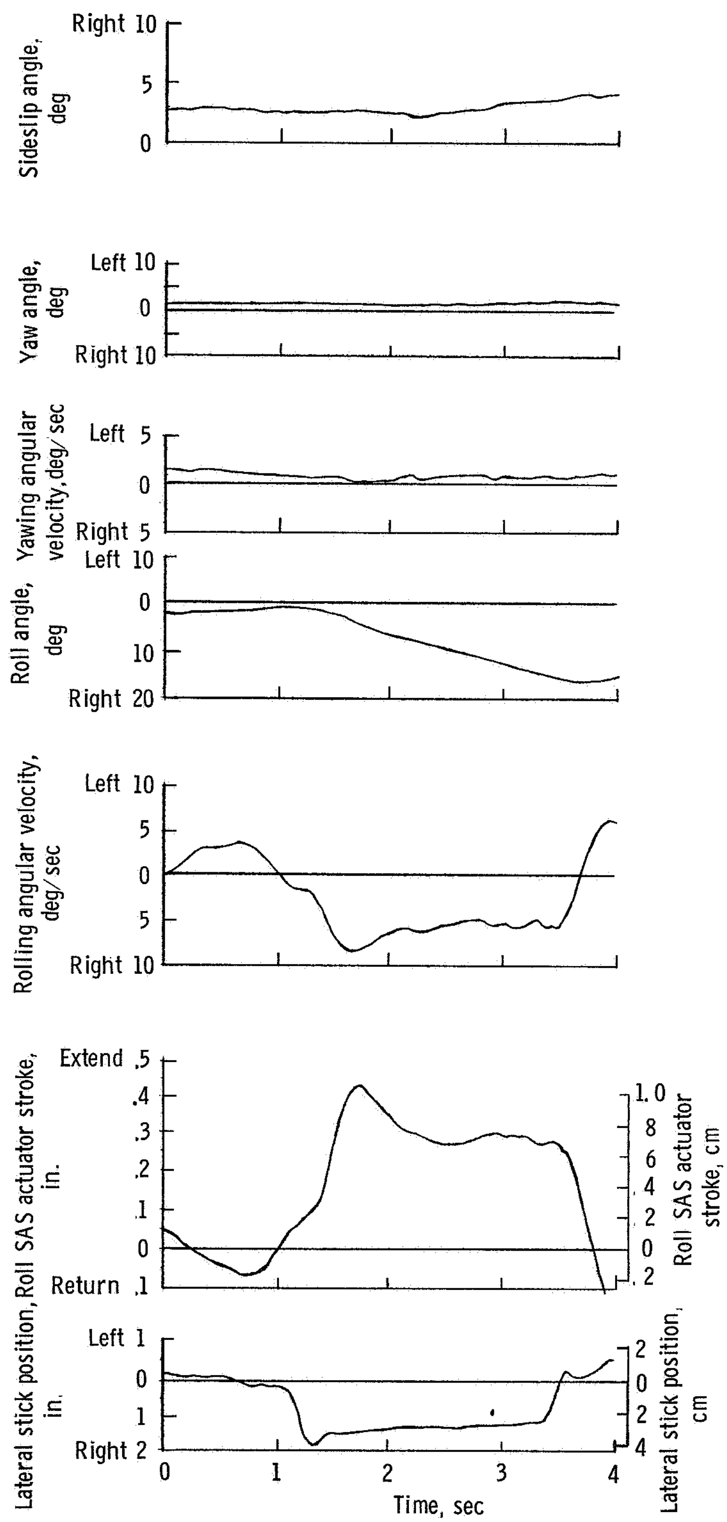

Figure 25.- Three time histories of lateral-control step inputs with roll SAS on. Airspeed of 185 knots; wing incidence of 0°; flap incidence of 0°

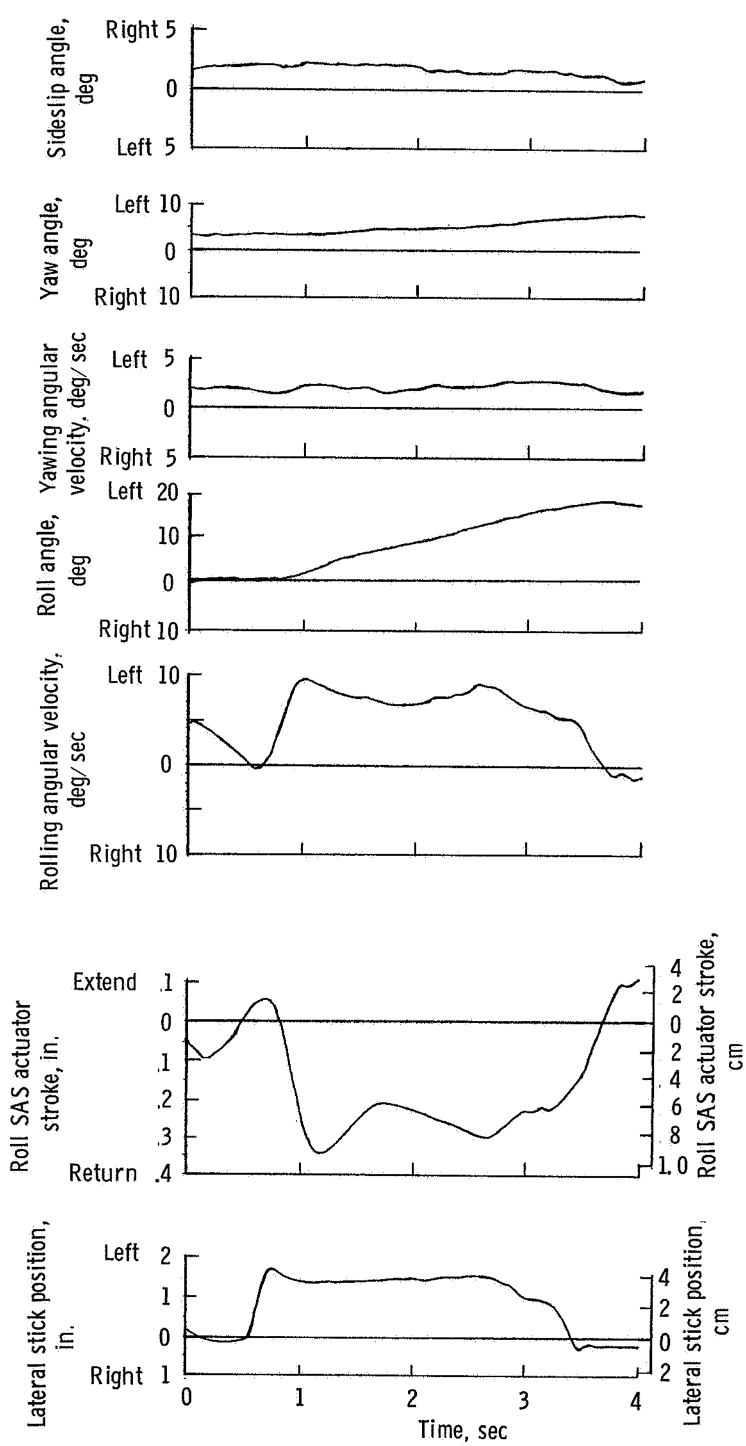

Figure 25. Continued.

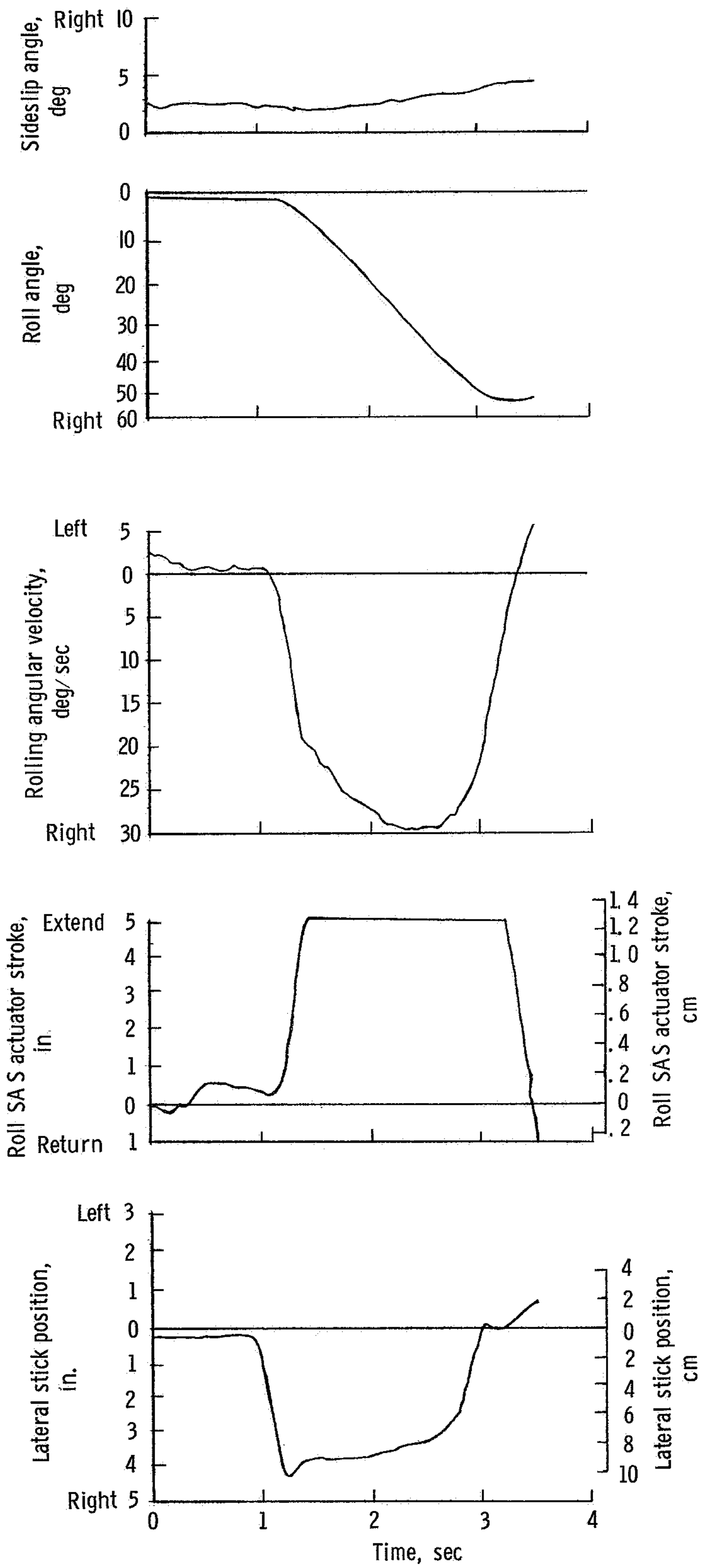

Figure 25.- Concluded.

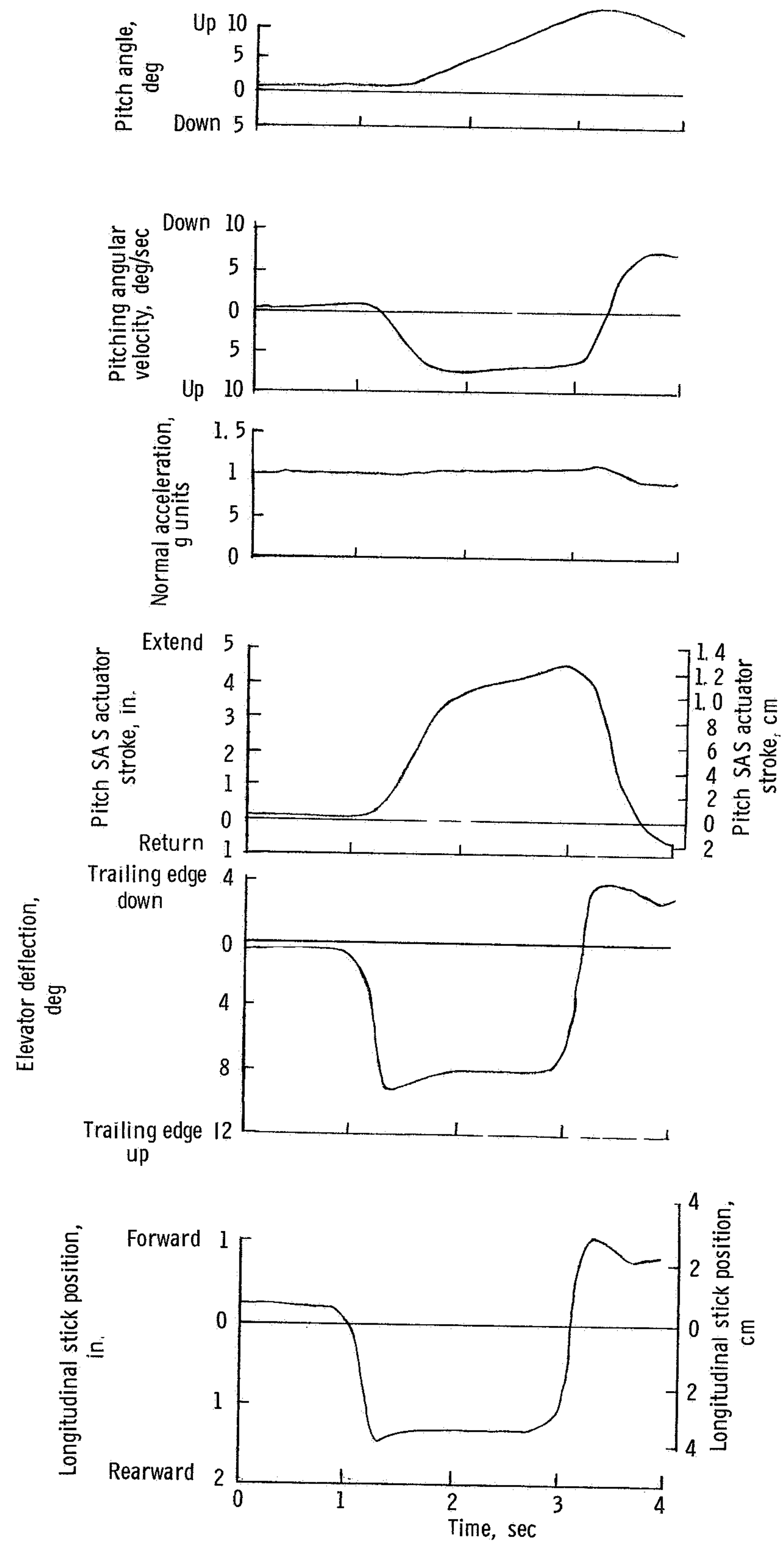

Figure 26.- Time history of longitudinal-control step pull-and-hold maneuver with pitch-attitude and pitch-rate SAS on. Airspeed of 42 knots; wing incidence of 40°; flap incidence of 24°

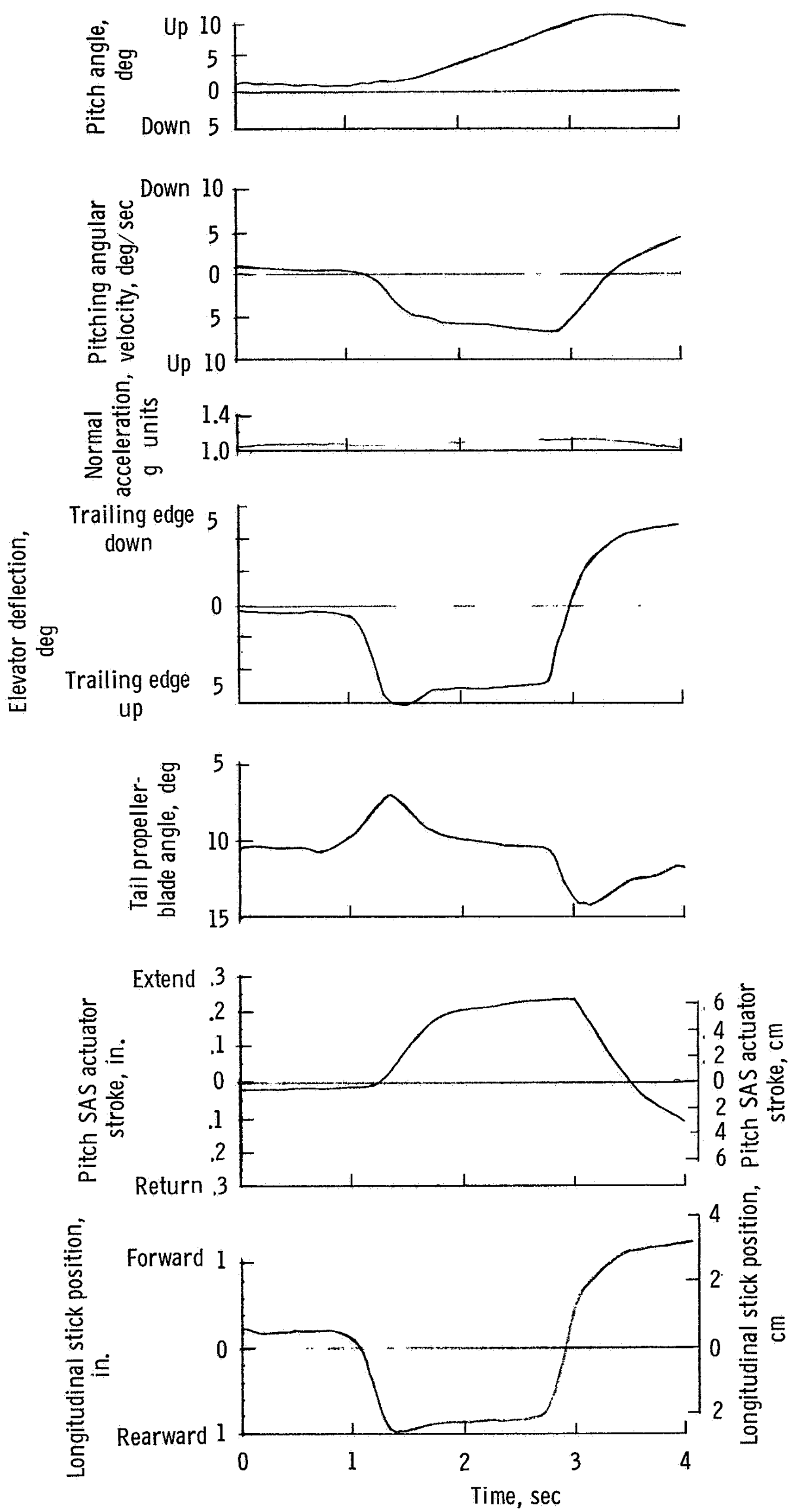

Figure 27 - Time history of longitudinal-control step pull-and-hold maneuver with pitch-attitude SAS off and pitch-rate SAS on. Airspeed of 42 knots; wing incidence of 40°; flap incidence of 24°

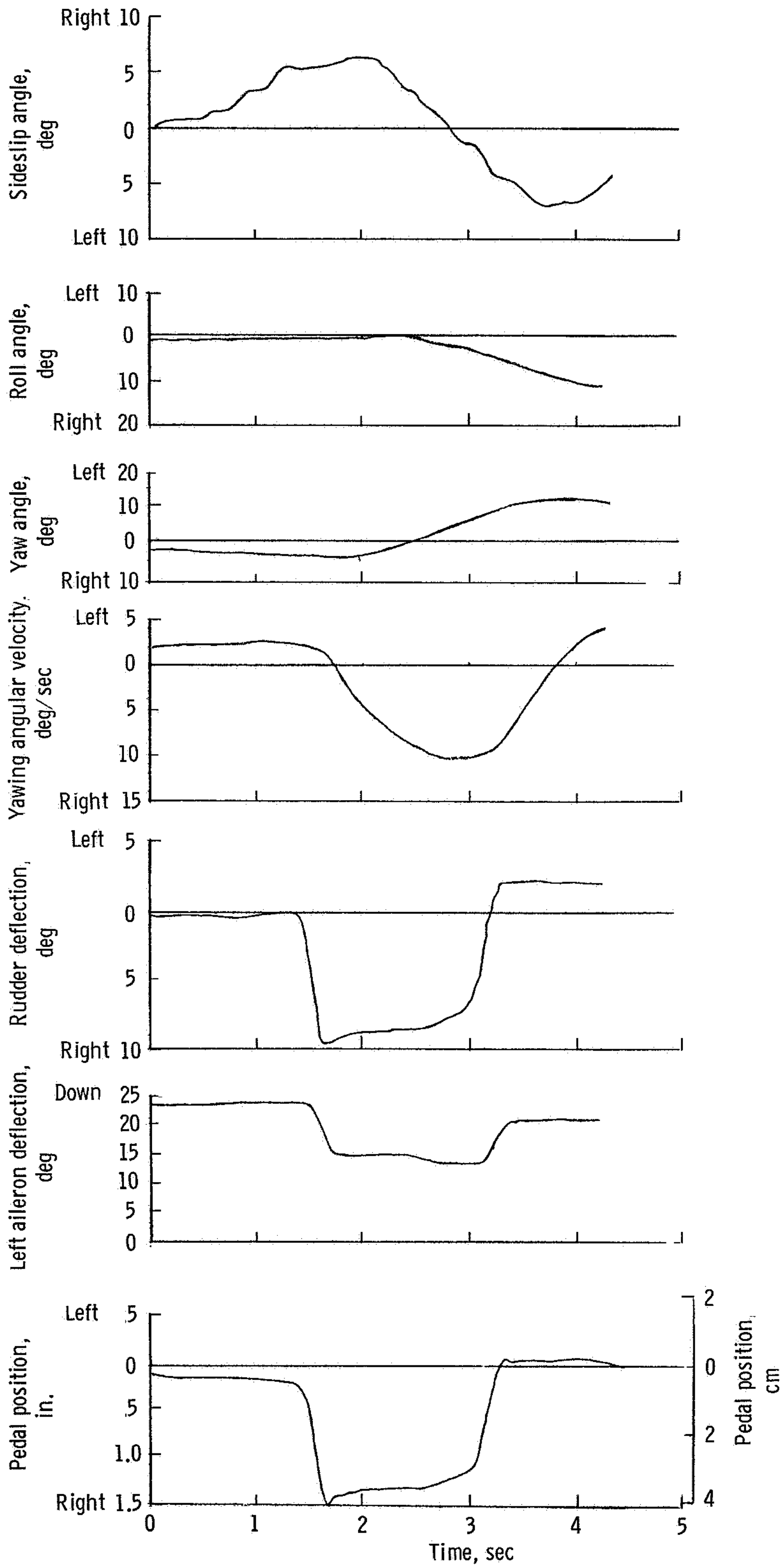

Figure 28.- Time history of directional-control step input with yaw SAS off. Pilot held lateral stick fixed during maneuver. Airspeed of 42 knots; wing incidence of 40°; flap incidence of 24°

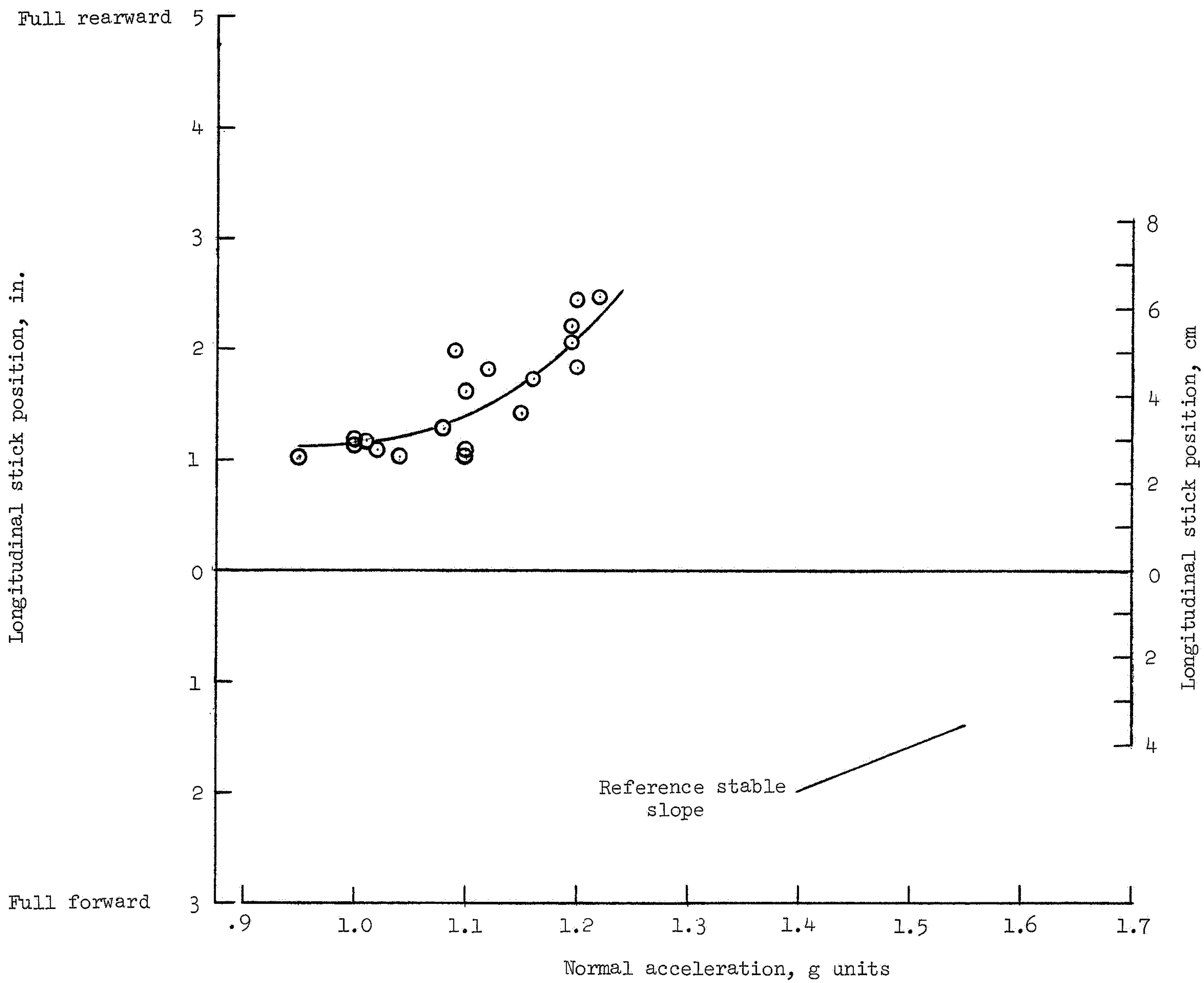

Figure 29.- Results of windup turn at 100 knots with pitch-rate and pitch-attitude SAS on. Wing incidence of 15°; flap incidence of 5°

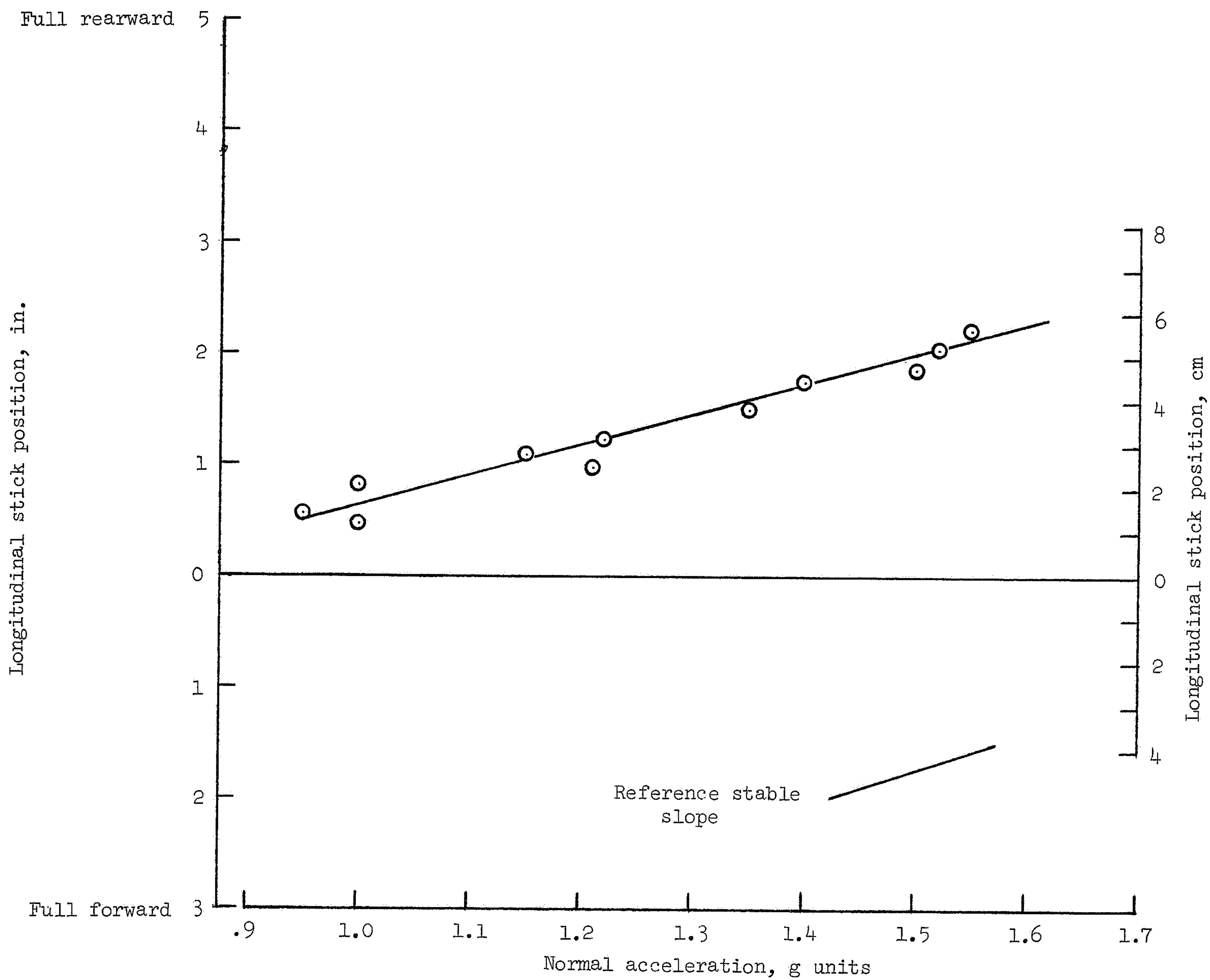

Figure 30. Results of windup turn at 175 knots. Wing incidence of 0°; flap incidence of 0°

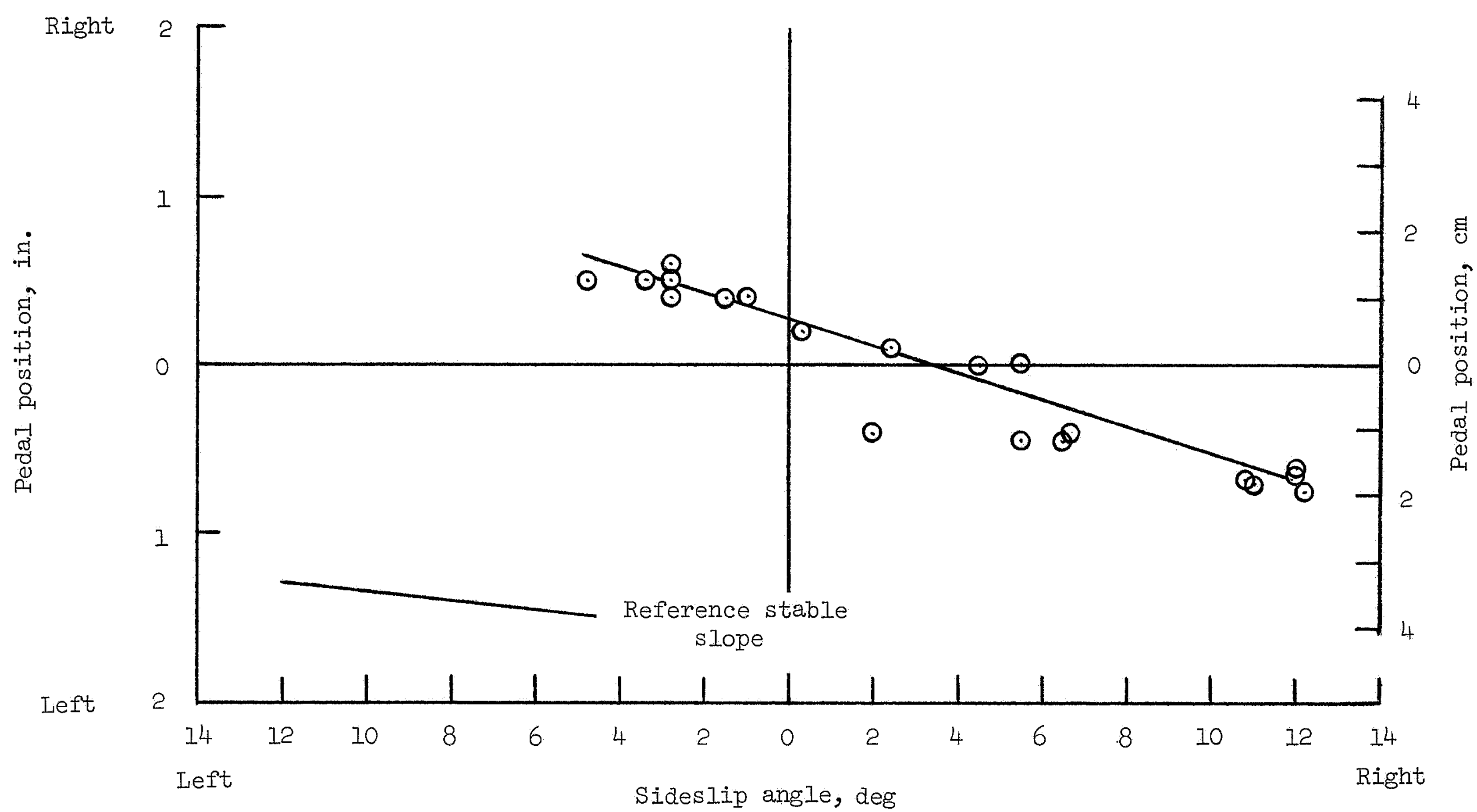

Figure 31.- Static directional stability at 42 knots. Wing incidence of 40°. flap incidence of 24°

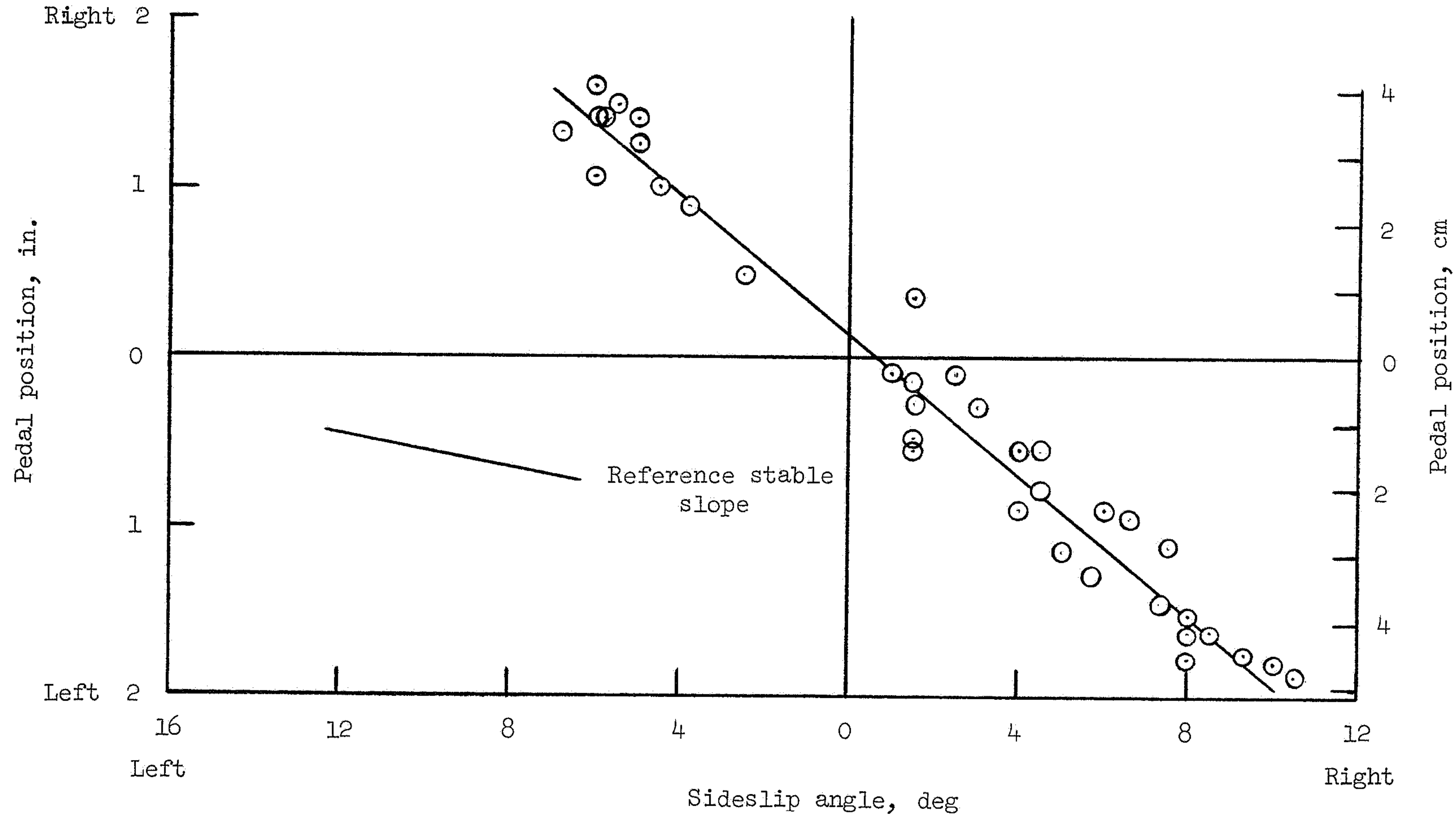

Figure 32.- Static directional stability at 100 knots. Wing incidence of 15°; flap incidence of 5°

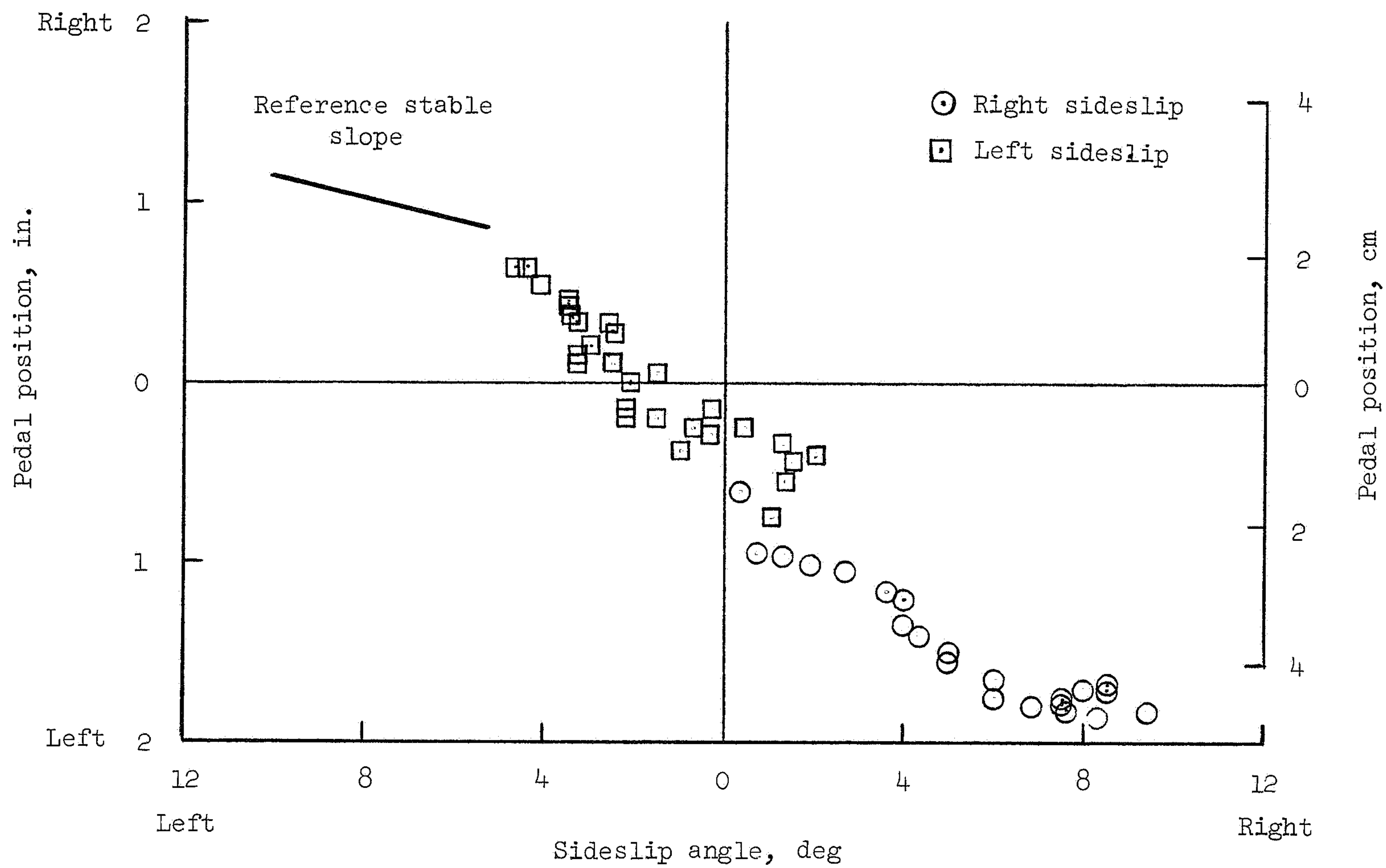

Figure 33. Static directional stability at 175 knots. Wing incidence of 0°; flap incidence of 0°

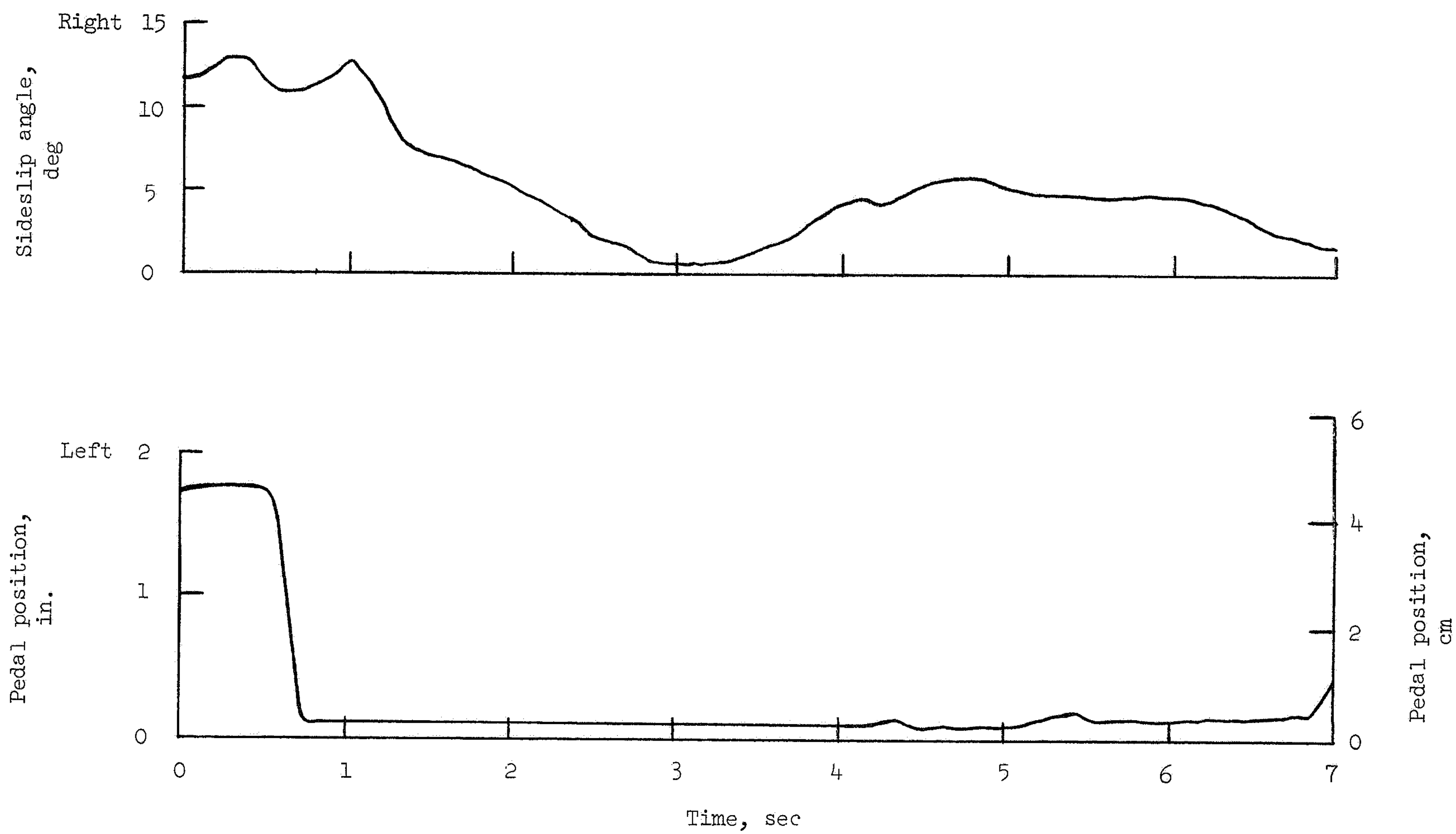

Figure 34.- Time history of pedal release from right sideslip with yaw SAS off. Airspeed of 100 knots; wing incidence of 15°; flap incidence of 5°

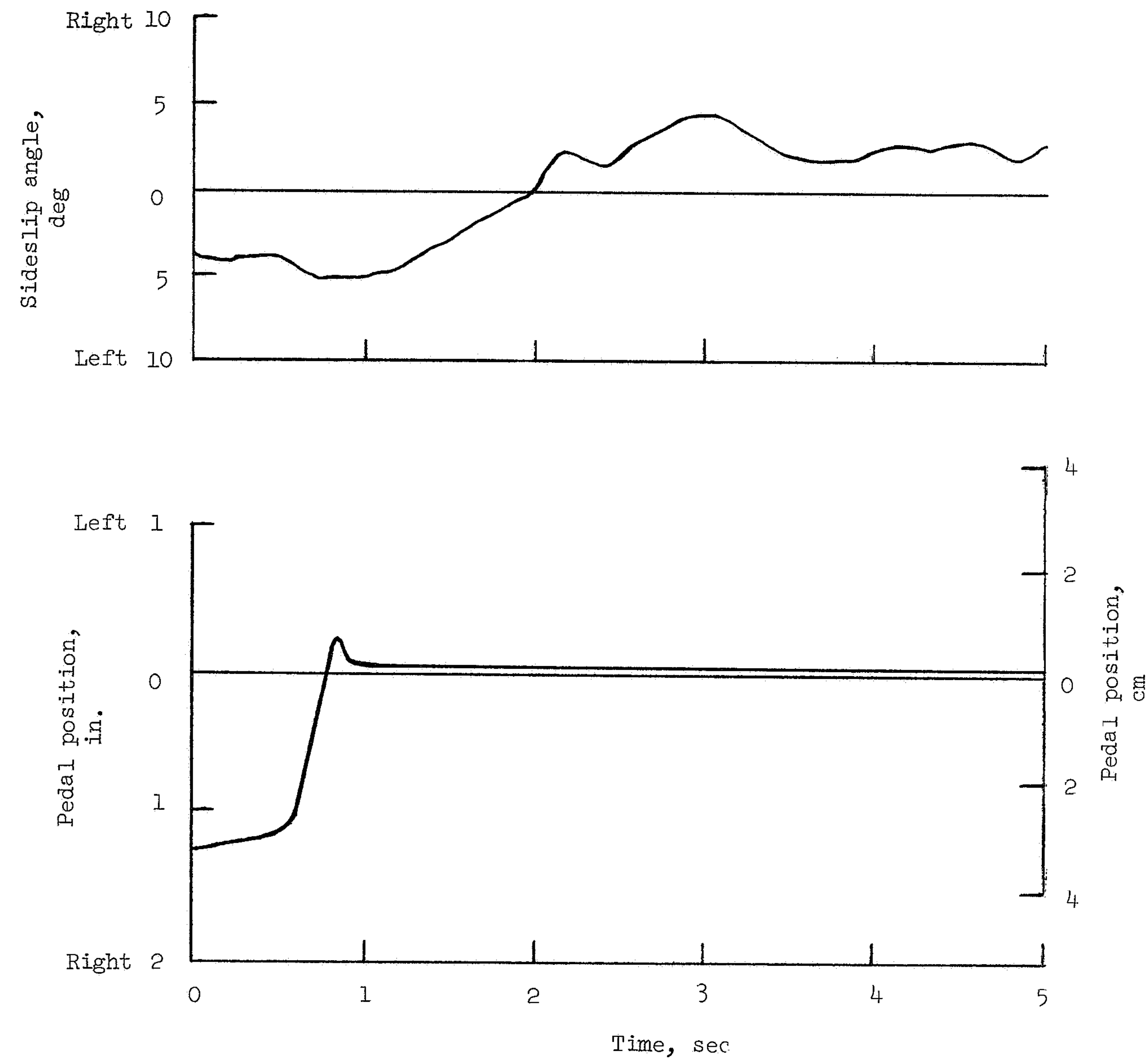

Figure 35.- Time history of pedal release from left sideslip with yaw SAS off. Airspeed of 100 knots; wing incidence of 15°; flap incidence of 5°

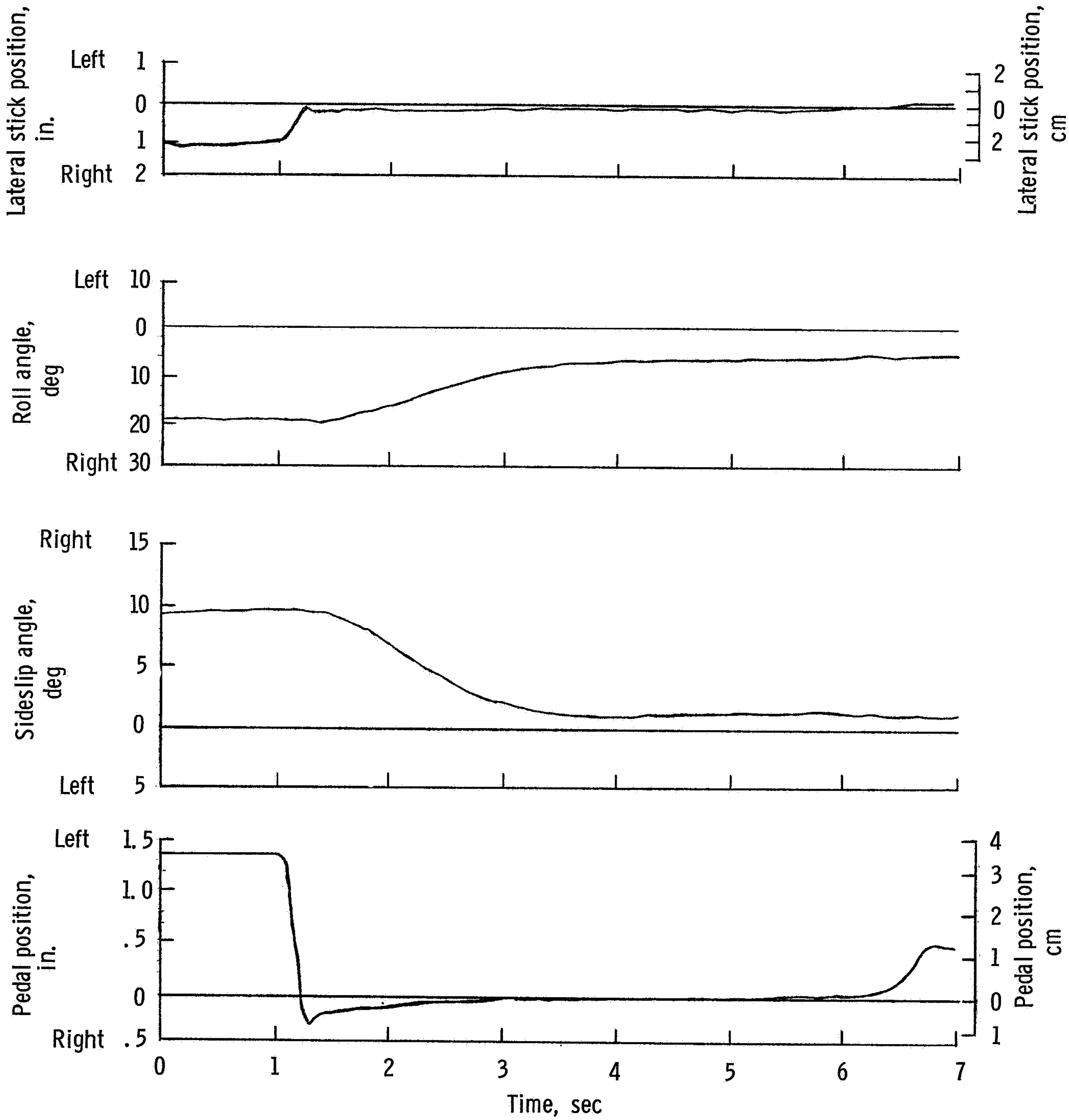

Figure 36.- Time history of pedal release from right sideslip with yaw SAS off. Airspeed of 175 knots; wing incidence of 0^{0}; flap incidence of 0^{0}

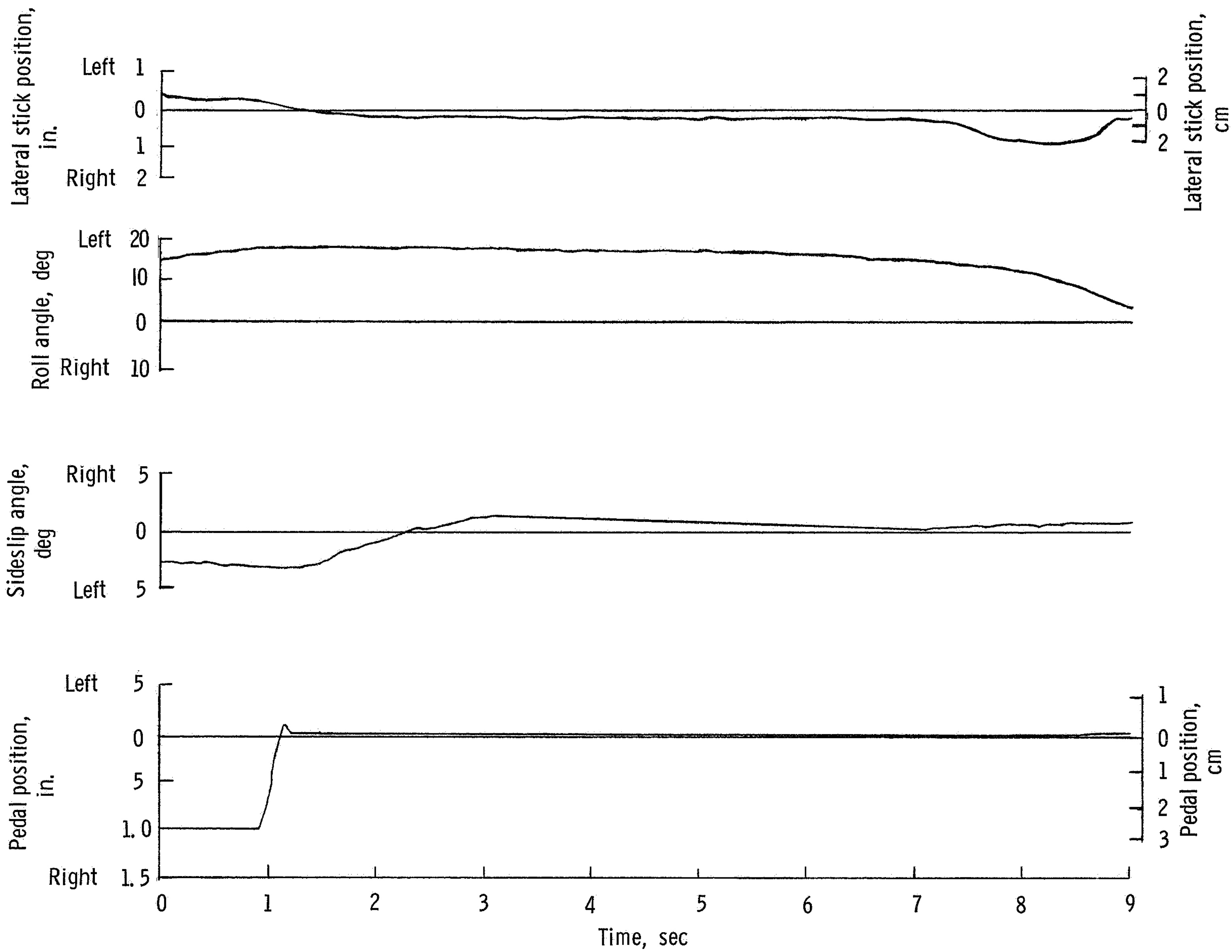

Figure 37.- Time history of pedal release from left sideslip with yaw SAS off. Airspeed of 175 knots; wing incidence of 0°; flap incidence of 0°

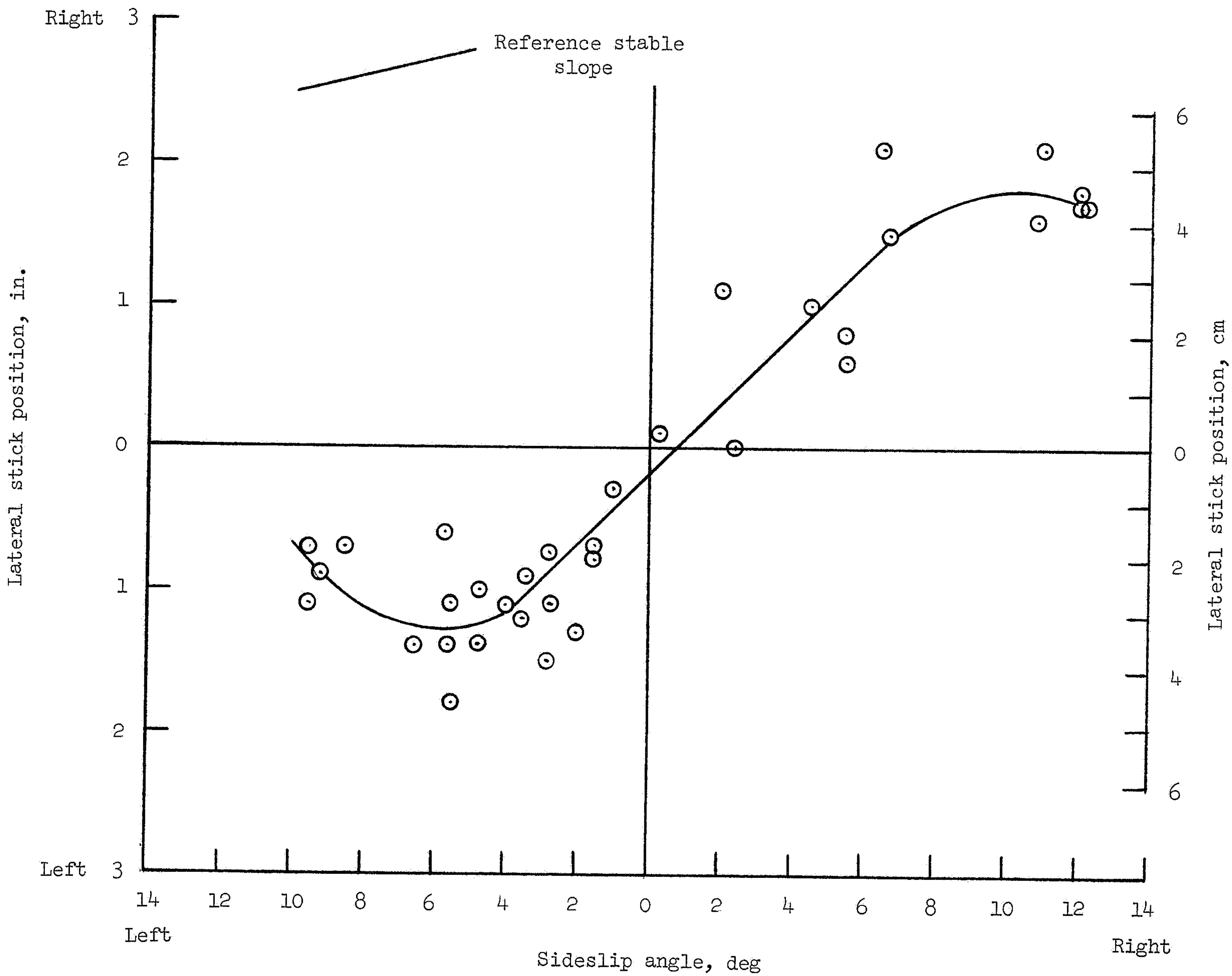

Figure 38.- Effective dihedral at 42 knots. Wing incidence of 40^{o}. flap incidence of 24^{o}

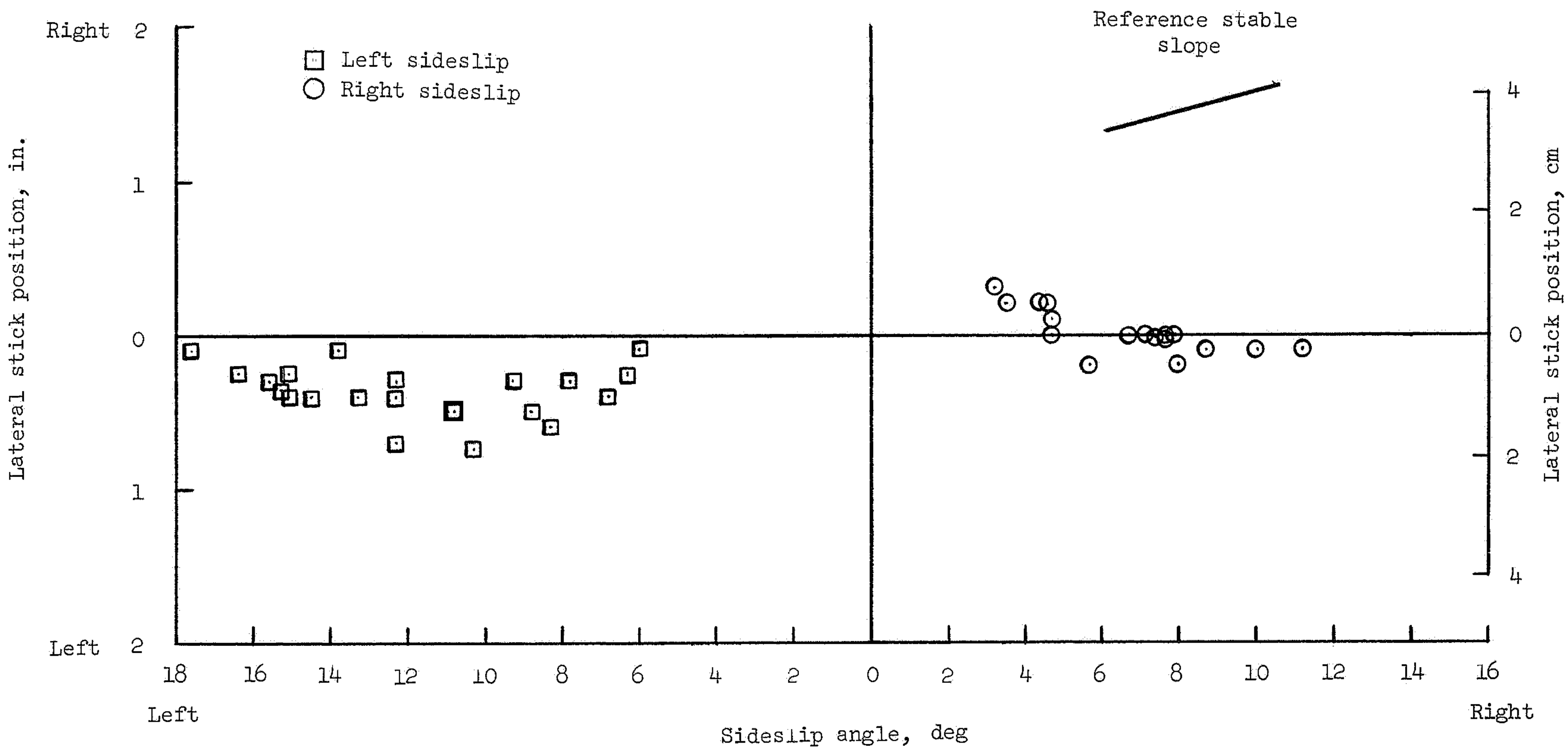

Figure 39.- Effective dihedral at 100 knots. Wing incidence of 15; flap incidence of 5^{0}

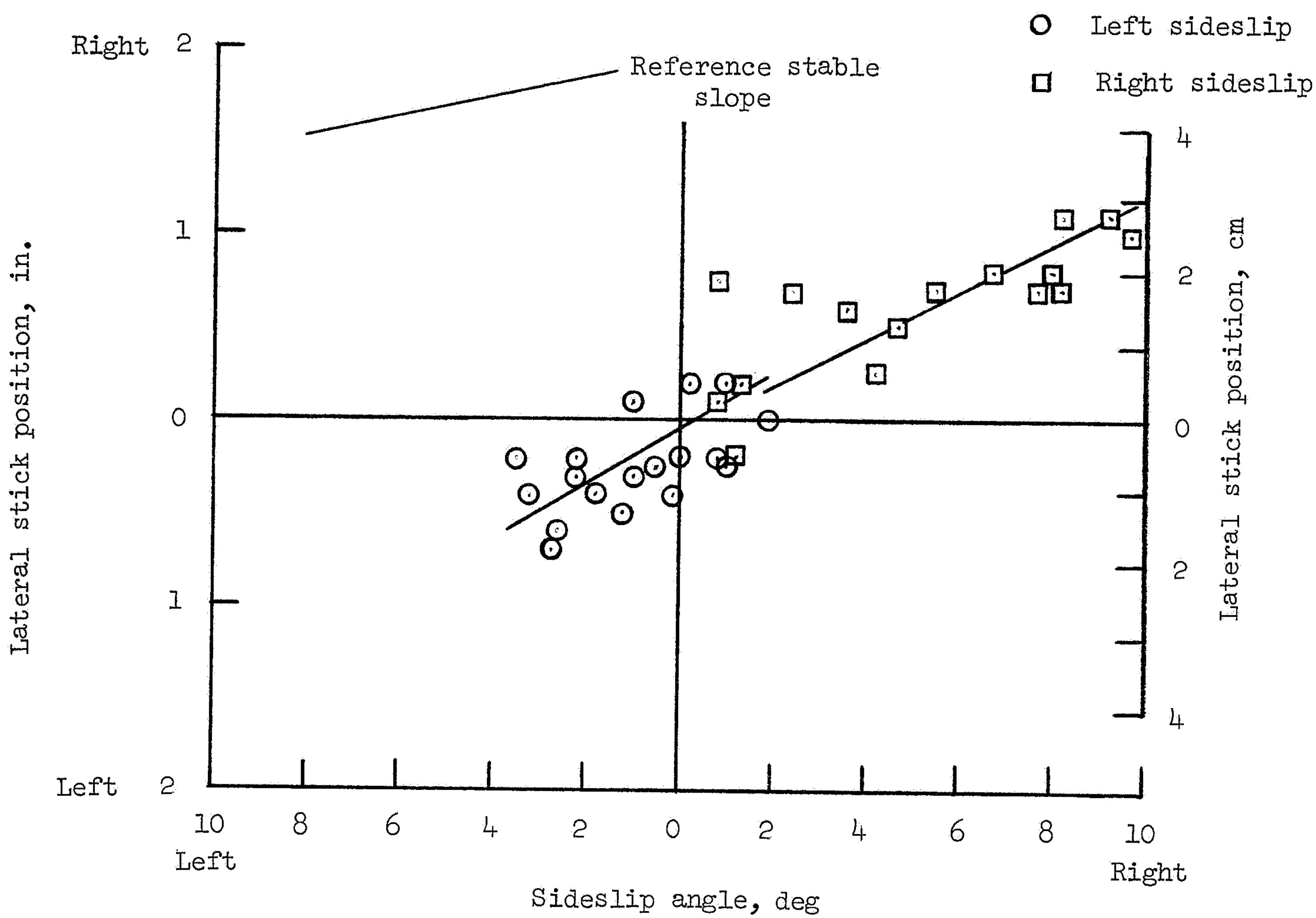

Figure 40.- Effective dihedral at 175 knots. Wing incidence of 0°, flap incidence of 0°

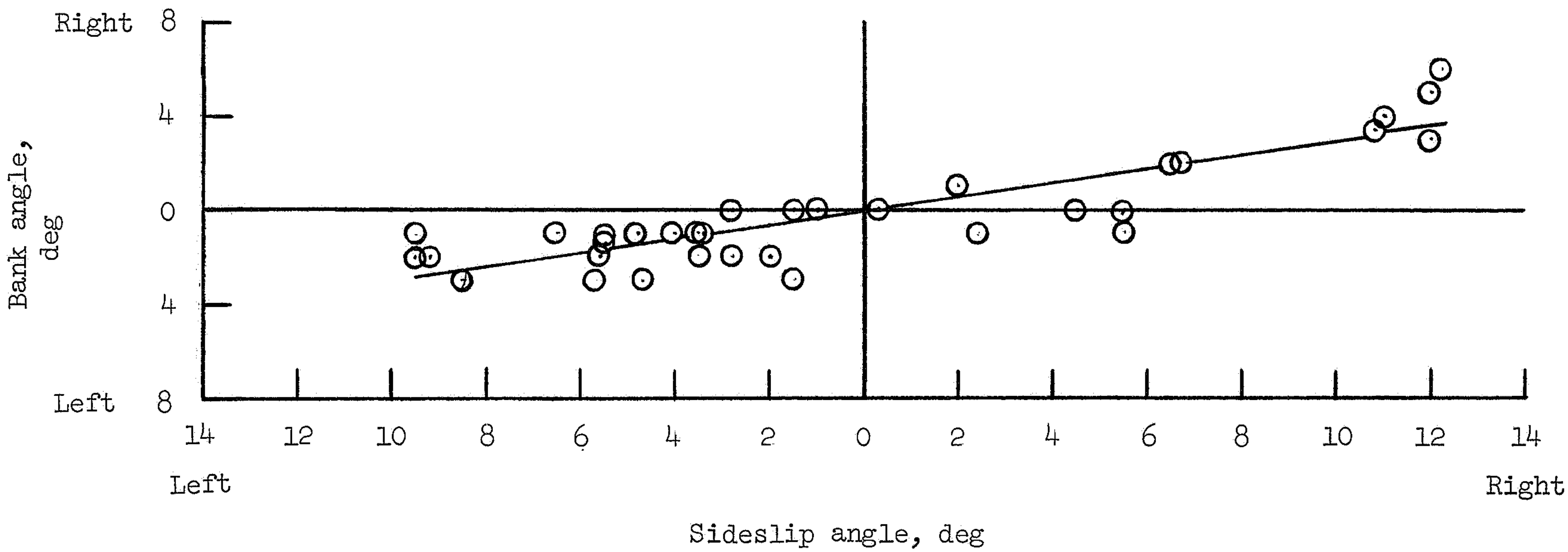

Figure 41.- Side-force characteristics at 42 knots in terms of bank angle required to maintain constant heading as a function of sideslip angle. Wing incidence of 40^0; flap incidence of 24^0

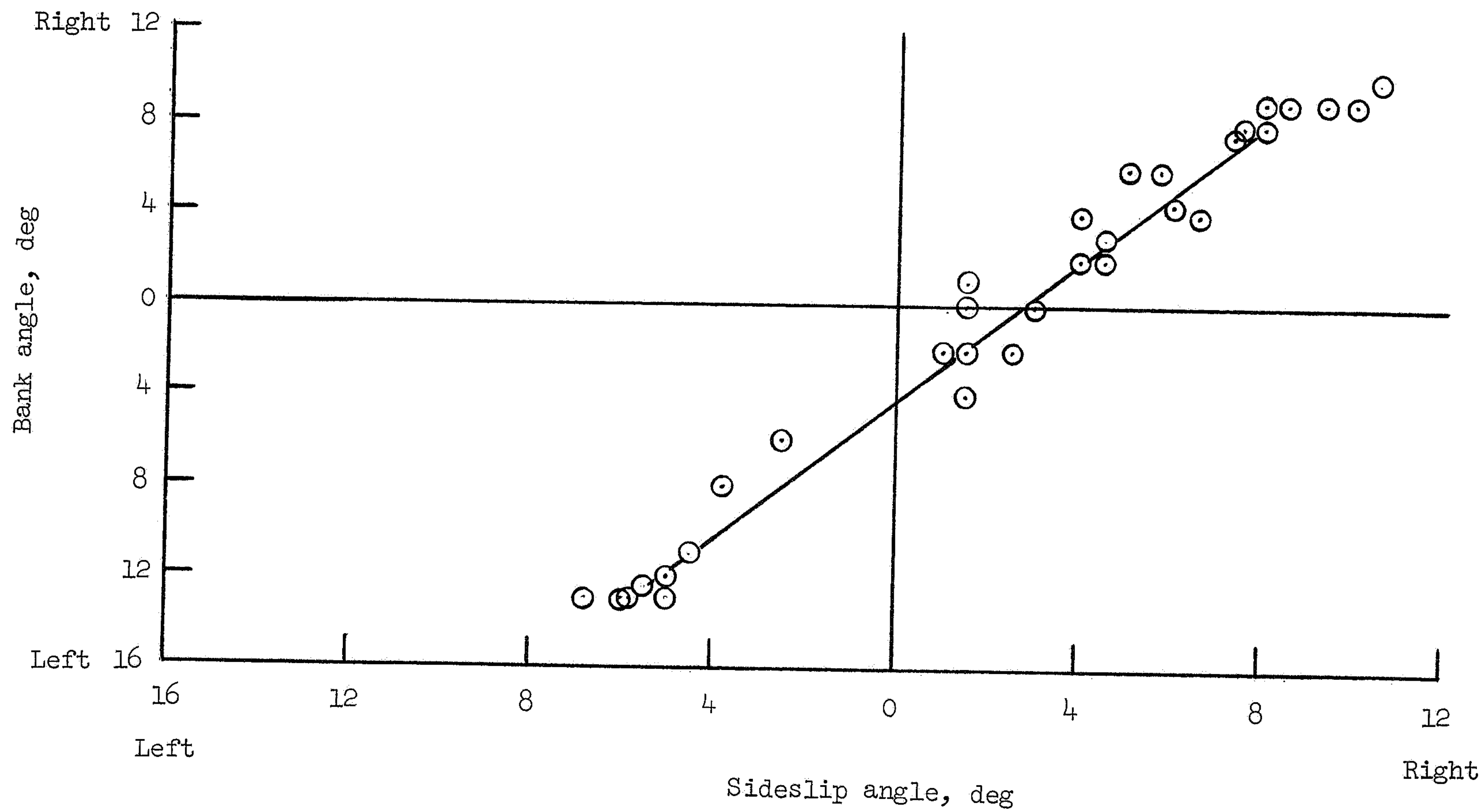

Figure 42.- Side-force characteristics at 100 knots in terms of bank angle required to maintain constant heading as a function of sideslip angle. Wing incidence of 15^0; flap incidence of 5^0

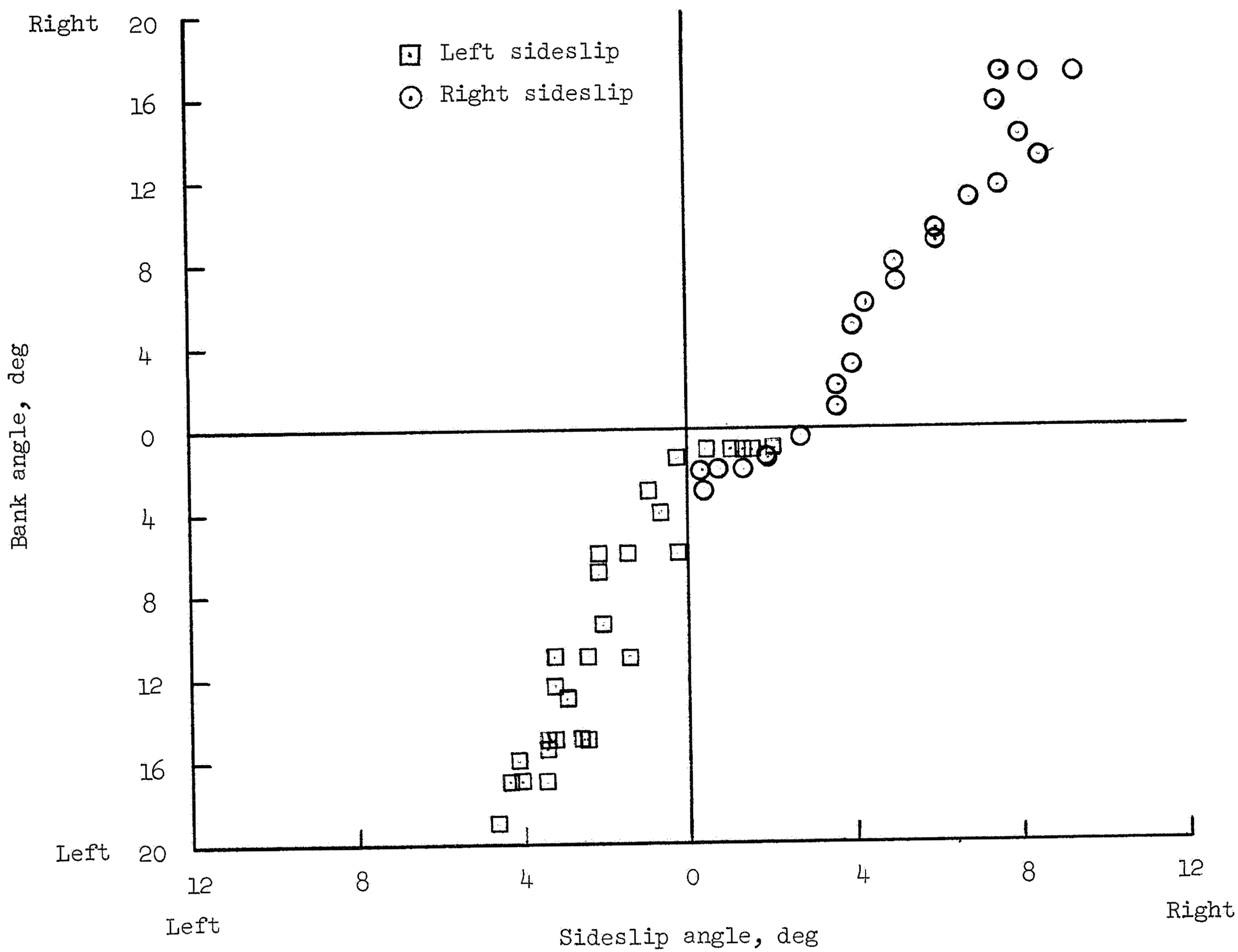

Figure 43.- Side-force characteristics at 175 knots in terms of bank angle required to maintain constant heading as a function of sideslip angle. Wing incidence of 0^0; flap incidence of 0^0

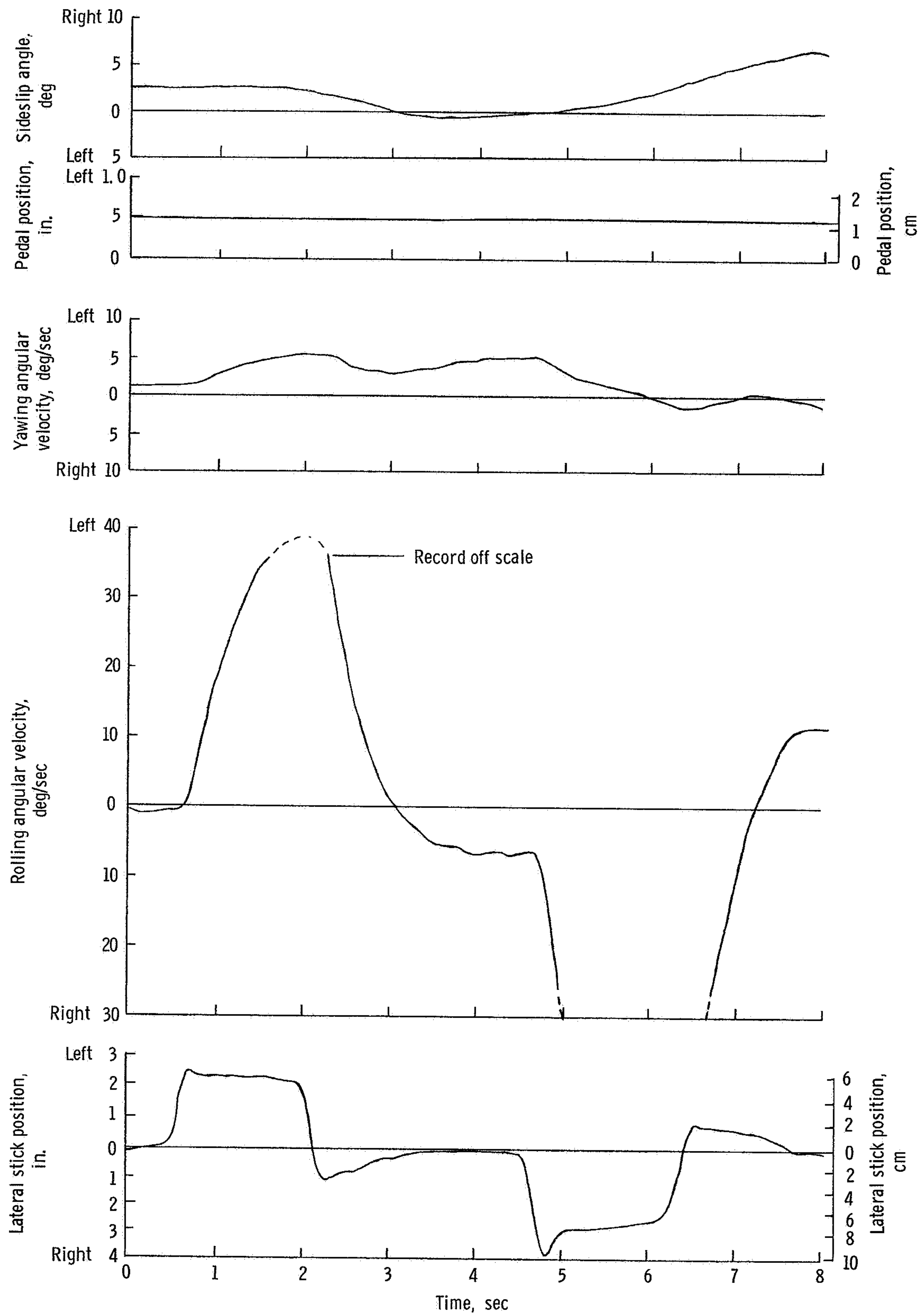

Figure 44.- Time history of pedals-fixed roll reversal in cruise flight with yaw SAS off. Airspeed of 175 knots; wing incidence of 0°. flap incidence of 0°

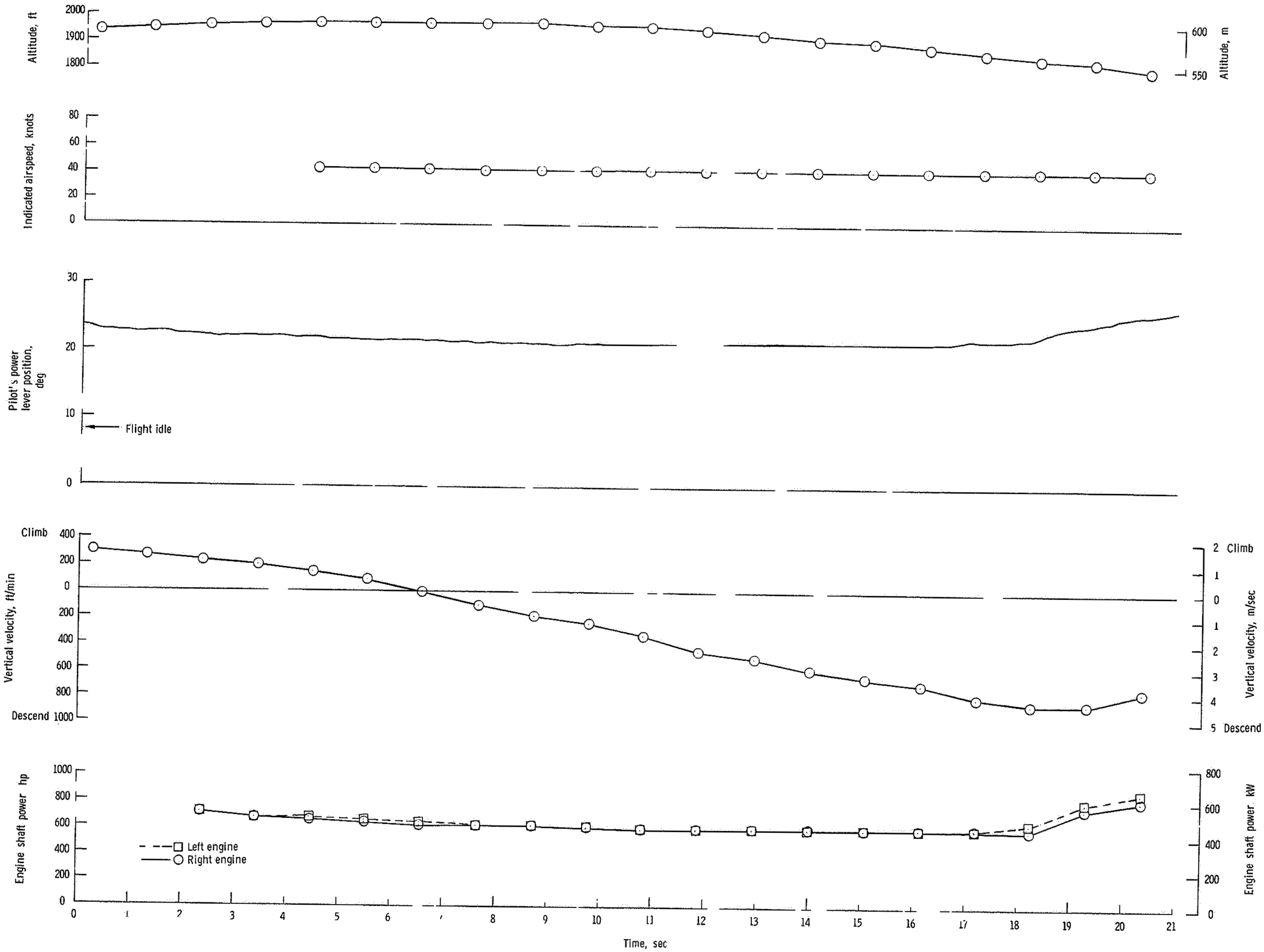

Figure 45.- Time history of rate-of-descent investigation at 42-knot airspeed indicating the slow arrest of rate of descent. Wing incidence of 40^{o}; flap incidence of 24^{o}.

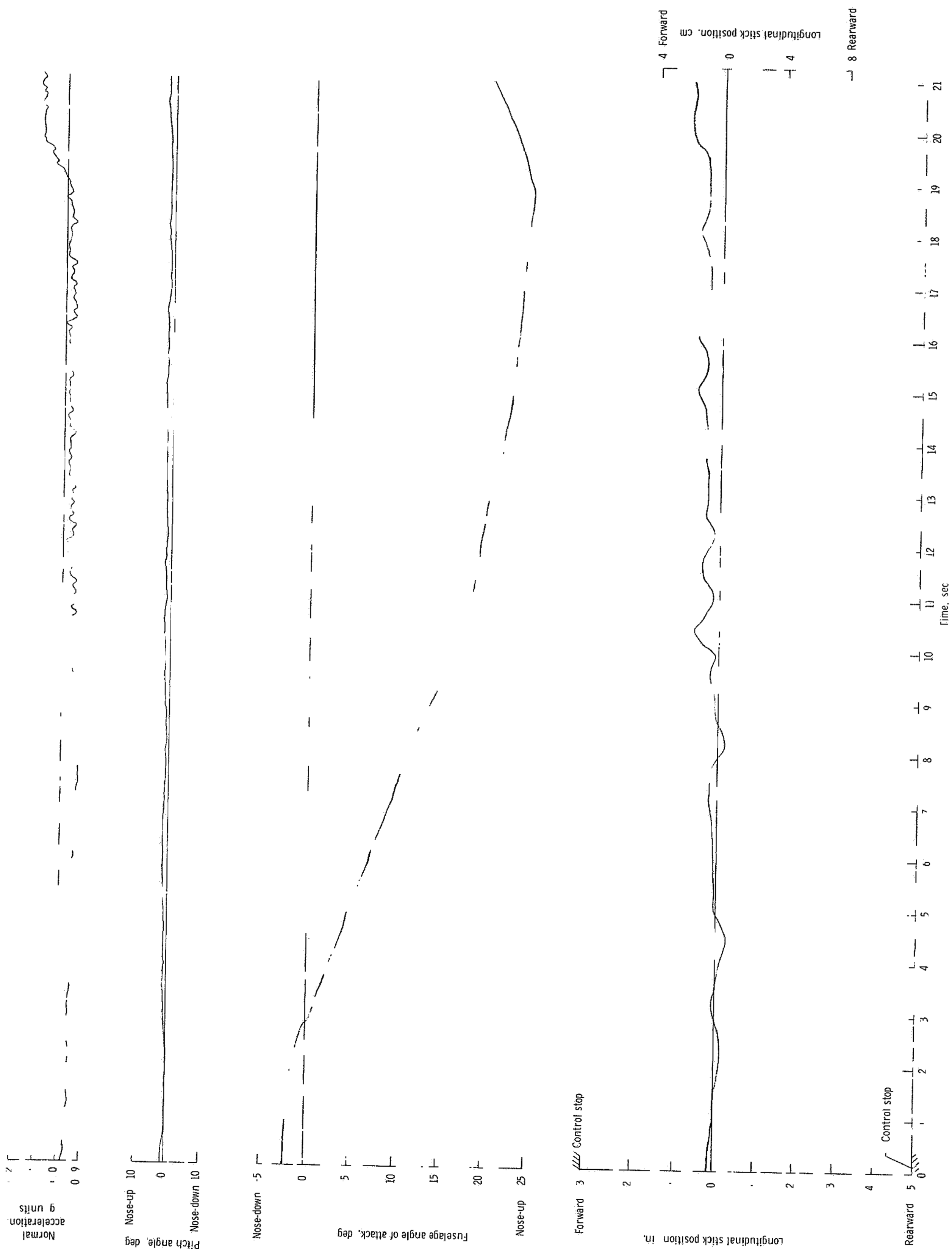

Figure 45.- Concluded.