NASA TECHNICAL NOTE

NASA TN D-6791

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NASA TN D-6791

A FLIGHT EVALUATION OF A VECTORED-THRUST-JET V/STOL AIRPLANE DURING SIMULATED INSTRUMENT APPROACHES USING THE KESTREL (XV-6A) AIRPLANE

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

1. Report No. NASA TN D-6791	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A FLIGHT EVALUATION OF A VECTORED-THRUST-JET V/STOL AIRPLANE DURING SIMULATED INSTRUMENT APPROACHES USING THE KESTREL (XV-6A) AIRPLANE		5. Report Date May 1972
		6. Performing Organization Code
7. Author(s) Samuel A. Morello, Lee H. Person, Jr., Robert E. Shanks, and Richard G. Culpepper		8. Performing Organization Report No. L-8254
		10. Work Unit No. 760-72-03-01
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 in-flight investigation was made to determine the terminal-area operating problems of a vectored-thrust-jet vertical and short take-off and landing (V/STOL) airplane under simulated instrument conditions. Handling-qualities data pertinent to the terminal-area approach and landing task are presented in the text, and additional documentation is included in the appendixes. Problems dealing with the cruise letdown to localizer capture, conversion to powered-lift flight, precise control of the glide slope, approach velocity or deceleration schedule, hover, and landing are discussed.

17. Key Words (Suggested by Author(s)) V/STOL approaches; Terminal-area operation; Jet vectored thrust		18. Distribution Statement Unclassified – Unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 76	22. Price* $3.00

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

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SUMMARY

A flight-test program was conducted to determine the problems associated with, and techniques suited to, operation of a simple vectored-thrust-jet vertical and short take-off and landing (V/STOL) airplane during simulated instrument flight in the terminal area. Results of the program indicated that attitude stabilization would be required to keep pilot workload at an acceptable level during instrument approaches. During the simulated instrument tasks that were evaluated, it was determined that conversion to powered-lift flight could be accomplished after glide-slope acquisition, and that glide-slope tracking by means of thrust modulation was more satisfactory than nozzle-angle modulation. Although approaches were accomplished at glide-slope angles up to 11°, the most satisfactory approaches were made on a 7° glide slope with a three-nozzle step deceleration to 65 knots.

INTRODUCTION

Most experience to date with V/STOL aircraft, other than helicopters, has been limited to visual flight with research aircraft. Several flight-test programs have been conducted to study terminal-area operations of different types of VTOL aircraft with particular emphasis on instrument flight. References 1 to 3, for example, discuss results of flight-test programs with a fixed-wing short take-off and landing (STOL) transport airplane having four turbopropeller engines, a V/STOL tilt-wing cargo aircraft having four turbopropeller engines, and a fixed-wing V/STOL transport having both lift and lift-cruise jet engines. The present investigation was made with a single-engine strike-reconnaissance V/STOL airplane to determine the problems associated with, and techniques suited to, a simple vectored-thrust-jet configuration. This configuration, which is similar to that of reference 3, has little or no vertical velocity damping when operating well below the wingborne stalling speed.

The program included take-off, deceleration from cruise, and approach to landing, the main emphasis being on the instrument landing system (ILS) approach task. Approaches were made over a range of glide-slope angles from 3° to 11° and at constant speeds of 110, 85, and 65 knots. (1 knot = 0.514 m/sec.) Some approaches were also made in which nozzle angle was programed with altitude to achieve a three-step decelerating approach rather than a one-step conversion as in the case of the constant-speed approaches.

SYMBOLS

Measurements and calculations were made in U.S. Customary Units. They are presented herein in the International System of Units (SI).

b	wing span, m
C_L	lift coefficient, $\frac{\text{Lift}}{qS}$
F_s	longitudinal stick force, newtons
g	acceleration of gravity, meters/second^2
h	height above runway, meters
I_{XX},I_{YY},I_{ZZ}	moments of inertia, kg-m^2
n_f	engine fan speed, percent of maximum speed
q	dynamic pressure, $\frac{1}{2}\rho V^2$, newtons/meter^2
S	wing area, meters^2
t	time, seconds
V	true airspeed, meters/second
Y	localizer lateral displacement, meters
y	wing spanwise coordinate, meters
α	angle of attack (from nose boom), deg
γ	flight-path angle, deg
δ_a	aileron deflection (positive when right aileron down), deg
δ_{tp}	tailplane deflection (positive trailing edge down), deg
θ	pitch attitude (nose-up attitude positive), deg

θ_j nozzle angle, deg

ρ density, kilograms/meter^3

TEST AIRCRAFT AND EQUIPMENT

A Hawker Siddeley Kestrel (XV-6A) was used as the test airplane in this flight investigation. The Kestrel is a prototype, single-place, vectored-thrust-jet V/STOL strike-reconnaissance airplane. A photograph of the instrumented test airplane is presented in figure 1 and a three-view drawing in figure 2.

A single Rolls Royce Pegasus Mark 5 engine powers the Kestrel. The Pegasus is an axial-flow, vectored-thrust turbofan engine with an uninstalled sea-level static thrust rating of 69 000 newtons. The fan and high-pressure compressor counterrotate to avoid gyroscopic coupling. Thrust is vectored through two pairs of controllable engine exhaust nozzles. The installed thrust is almost equally distributed between the forward nozzles which exhaust cool air from the fan and the aft nozzles which exhaust turbine air. The nozzles are mechanically interconnected and can be rotated, at rates up to 90°/sec, to any position, from fully aft $(\theta_j = 0^\circ)$ for conventional flight to 5° forward of vertically downward $(\theta_j = 95^\circ)$. Nozzle angle is controlled by a single lever located inboard on the throttle quadrant which is the only additional control required for V/STOL flight in the Kestrel. General arrangements of the engine, nozzle drive system, and throttle quadrant are presented in figure 3.

Control moments during wingborne flight are provided by conventional aerodynamic surfaces. The ailerons and tailplane are powered by tandem hydraulic systems; however, the rudder is unpowered. Lateral control forces are provided by a nonlinear feel spring unit and longitudinal forces by a q-feel unit supplemented with a feel spring. A bobweight in the control run increases longitudinal maneuvering forces by 8.9 N/g for normal acceleration, and 4.9 N/(rad/sec^2) for pitch acceleration.

Reaction control moments are added to those produced by the normal aerodynamic surfaces during powered-lift operations. As the nozzle angle is deflected from the aft position (0°), high-pressure engine bleed air is directed to reaction control shutter valves at the nose, tail, and wing tips. Full reaction control bleed for 4 N/sec is obtained when the nozzle angle has reached 39°. The nose shutter is mechanically connected to the control stick and the remaining shutters to their adjacent aerodynamic control surfaces. No stability augmentation system (SAS) is provided. Additional aircraft and engine data are presented in table I.

Data Instrumentation

All data were stored on an onboard magnetic tape recorder using wide-band frequency-modulated (FM) recording techniques. To increase channel capacity, two channels were time shared by use of pulse-amplitude-modulation recording techniques. All data channels were also recorded on an onboard oscillograph for "quick-look" purposes. Electronic data conversion methods were used with the tape records to reduce the data to engineering units on tabulated printouts and plots for data analysis.

Cockpit Controls, Instrumentation, and Displays

Figures 4(a) and 4(b) illustrate the general cockpit arrangement, including engine and flight controls, and the primary cockpit display used in this evaluation. Raw glide-slope and localizer ILS error information were displayed on the attitude director indicator (ADI) and on the horizontal situation indicator (HSI). Flight director or command information was not available. Angle of attack was displayed on both the angle-of-attack indicator and an approach indexer which was set up for a nominal angle of attack of 6°. Sideslip indications were obtained visually from the boom-mounted instrumentation vane (fig. 1).

Approach Guidance

An AN/GSN-5 ground-based precision tracking radar system provided spatial position information from which both glide-slope and localizer deviation signals could be computed and displayed to the pilot. The radar guidance equipment has the capability of providing a wide range of glide-slope angles, geometries, and beam widths. Figure 5 presents a typical glide-slope and localizer geometry used in the program. Glide-slope beam width was varied between $+0.7^{\circ}$ and -0.7° for the 3° and 5° glide-slope approaches and between $+3.0^{\circ}$ and -3.0° for the 7°, 9°, and 11° glide-slope approaches. Both the glide-slope and localizer beam patterns were a combination of a constant-width segment followed by a constant-angle segment. During most of the tests, the apex of the constant-angle segment of the beam began at a horizontal range of 2440 meters, with the resulting glide-slope and localizer geometries illustrated in figure 5. The wider constant-angle segments for the glide slope were used mainly to give the pilot sufficient lead time before intercepting the steeper glide-slope center lines. The localizer constant-angle segment was $\pm 2.5^{\circ}$ for all the tests.

Test Procedures

Terminal-area flight tests were flown at the NASA Wallops Station (field elevation 10 meters). Because of the airplane's instabilities in the powered-lift mode (discussed under "Handling Qualities"), and because there was no safety pilot, simulated instrument approaches were flown by using a "peek-a-boo" instrument flight technique in which the pilot's vision was unobstructed. By using this technique, the pilot's concentration was primarily on his instrument task, but he had the benefit of peripheral visual cues for attitude stabilization and reduced localizer workload. The conversion to powered-lift flight was accomplished both prior to and after glide-slope intercept. During the latter part of the program, decelerating approaches to 65 knots at breakout were completed. The approach conditions were as follows:

Glide-slope angle, deg	Target final-approach velocity, knots
3	110, 85, 65
5	110, 85, 65
7	110, 85, 65, decelerating to 65
9	85, 65, decelerating to 65
11	65, decelerating to 65

Glide-slope intercept and conversion altitudes were chosen to provide a minimum of 90 seconds tracking time on the glide slope before breakout at 61 meters. Actually, for safety considerations, only a few conversions were made below 490 meters. Figure 6(a) presents the variation of intercept and conversion altitude with glide-slope angle and airspeed for the approaches. Figure 6(b) presents the corresponding rates of descents for the glide-slope angles and airspeeds of the test.

Airspeed, knots	Glide-slope angle, deg, of –									
	3		5		7		9		11	
	Nozzle angle, θ_j, deg	θ, deg	Nozzle angle, θ_j, deg	θ, deg	Nozzle angle, θ_j, deg	θ, deg	Nozzle angle, θ_j, deg	θ, deg	Nozzle angle, θ_j, deg	θ, deg
110	65	3	67	1	70	-1	--	--	--	--
85	71	3	73	1	76	-1	78	-3	--	--
65	77	3	79	1	83	-1	84	-3	86	-5

These approach speeds and glide-slope angles were flown with the nozzle angle fixed and the pilot maintaining, as closely as possible, a fixed-pitch attitude (θ). The nozzle-angle and pitch-attitude combination produced the desired approach speed and a nominal angle of attack of 6°. This condition left a safe margin for the angle-of-attack excursions ($\pm 4^{\circ}$) expected during glide-slope corrections.

RESULTS AND DISCUSSION

Handling Qualities

This section of the report will deal only with those handling qualities and characteristics of the Kestrel that directly affected the terminal-area results. Detailed documentation of the aircraft's longitudinal and lateral directional characteristics at each approach velocity is presented in appendix A. Miscellaneous aerodynamic data are presented in appendix B. Engine and control characteristics are presented in appendixes C and D.

Longitudinal handling qualities.- The longitudinal handling qualities of the Kestrel during low-speed conventional flight with the gear and flaps down are satisfactory for both visual and instrument approaches. Longitudinal static stability is low but positive. Pitch response is immediate, control sensitivity pleasant, the short period well damped, and the phugoid not bothersome. Trim changes with gear, flaps, and thrust are acceptable. As the nozzles are positioned for powered-lift flight, the longitudinal axis is degraded to unacceptable for the instrument approach task. Initially, a strong nose-up trim change (requiring about 35-percent forward stick) is encountered with the first 20° of nozzle movement. Once this large trim change is overcome, the pilot is aware of his inability to trim for hands-off flight in the longitudinal axis, and constant attention is required to prevent pitch divergences. The nose-up trim change and longitudinal instability are attributed mainly to the change in the downwash pattern at the tail during powered-lift flight. Reference 4 discusses the effects that the jet interference forces, induced by the exhaust jets on the fuselage and lower wing, have on trim. Attempts were made to document the effect of the longitudinal instability on instrument flight rules (IFR) terminal-area operation. Figure 7 is a time history of a typical pitch divergence at an indicated airspeed (KIAS) of 85 knots. This flight record illustrates the type of pitch divergence which might occur during instrument flight if the pilot were distracted from his primary control task. At time 0 to 4 seconds, there are no stick inputs by the pilot, stick force is zero, and the tailplane angle is constant. During this time period, an increasing nose-down pitch rate develops and the pitch-attitude divergence is approximately 15° in 2 seconds. During instrument flight at low speed where the acceleration cues are too small to be perceived by the pilot, this rate of divergence could be disastrous. This same type of divergence was also encountered in the powered-lift modes at 110 and 65 knots.

Lateral-directional handling qualities.- Generally, the lateral-directional characteristics of the Kestrel during low-speed conventional flight with gear and flaps down are satisfactory. The spiral mode is essentially neutral, roll response crisp, lateral control sensitivity well tailored, roll-rate damping satisfactory, and directional stability adequate for precise aileron-only turns. The Dutch roll mode which is easily excited and lightly damped is bothersome, but manageable. Stability characteristics are degraded during powered-lift operations. Effective dihedral (roll response to sideslip) is pronounced and directional stability decreases with airspeed. The Dutch roll also changes character with speed. At an indicated airspeed of 110 knots, the oscillation is easily excited and lightly damped with roll and yaw; there is also a tendency to couple into the pitch axis that is apparent to the pilot. As the speed decreases to 85 knots, the roll-yaw ratio becomes larger and the aircraft is easily disturbed laterally. At an indicated airspeed of 65 knots, the roll-yaw ratio is small and directional stability is no longer apparent. The pilot is aware of a low-frequency yawing oscillation which seems to be sustained by rudder inputs in an attempt to hold heading and/or to reduce sideslip.

The crosswind limitations imposed on the Kestrel during powered lift are an attempt to reduce or eliminate dynamic sideslipping maneuvers that can lead to a loss of control due to the high effective dihedral which, in this case, may produce rolling moments exceeding the available control moments. These limitations are as follows:

(1) The maximum crosswind component for vertical take-off and landing (VTOL) and transition is 15 knots and for short take-off and landing (STOL) is 10 knots.

(2) Flight at 0 to 30 knots:

(a) Positioning maneuvers involving turns are permitted.

(b) When translating rearwards or sideways, the airspeed component should not exceed 20 knots.

(3) Flight at 30 to 90 knots:

(a) Large turning maneuvers are not permitted.

(b) Sideslip should be minimized.

(4) Flight at 90 to 150 knots – straight flight and turning maneuvers are permitted provided that

(a) 20° bank angle is not exceeded.

(b) Sideslip is minimized.

(c) A heading change of 90° is not exceeded.

Steady sideslip documentation data (see fig. 23) indicate that under controlled conditions, it is possible (but not easy) to establish relatively steady sideslip angles with the data indicating stable slopes. Dynamic sideslips, however, are somewhat different. Figure 8 illustrates a documented loss of lateral control at an indicated airspeed of 110 knots initiated by a rudder false start. A small initial left rudder pulse followed by 60-percent right rudder was used to trigger the divergence. As the left sideslip angle increased to 8°, right roll rate increased to 32°/sec and was then stabilized momentarily with full left aileron. When the aileron was relaxed, roll rate continued to increase to beyond 60°/sec and the aircraft rolled beyond 60°. Full aileron was not sufficient to allow recovery until sideslip was eliminated with the rudder. The roll divergence occurred in approximately 2 seconds and could be catastrophic near the ground. The severity of the problem is increased with angle of attack and is adequately discussed in reference 5.

To document the pilot's directional handling problems, precision-heading changes were attempted in the 110- and 65-knot configurations. Figure 9(a) is a time history of the response of the aircraft at 110 knots during attempts at precision-heading changes. The heading changes are slightly oscillatory but the pilot was able to capture the target heading without great difficulty. Figure 9(b) is a time history of the response of the aircraft at 65 knots during attempted precision-heading changes similar to those that may be required during an instrument approach. Because of the reduced lateral-directional stability at this speed, the turns to the target headings are erratic and cannot be accomplished in a precise manner. Lateral-stability augmentation in terms of roll stabilization with turn coordination and/or heading hold would be required for precise localizer tracking during instrument approaches.

Directional handling problems occur at low speeds because the "weathercock" stability decreases with speed. An unstable yawing moment, due to the intake momentum drag ahead of the center of gravity, tends to turn the nose of the aircraft out of the relative wind.

Terminal Area

The main part of this program focused on identifying the problems associated with managing powered lift in the terminal area and developing operational techniques to best utilize the vectored-thrust concept. The research effort concentrated on the conversion to powered-lift flight prior to and after glide-slope acquisition and the use of thrust modulation or nozzle-angle modulation as a means of controlling the glide slope. The stability and control characteristics of the aircraft which hindered the instrument approach task were identified and, in some instances, the required corrections were noted. Problems dealing with the cruise letdown to localizer capture, breakout, flare, and landing were examined on a limited basis.

Cruise letdown to localizer capture.- From cruise, a straight-in descent at 250 knots and 3000 meters was made into the terminal area. As a conventional aircraft (nozzles aft), the Kestrel exhibited low but positive static longitudinal stability and an apparently neutral spiral mode. Simulated instrument flight across an initial approach "fix" was a relatively easy task except for the small effort required to maintain precise altitude control. Trim changes associated with speed-brake actuation and thrust changes were acceptably small and the straight-in descent and leveling off prior to glide-slope intercept was made at a low workload level. Leveling off prior to glide-slope intercept presented no problem in this airplane. The 250-knot speed may be considered to be excessive for current terminal-area operation. Therefore, maneuvering speeds of 180 to 200 knots were tried in the clean configuration (gear and flaps up), but were undesirable because at the high angle of attack required, a poorly damped Dutch roll invited pilot-sustained oscillations. A flaps-down maneuvering speed of 150 to 165 knots was finally selected as it provided a comfortable combination of angle of attack and thrust. The Dutch roll, however, was still easily excited, poorly damped, and distracting. In the Kestrel, most of the nose-up trim change associated with nozzle deflection occurs during the first 20° of travel and is minor for further increases in nozzle angle. On all the flights, therefore, a preconversion nozzle angle of 30° was selected after the gear and flap extension in level flight at an indicated airspeed of 150 knots and prior to selecting the nozzle angle required for full conversion to the desired approach speed.

Localizer tracking.- The localizer was normally acquired in the preconversion configuration (gear and flaps down, 30° nozzle angle) about 6.5 kilometers prior to glide-slope intercept at an indicated airspeed of 150 knots. This acquisition provided 60 to 90 seconds of tracking time before the conversion to powered-lift flight where the major emphasis was on the glide-slope tracking task. The pilot's scan pattern on the powered-lift approaches included a look at the boom-mounted sideslip vane and, therefore, invalidates localizer tracking performance data. Qualitatively, the pilot felt that lateral stability augmentation including turn coordination would be mandatory and heading hold would be highly desirable for actual instrument operations.

Conversion from wingborne to powered-lift flight.- One of the basic questions concerning the management of vectored thrust in the terminal area has been when and where to perform the conversion from wingborne to powered-lift flight. Two conversion techniques were investigated: the level conversion before glide-slope intercept and the conversion after the glide slope had been acquired.

The conversion in level flight (prior to glide-slope intercept) was performed first because it was thought that this procedure would evenly distribute and minimize the piloting tasks during the final approach as discussed in reference 6. Without additional onboard equipment, however, to predict and display the time remaining to glide-slope intercept, it was difficult for the pilot to initiate conversion at an optimum point. If the conversion was accomplished too soon, high power, with resulting high fuel consumption, was required longer than necessary. Also, the pilot was reluctant to use the high power required (because of reduced engine lift considerations) with the resultant settling tendency illustrated in figure 10(a). With inadequate thrust, settling and the resultant increase in angle of attack are inherent in the vectored-thrust-jet concept, which has little or no vertical velocity damping. If, however, the conversion was late and not completed by the time the glide slope was intercepted, the glide slope was overshot because of the overspeed condition, as illustrated in figure 10(b). The pushover and acquisition of the glide slope became an awkward and demanding task from this initial condition. In both cases, the glide-slope intercept and acquisition tasks were difficult, were time consuming, and reduced the available tracking time.

In addition, a low final approach velocity at small glide-slope angles requires an unrealistically low glide-slope intercept altitude (see fig. 6(a)) in order to minimize the time required at high thrust levels on the glide slope. Only a few conversions were made, therefore, at altitudes below 490 meters because low conversions are operationally unattractive from both safety and noise considerations.

After several conversions were made on the glide slope, it was realized that this technique posed less piloting problems and possessed certain advantages over the level conversion. Intercept, acquisition, and initial tracking of the glide slope were performed in nearly complete wingborne flight. (A partial conversion to 30° nozzle angle and 150 knots was made to take care of the initial trim change associated with nozzle deflection.) Maintaining this 150-knot configuration until final conversion on the glide slope eased the piloting task during acquisition, allowed higher intercept altitudes without increasing the time required on the approach, reduced the noise footprint since the required thrust is lower, and, in turn, reduced total fuel from conversion to landing. The conversion to final approach velocity was delayed to a predetermined altitude based on the deceleration and tracking time required. The conversion point in this case is well defined simply by an altitude on the glide slope.

As would be expected, the fuel required for an approach using the level conversion technique was considerably higher than that for an approach using the glide-slope conversion technique because of the greater time at high power. This condition is illustrated in figure 11 which compares the rates of fuel consumption for the two techniques during two 65-knot approaches on a 5° glide slope. When the conversion is made on the glide slope, the required high power is delayed; thus, a fuel saving of approximately 46 percent and a time saving of approximately 1 minute resulted. Although it is recognized that conversion at a lower altitude for the level-conversion technique would still provide the desired $1\frac{1}{2}$ minutes on glide slope and lower fuel consumption, it is unlikely that lower conversions would be acceptable from safety and noise considerations.

Glide-slope control.- Figure 12 illustrates the two methods of glide-slope control that were investigated during this program: (1) thrust modulation for direct lift control, and (2) nozzle angle modulation.

When the thrust modulation technique is used, the nozzle angle is dictated by the desired final approach velocity or deceleration schedule and is constant, pitch attitude is stabilized, and thrust modulated for direct lift control of the glide slope. The small variations in angle of attack during glide-slope error corrections were acceptable, and the deceleration schedule and final approach speed were essentially unaffected.

By using the nozzle-angle modulation technique, it has been anticipated that the thrust level would be constant as the nozzle angle was modulated for glide-slope control, and the pitch attitude altered during corrections to maintain a constant angle of attack and airspeed. The problems associated with simultaneous control of pitch attitude and nozzle angle for glide-slope corrections at a constant airspeed and with the inability to predict exactly the proper thrust level produced too high a workload for the pilot. A modified technique using nozzle-angle modulation at a constant pitch attitude at the expense of constant airspeed and angle of attack reduced the pilot workload to an acceptable level.

Figure 13 compares the two methods of glide-slope control used during 5°, 65-knot approaches. The conversion to powered-lift flight was accomplished on the glide slope for both approaches. For the thrust-modulation approach, the nozzle angle was fixed as a function of the desired approach velocity and glide-slope angle. The thrust was used as a direct lift control with little or no influence on speed. The pitch attitude was held as nearly constant as possible, and the variations in angle of attack experienced were between $+4^{\circ}$ and -4° of trim. Pitch attitude can be selected according to the glide-slope angle so that an adequate stall margin is maintained during the angle-of-attack excursions from trim. It can be seen that the throttle was the only control that the pilot used for tracking. In the approach power range, the engine time constant was about 1/2 second and was considered to be very satisfactory by the pilot.

For the nozzle-angle modulation approach, an attempt was made to set the thrust level and modulate the nozzle angle. It can be seen in the approach, however, that the pilot was unable to set a thrust level that suited the entire approach. Therefore, throttle activity to match nozzle settings added to pilot workload and to his concern about preventing settling or ballooning. Nozzle-angle changes are a powerful but sluggish velocity control as can be seen by the variations in the velocity during the approach. A nozzle-angle change produces little normal acceleration as compared with longitudinal acceleration and is, therefore, unsatisfactory for a precision tracking task. Also, during steep, slow-speed approaches, high nozzle angles were required, and modulation of the nozzle handle up to and over the hover stop was undesirable. The use of thrust modulation was the preferred technique for controlling the glide slope.

Decelerating approaches.- Although 85-knot, 7° glide-slope approaches were made to a hover, the pilot felt the rate of sink for this condition, 5.2 meters per second, would be unacceptably high for a 61-meter breakout and felt that the rate of sink should not exceed that corresponding to a 65-knot, 7° glide slope, or 4 meters per second. A number of decelerating approaches were, therefore, made to investigate this method of providing acceptable rates of descent during the final stages of steep angle approaches. With thrust modulation determined to be the better glide-slope control and nozzle angle modulation a good speed control, an attempt was made to achieve an approach with constant deceleration by programing nozzle angle changes with altitude, since the altimeter was the only available indicator of position along the glide slope. The nozzle angle was increased in three steps to reduce the speed from 150 knots to about 70 knots at breakout. Figure 14 is a time history of one of the decelerating approaches made. The glide-slope angle is 7° and the glide-slope control was by means of throttle modulation with the nozzle angle constant between the clearly defined nozzle steps.

A comparison is made in figure 15 of the time and fuel used for this approach and for a constant-speed, 65-knot approach. Initial conditions of 160 knots at a range of 6100 meters are the same for both approaches, but the decelerating approach started from an altitude of about 580 meters, whereas the initial altitude of the constant-speed approach was 460 meters. Although the conversion for the constant-speed approach was made at a lower altitude than the decelerating approach, 427 meters as compared with 580 meters, it required 28 seconds longer to reach the breakout altitude of 61 meters with a corresponding increase in approach fuel used of approximately 47 percent.

Breakout and flare.- The simulated instrument part of all approaches ended with a breakout to visual conditions at approximately 61 meters. After the breakout, the pilot must decelerate to a hover over the desired touchdown point and attain landing attitude. The time required from breakout to a stable hover is a function of the distance from the breakout to the touchdown point, final approach velocity, and acceptable deceleration rate. Glide-slope angle and its runway intercept point may be varied to establish the desired breakout distance. Therefore, steep angle, low-speed approaches require a runway intercept point relatively closer to the touchdown point than shallower angle, high-speed approaches.

The nose-down attitude required for an acceptable angle of attack during steep angle approaches in the Kestrel posed some interesting piloting problems. If the airplane was flared smoothly, visual contact with the touchdown point was lost; this condition is unacceptable. To gain better visibility for touchdown point precision, the Kestrel was decelerated to the hover in the nose-down approach attitude. At this point, simultaneous control of pitch attitude, nozzle angle, and thrust was required to establish the landing attitude. This task was a formidable one without aircraft stabilization since separate pilot controls for pitch, nozzle angle, and thrust are provided in the Kestrel. Ideally, the final stages of an approach would leave the V/STOL airplane in the proper touchdown attitude and configuration, with only thrust modulation being required for touchdown.

Ground effects in hover and landing.- A deliberately slow vertical descent from a hover to study recirculation effects near the ground is illustrated in figure 16. The time history shows airplane attitudes and control positions during a vertical landing from a hover at an altitude of 15 meters (altitude refers to main-wheel axle height above the ground). At the higher altitudes, above 6 meters, where the airplane was out of ground effects, the pilot described his workload as comfortably low because of the good control characteristics about all axes provided by the reaction control system and the good visibility from the cockpit. In hover out of ground effects, the airplane was neutrally stable statically and has essentially no damping. Yaw and roll control were used to maintain desired heading and keep the wings level, respectively, and pitch control was used to maintain zero ground speed by tilting the thrust vector through aircraft rotation since the nozzle angle was fixed in the hover stop position. For a height of about 5 meters (at $t = 34$ sec) on down to touchdown (at $t = 54$ sec), there was a noticeable increase in control activity that indicated increased pilot workload as the recirculation disturbances were encountered and the pilot operated his controls to minimize the angular velocities so that the actual airplane displacements were not appreciably greater near the ground than those at the higher altitudes. At about 4 meters (at $t = 37$ sec) the airplane exhibited a nose-down moment, probably due to increased lift on the horizontal-tail surface due to the reflection of the jet from the ground; this condition required trim corresponding to about 2° of tailplane (from $t = 37$ to 44 sec) to return to the desired pitch attitude of 5° for touchdown. At a height of approximately 2 meters (at $t = 46$ sec), there is a small "suckdown" which is compensated for by an increase in throttle as shown by the increase in fan speed.

Hot-gas reingestion during landing.- Two temperature probes, one at the bottom of each side of the inlet, were used to define the magnitude and character of the hot-gas reingestion during landing. A time history of a typical slow roll-on landing of approximately 15 knots ground speed is presented in figure 17. It can be seen that a slight increase in inlet temperature occurs at approximately 9 meters and remains essentially constant down to approximately 2.5 meters. At a height of approximately 2.5 meters to touchdown, the inlet temperature continues to increase depending upon how promptly the aircraft is landed and the thrust retarded. A typical increase of approximately 15° C was recorded during numerous slow roll-on landings. Landing vertically usually resulted in an inlet temperature increase of approximately 20° C, which occurred just prior to landing. The two temperature probes are not sufficient to show the temperature distortion across the inlet that can cause compressor stalls, but compressor stalls were not experienced throughout the program.

Performance and procedures for short take-off.- A typical short take-off is presented in figure 18. With the nozzles set at 30° down from the horizon, the airplane is accelerated by applying nearly full thrust with the throttle lever. When the speed of the airplane reaches 70 knots, the nozzles are brought down to 50° and the airplane becomes airborne almost immediately. The nozzles can then be slowly moved to the cruise position (0^{o}) as the airspeed increases. In this case, the nozzles are back to zero when the airspeed reaches 125 knots. This take-off is not a maximum-performance short take-off, but the ground roll and distance to clear a 17-meter obstacle give an indication of the take-off capability of the airplane.

Hot-gas reingestion during take-off.- Figure 19 is a time history of a typical vertical take-off and illustrates the reingestion before lift-off and its duration after the lift-off into the hover. It can be seen that the inlet temperature begins to increase when the nozzles are directed downward and the thrust is increased for take-off. As soon as the airplane is off the ground, the inlet temperature begins to decrease and continues to decrease before the conversion to wingborne flight is started.

Examination of inlet temperature data during short take-offs indicates that no significant reingestion occurs because the nozzles are at a relatively low angle of 30^{o} at the initial very low speeds; whereas at lift-off, where the nozzle angle was increased to 50^{o}, the forward speed was approximately 70 knots.

SUMMARY OF RESULTS

The results of a flight-test program using a single-place, single engine, vectored-thrust-jet airplane during simulated instrument approaches can be summarized as follows:

1. Although the Kestrel was neutrally stable to unstable about all axes in powered-lift flight, the airplane was easily controlled in visual flight because of a well-tailored control system. The control forces, sensitivities, and harmony were excellent.

2. Because of the lack of stability during powered-lift flight, pitch-attitude stabilization will be required for the instrument landing system (ILS) approaches. In addition, lateral stability augmentation in terms of roll stabilization with turn coordination and/or heading hold will undoubtedly be required.

3. Conversion from wingborne to powered-lift flight was accomplished more easily after glide-slope acquisition than before glide-slope intercept.

4. Glide-slope tracking by means of thrust modulation was more satisfactory than by means of nozzle angle modulation.

5. Although 11^{o}, 65-knot approaches were accomplished, the rate of descent at breakout (6.5 meters per second) was excessive. The most satisfactory was the 7^{o}, three-nozzle step decelerating approach, since for this case the rate of descent was decreased to 4 meters per second at breakout.

6. The programed decelerating approaches were made without great difficulty and provided a saving in time and fuel.

7. Although recirculation effects near the ground increased pilot workload significantly, they produced no serious control or trim problems.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., April 13, 1972.

APPENDIX A

HANDLING QUALITIES DOCUMENTATION

A brief handling qualities investigation was conducted prior to the terminal-area study. Most of the stability and control characteristics of the airplane were determined in steady descending flight at each of the approach airspeeds (165, 110, 85, and 65 knots) with the gear and flaps down at altitudes below 1500 meters. No attempt was made to determine fully the handling qualities at high speed or in the hover mode.

Static Longitudinal Stability

The data were obtained by first trimming the airplane at the desired airspeed and configuration. Without changing power or trim, the pitch attitude of the airplane was increased by aft stick movement to decrease the airspeed by approximately 5 knots. When stabilized at this condition, a data point was taken. The attitude was then increased further to reduce the airspeed for another data point. The data points for airspeeds greater than the trim airspeed were obtained in a similar manner where the pitch attitude was decreased to increase the airspeed.

Figure 20 presents plots of the variation of tailplane angle, longitudinal stick force, angle of attack, and pitch attitude with trim airspeed for 165, 110, 85, and 65 knots. The longitudinal static stability at 165 knots is positive and satisfactory for both visual and instrument flight. The data at 110, 85, and 65 knots were obtained by discrete data analysis, since the stick is constantly in motion. Although neutral stability is indicated in these data, the airplane actually possesses neutral to unstable longitudinal stability with divergent tendencies in the powered-lift modes.

Dynamic Longitudinal Stability

At 165 knots, a longitudinal control doublet was executed to evaluate the short period. The motion following the doublet was nonoscillatory and the damping ratio approximately 1.0, as determined from the flight records. Short-period data at 110, 85, and 65 knots were characterized by a slow to rapid divergence of pitch attitude following the doublet. Figure 21 illustrates the rate of divergence following a doublet at 85 knots. Some damping is evident in the pitch rate after the tailplane is centered. It can be seen, however, that the pitch attitude continues to diverge until a corrective input is made.

Pitch Control Power and Sensitivity

Figure 22 presents the pitch acceleration capability with tailplane angle for the four approach airspeeds and at hover. The data were obtained from pitch reversals at each airspeed. The hover data were taken from reference 7. Pitch control power in hover is 0.97 rad/sec^2 stick forward, and 0.53 rad/sec^2 stick aft as stated in reference 8.

Lateral-Directional Static Stability

The data during steady sideslips were obtained by first trimming the airplane at the desired airspeed and configuration with zero sideslip. Sideslip was then slowly developed (at a rate less than 1°/sec) with rudder inputs, and a constant flight path was maintained by using opposite aileron and bank angle as necessary.

Figure 23 presents steady sideslip data for each approach speed. Figure 24 shows the aileron required during wings-level sideslips at 110 and 85 knots. A steady sideslip was performed at 240 knots for comparison purposes and is presented in figure 25.

Lateral-Directional Dynamic Stability

The Dutch roll characteristics of the airplane were obtained from abrupt releases from the steady sideslip maneuvers. Figures 26(a) and 26(b) show the Dutch roll motion after the release from the sideslip. At 240 knots the period is 2.2 seconds, time to damp to half-amplitude is 1.6 seconds, and damping ratio is 0.155. At 165 knots the period is 3.0 seconds, time to damp to half-amplitude is 2.85 seconds, and damping ratio is 0.120. The releases at 110 knots (fig. 26(c)) were somewhat questionable because of small inadvertent aileron inputs during the motion, but the following approximate characteristics were recorded: Dutch roll period approximately 3.4 seconds, time to damp to half-amplitude approximately 6.8 seconds, and damping ratio 0.06. Because of the rolling and yawing motion following sideslip releases at 85 and 65 knots, it was impossible for the pilot not to add lateral inputs inadvertently during the motion. Lateral-directional oscillatory characteristics at 110 knots were judged to be easily excited and magnified by pilot inputs. Figure 26(c) illustrates a typical lateral-directional oscillation that occurred during a 110-knot approach.

Lateral Control Power and Sensitivity

Roll accelerations as functions of aileron deflections obtained during roll reversals are presented in figure 27 for the 165-, 110-, 85-, and 65-knot configurations, and at hover. The hover data were taken from reference 7. Lateral control power in hover is 1.88 rad/sec^2, as stated in reference 8.

Directional Control Power and Sensitivity

Yaw accelerations as functions of rudder deflections are presented in figure 28 for each of the four approach velocities and at hover. Hover data were taken from reference 7. Directional control power is 0.38 rad/sec^2 as stated in reference 7.

APPENDIX B

AERODYNAMIC DATA

Figure 29 presents the variation of lift coefficient with angle of attack taken from level-flight data. The data are for the clean airplane with zero nozzle angle. Also shown for comparision are the data from wind-tunnel tests of reference 9 for trimmed conditions. Figure 30 illustrates the variation of wing angle of attack with spanwise location during partial powered-lift flight. The data points indicate the spanwise location of four angle-of-attack vanes. These vanes sensed the flow at a position 10 percent of the local chord forward of the leading edge and 10 percent of the local chord below the chord line of the wing. The data show the effect of a general flow change over the aircraft due to the induced entrainment of air when the thrust is deflected downward.

Figure 31 presents the variation of the powered lift required as speed is reduced from total wingborne flight at 165 knots and above to the hover condition.

Figure 32 presents trim data points at 155 knots in level flight showing the angle of attack, engine fan speed, and nozzle angle required. Figure 33 presents tailplane angle trim data at 155 knots level flight with varying nozzle angle conditions.

APPENDIX C

ENGINE CHARACTERISTICS

Figure 34 presents the variation of engine fan speed with throttle deflection. The calibration was performed during engine runs on the ground. Figure 35 presents the engine response characteristics at altitude during engine acceleration tests. Figure 36 presents a summary of engine fuel flow readings during ground runs.

An attempt was made to determine the actual installed thrust in the aircraft in hover. The weight of the aircraft at the beginning of each flight was known (within ±222.5 newtons) and also when each 44.5 newtons of fuel is used (from fuel totalizer records). Therefore, the weight of the aircraft at any specific time during the flight could be determined. Figure 37 is a plot of the fan speed required during several steady hovers at different weight conditions. The scatter in the data is probably due to the data correction process to standard barometric pressure and air temperature conditions, and to the realization that the fan speed is known to within ±0.5 percent. To estimate the actual thrust that the engine is producing at these fan speeds, the hovering weight must be multiplied by 1.05, since a 5-percent loss in thrust (approximately) occurs because of reaction control bleeding of the engine.

APPENDIX D

CONTROL CHARACTERISTICS AND RELATIONS

The variations of the conventional control surface deflection with the pilot control for the longitudinal, lateral, and directional axes are presented in figures 38 to 40. Figure 41 presents the longitudinal stick-force characteristics. These data are results of static calibrations taken on the ground.

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3. Holzhauser, Curt A.; Morello, Samuel A.; Innis, Robert C.; and Patton, James M., Jr.: A Flight Evaluation of a VTOL Jet Transport Under Visual and Simulated Instrument Conditions. NASA TN D-6754, 1972.

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7. Andrews, S. J.; Fisher, I. A.; Norris, E. J.; Smith, J. P.; Warren, J. F.; and Patterson, G. A.: Kestrel F. G. A. Mk. 1 C.A. Release Trials. Rep. No. AAEE/939, Pt. 3, Brit. Min. Aviat., Dec. 10, 1965.

8. McKinzie, Gordon A.; Ludwig, John H.; Bradfield, Edward N., Jr.; and Casey, William R.: P-1127 (XV-6A) VSTOL Handling Qualities Evaluation. FTC-TR-68-10, U.S. Air Force, Aug. 1968.

9. Margason, Richard J.; Vogler, Raymond D.; and Winston, Matthew M.: Wind-Tunnel Investigation at Low Speeds of a Model of the Kestrel (XV-6A) Vectored-Thrust V/STOL Airplane. NASA TN D-6826, 1972.

TABLE I.- GENERAL AIRCRAFT AND ENGINE DATA

Weights and inertia:	
Empty weight, N	45 390
Design gross weight, N	78 320
Maximum hovering weight, N	57 850
Total internal fuel, N	22 250
I_{ZZ} at 51 200 N, kg-m^2	3.20×10^4
I_{YY} at 51 200 N, kg-m^2	2.95×10^4
I_{XX} at 51 200 N, kg-m^2	0.47×10^4
Fuselage:	
Length, m	12.97
Height to top of vertical tail, m	3.28
Wetted area, net, m^2	45.99
Wing:	
Area, gross, m^2	17.32
Area, net, m^2	12.27
Span, m	6.98
Mean aerodynamic chord, m	2.49
Dihedral angle, deg	-12.0
Taper ratio	0.40
Aspect ratio	2.8
Sweepback of leading edge, deg	40.0
Aileron area, m^2	0.98
Left-aileron travel limits:	
Trailing edge full down, deg	12.0
Trailing edge full up, deg	13.0
Trim range, deg	±3.5
Flap area (left and right), m^2	1.23
Flap travel limit, deg	50
Tailplane:	
Area, gross, m^2	4.41
Area, net, m^2	3.84
Span, m	4.24
Aspect ratio	3.26
Dihedral angle, deg	-15.5
Standard mean chord, m	1.04
Tailplane travel limits:	
Trailing edge full down, deg	11.5
Trailing edge full up, deg	10.0
Trim range, deg	7.5 to -3.5

TABLE I.- GENERAL AIRCRAFT AND ENGINE DATA – Concluded

Vertical tail:

Area, gross, m^2 . . . . 2.42

Aspect ratio 1.22

Rudder area, m^2 . . . . 2.58

Rudder travel limits:

Trailing edge left and right, deg 15.0

Trim tab movement, deg . . . . ±5.0

Reaction control system:

Full nose-up reaction pitch control at tailplane angle (trailing edge up), deg . . . 4.5

Full pitch control, tailplane (trailing edge down), deg 10.0

Full roll control, aileron (total), deg . . . . ±14

Full yaw control, rudder, deg . . . . ±10

Pitch reaction control arm about center of gravity:

Pitch, nose upward, m 4.62

Pitch, nose downward, m 7.26

Roll reaction arm about center line, m 3.39

Yaw reaction arm about center of gravity, m 7.08

Engine data:

Number and model . . . . Rolls Royce Pegasus Mark 5

Type . . . . Ducted fan

Intake area, m^2 . . . . 0.87

Bypass ratio 1.4

Maximum sea level thrust, uninstalled, N 69 000

Operating limitations:

Power rating	Reaction control bleed	n_f, percent	Exhaust gas temperature, °C	Time limit
Maximum	With bleed	93.5	645	2.5 min.
	No bleed	93.5	595	2.5 min.
Maximum continuous	With bleed	85.0	540	Unlimited
	No bleed	89.0	540	Unlimited

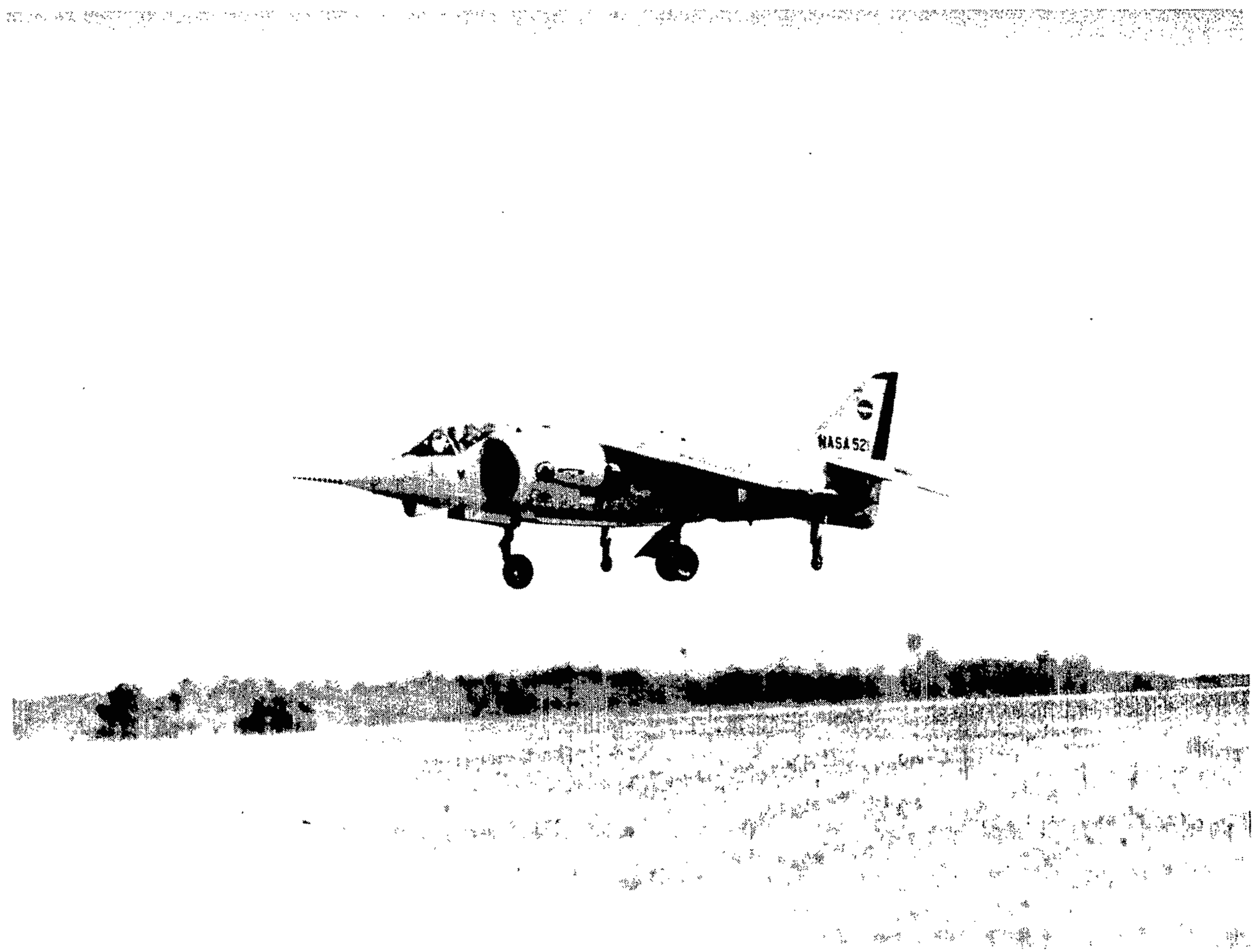

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Figure 1.- Photograph of Kestrel in hover flight.

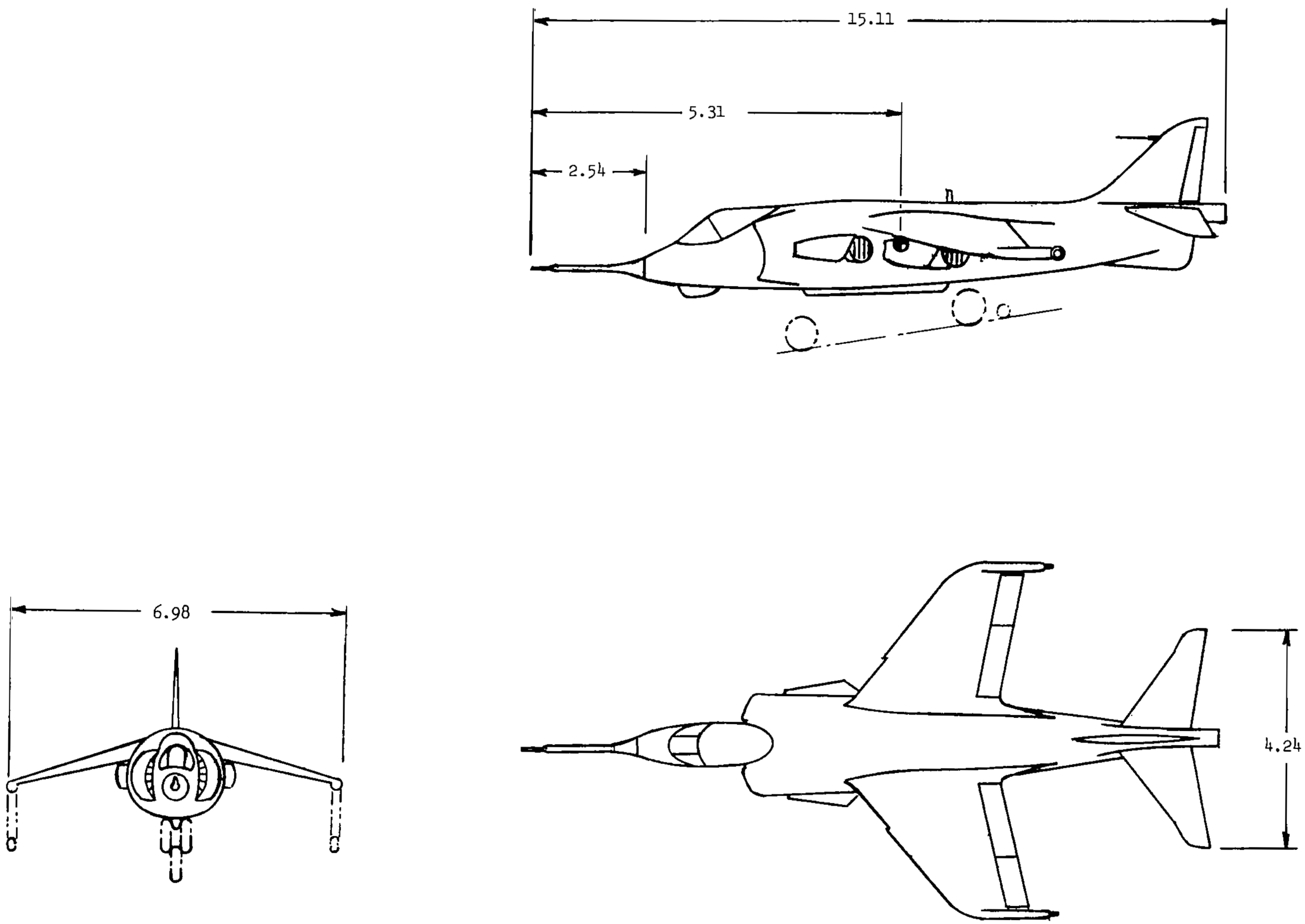


Figure 2.- Three-view drawing of test airplane. All linear dimensions are in meters.

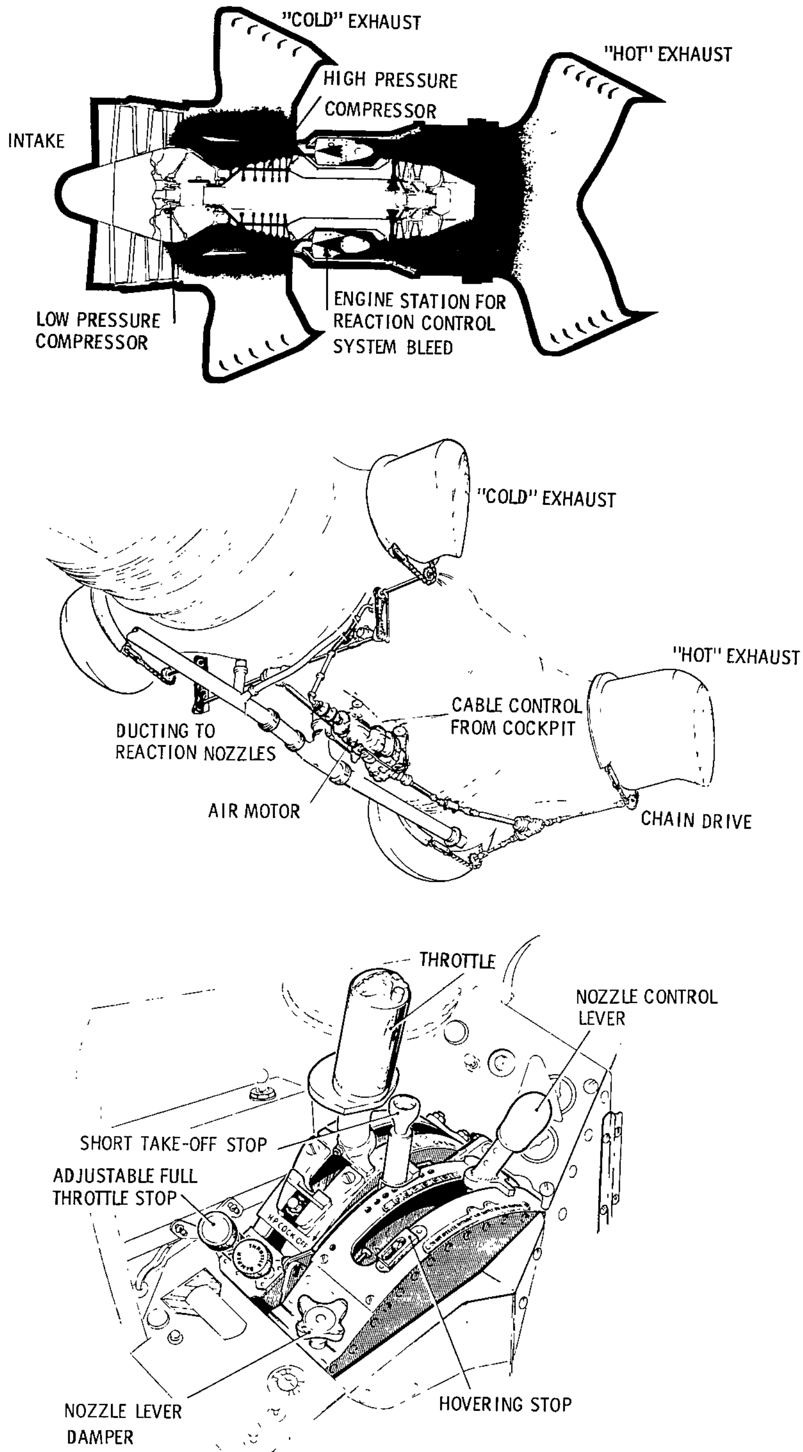
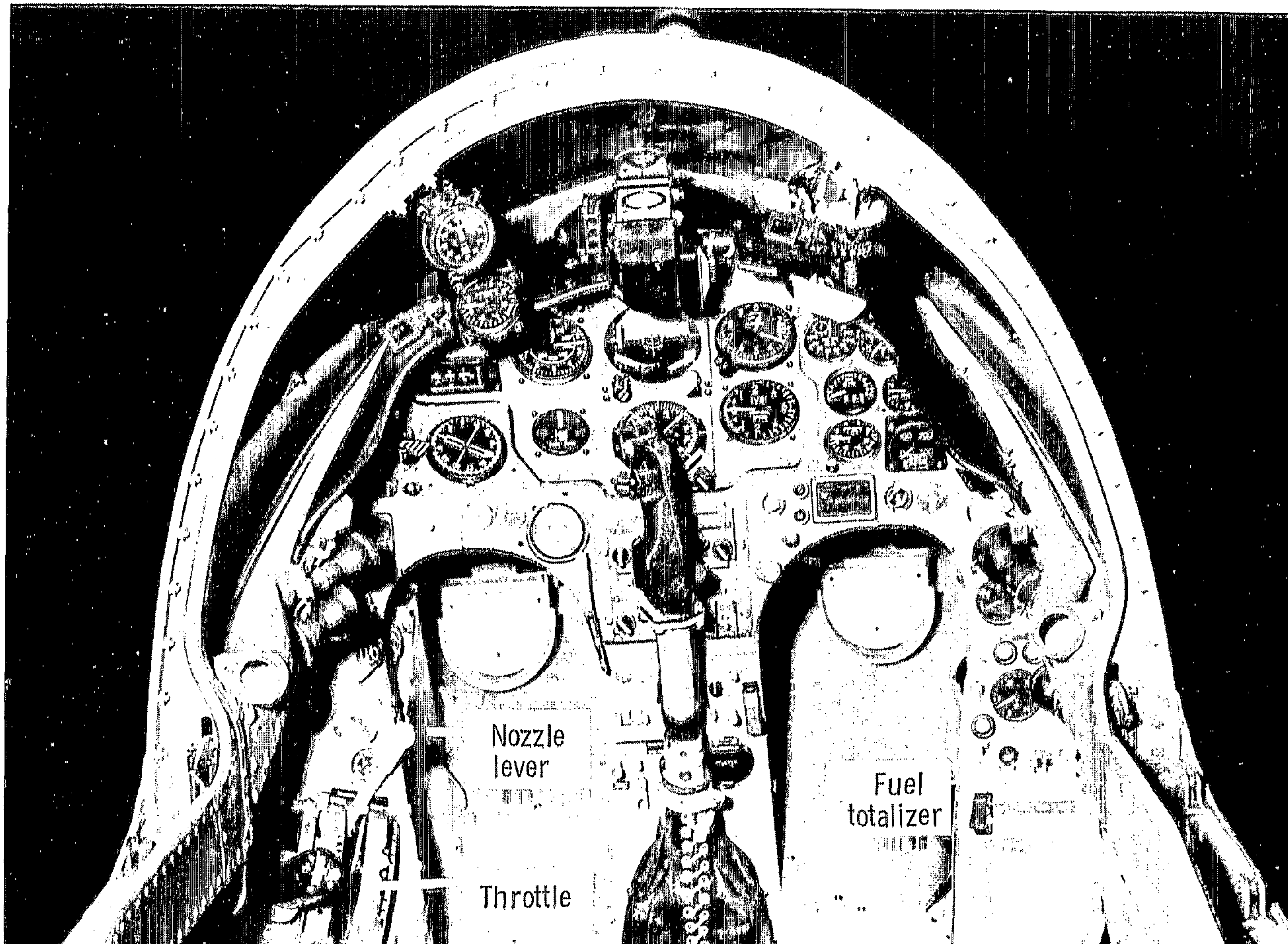


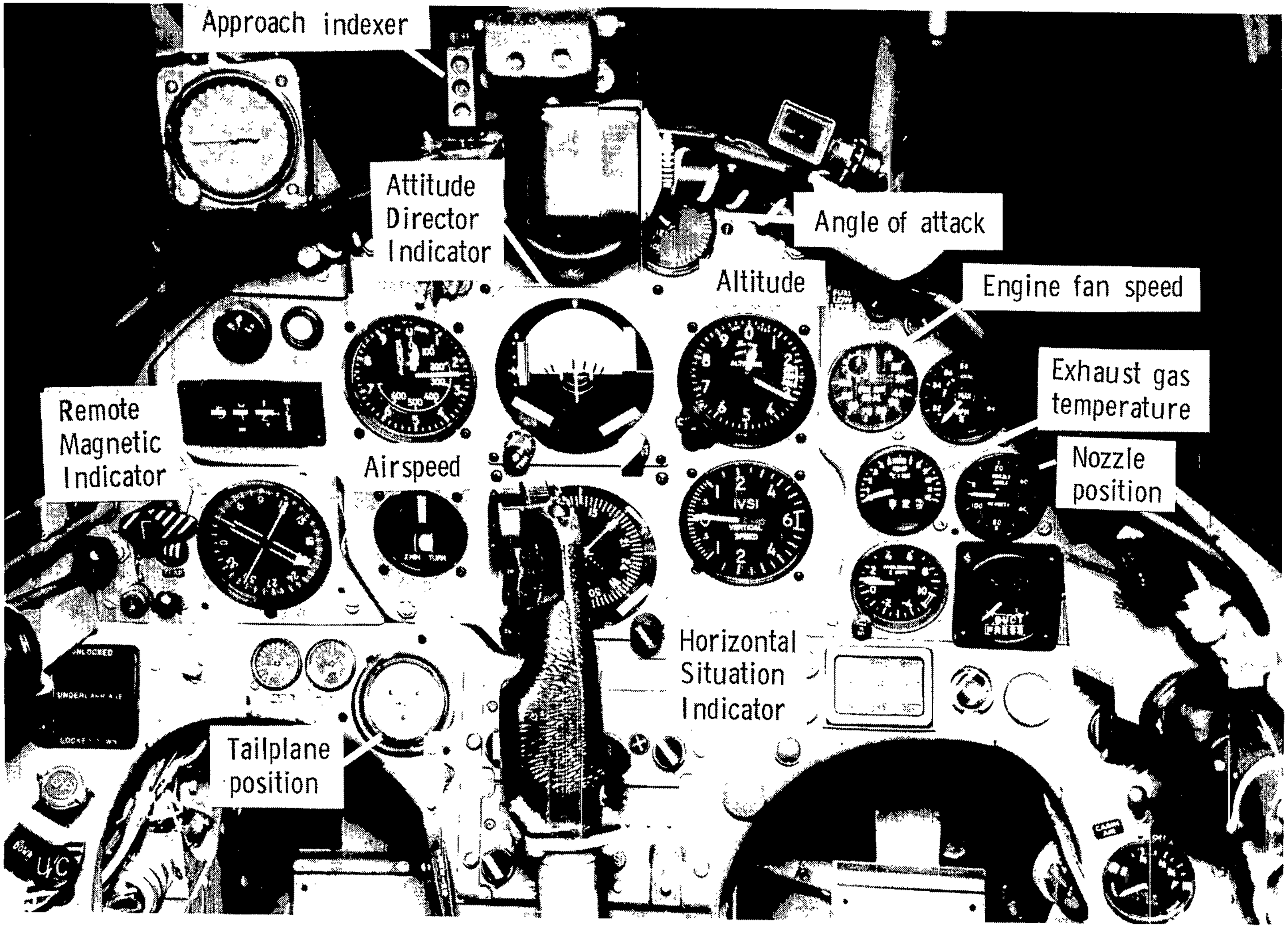
Figure 3.- Engine, nozzle drive system, and pilot controls.



L-72-373.1

(a) General layout.

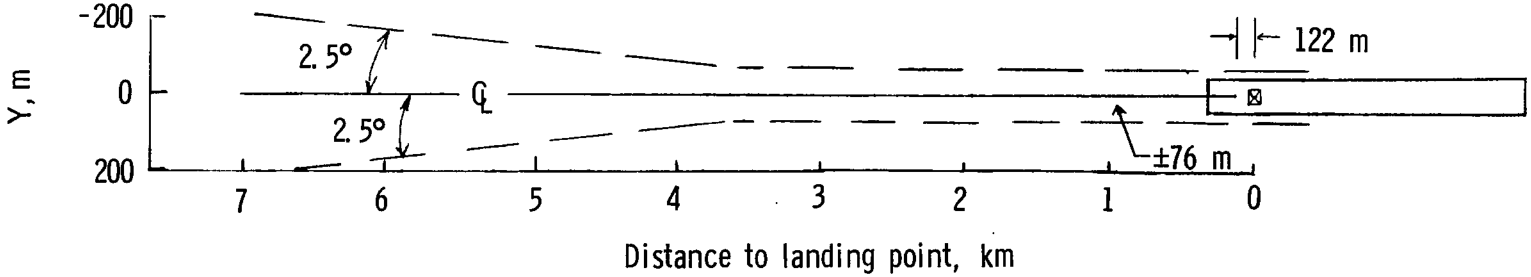
Figure 4.- Cockpit arrangement.



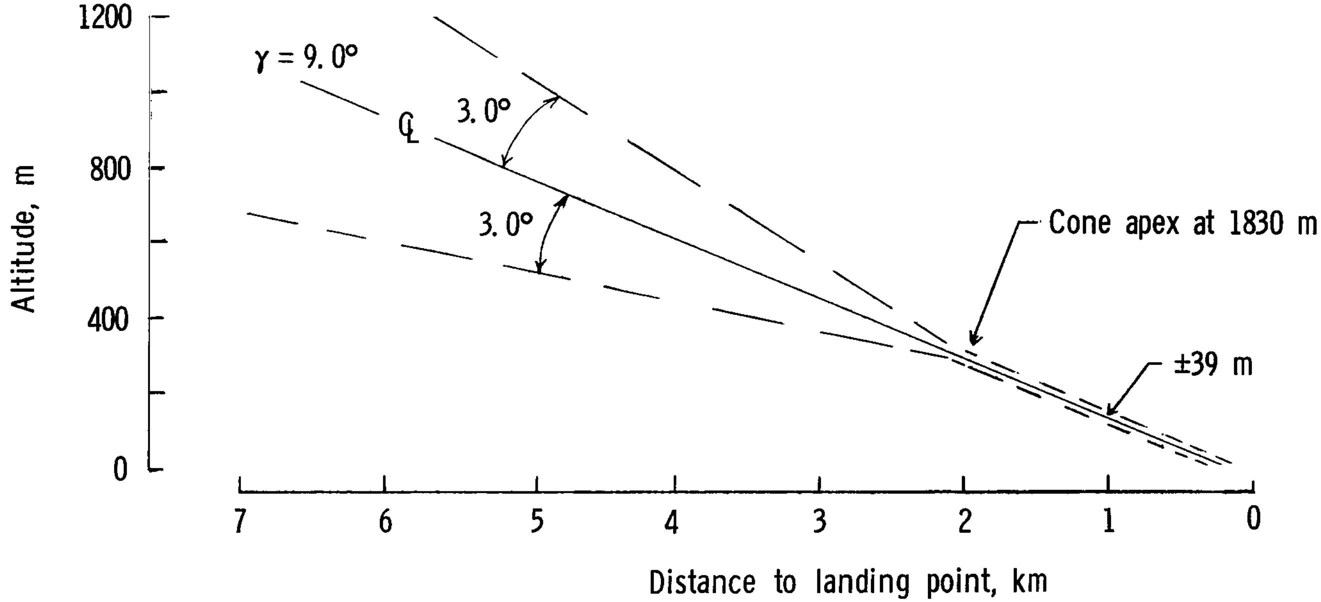
L-72-372.1

(b) Displays.

Figure 4.- Concluded.

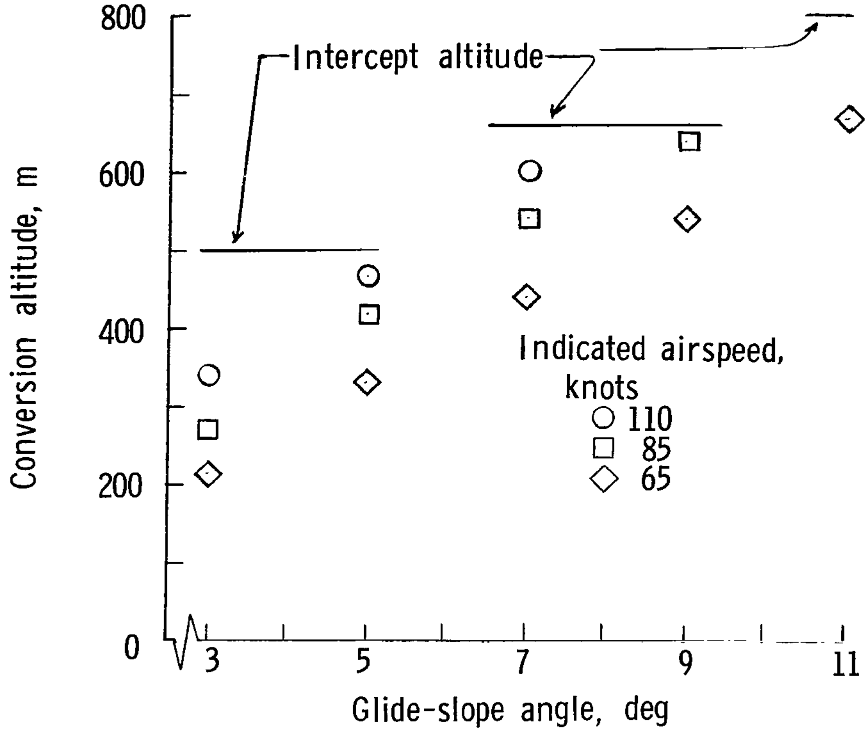


(a) Localizer geometry.

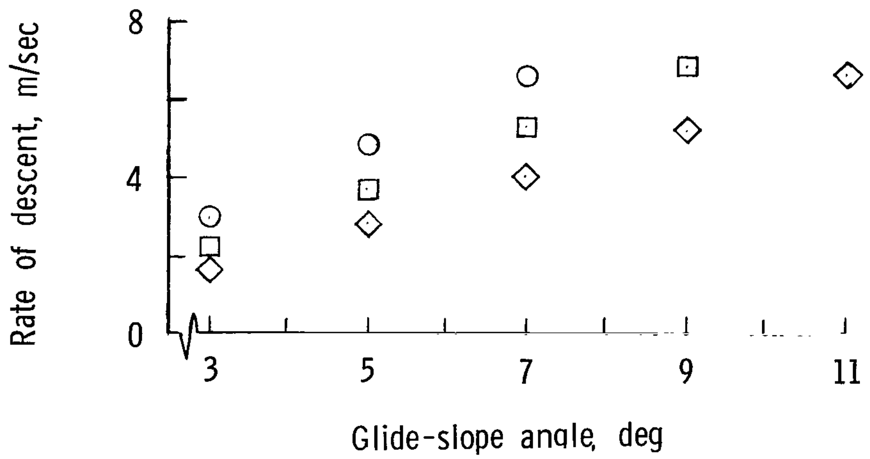


(b) Typical glide-slope geometry.

Figure 5.- Guidance characteristics for full-scale error deflection on cockpit instruments.



(a) Intercept and conversion altitudes.



(b) Rate of descent variation with glide-slope angle and airspeed.

Figure 6.- Approach speed and glide-slope angle test conditions.

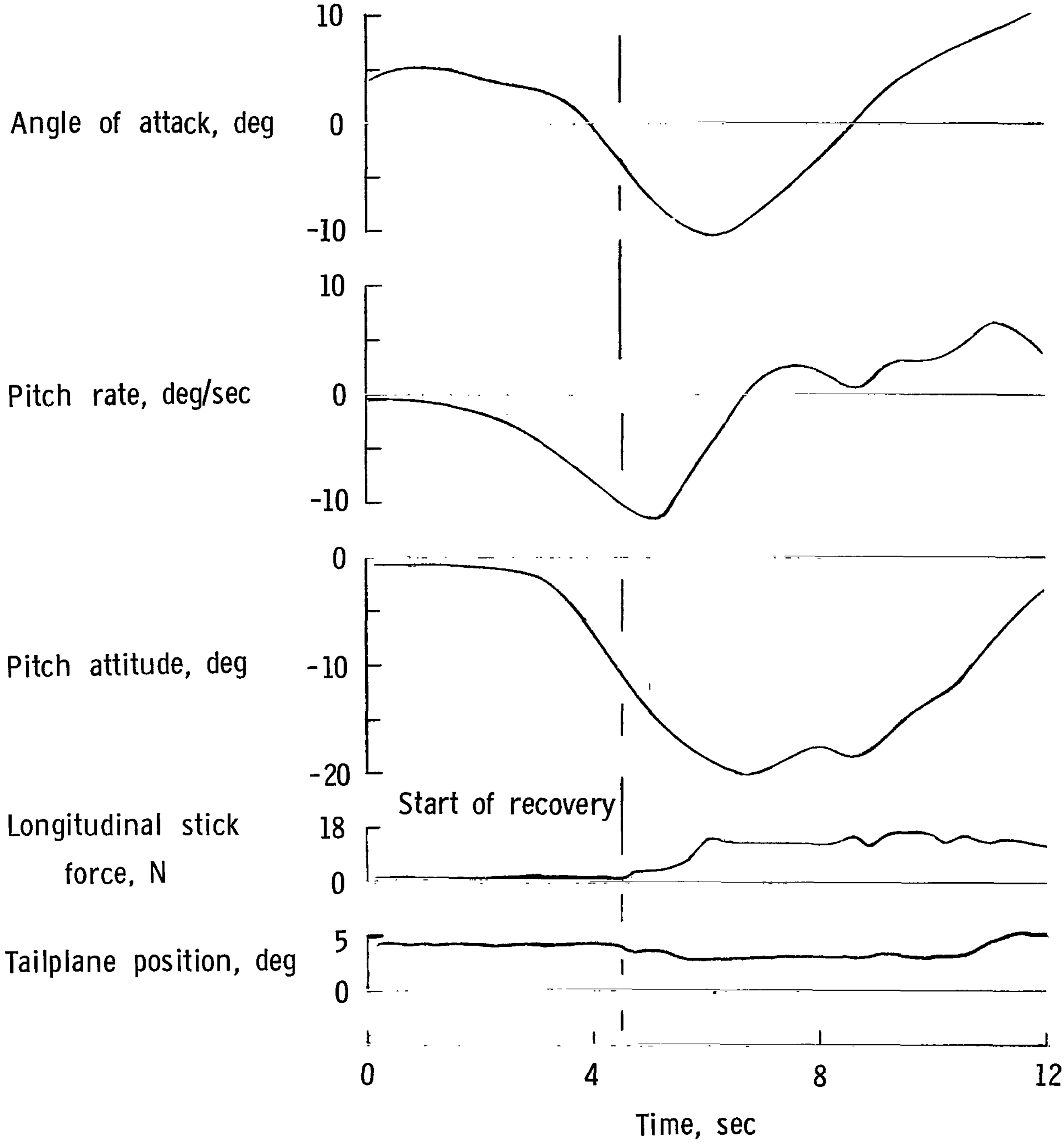


Figure 7.- Pitch divergence at 85 knots.

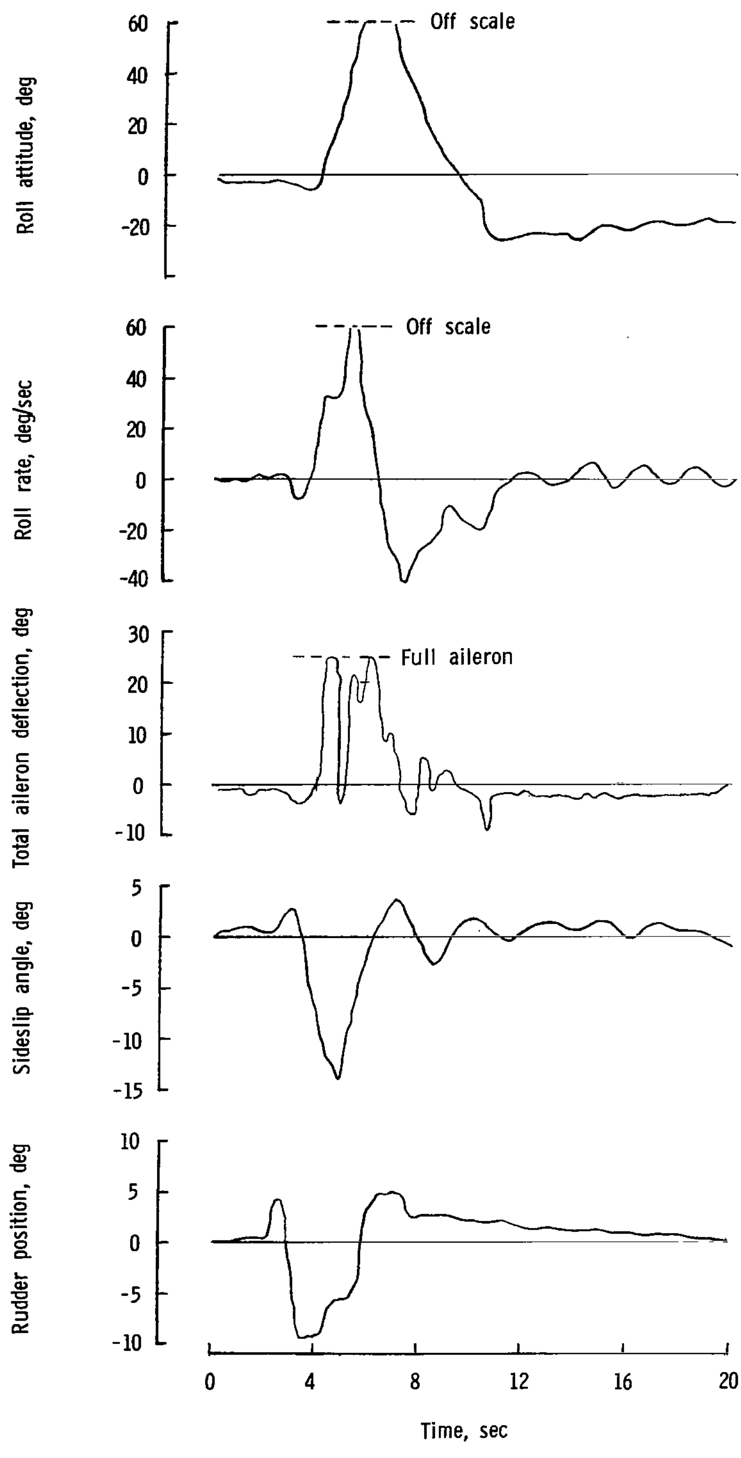
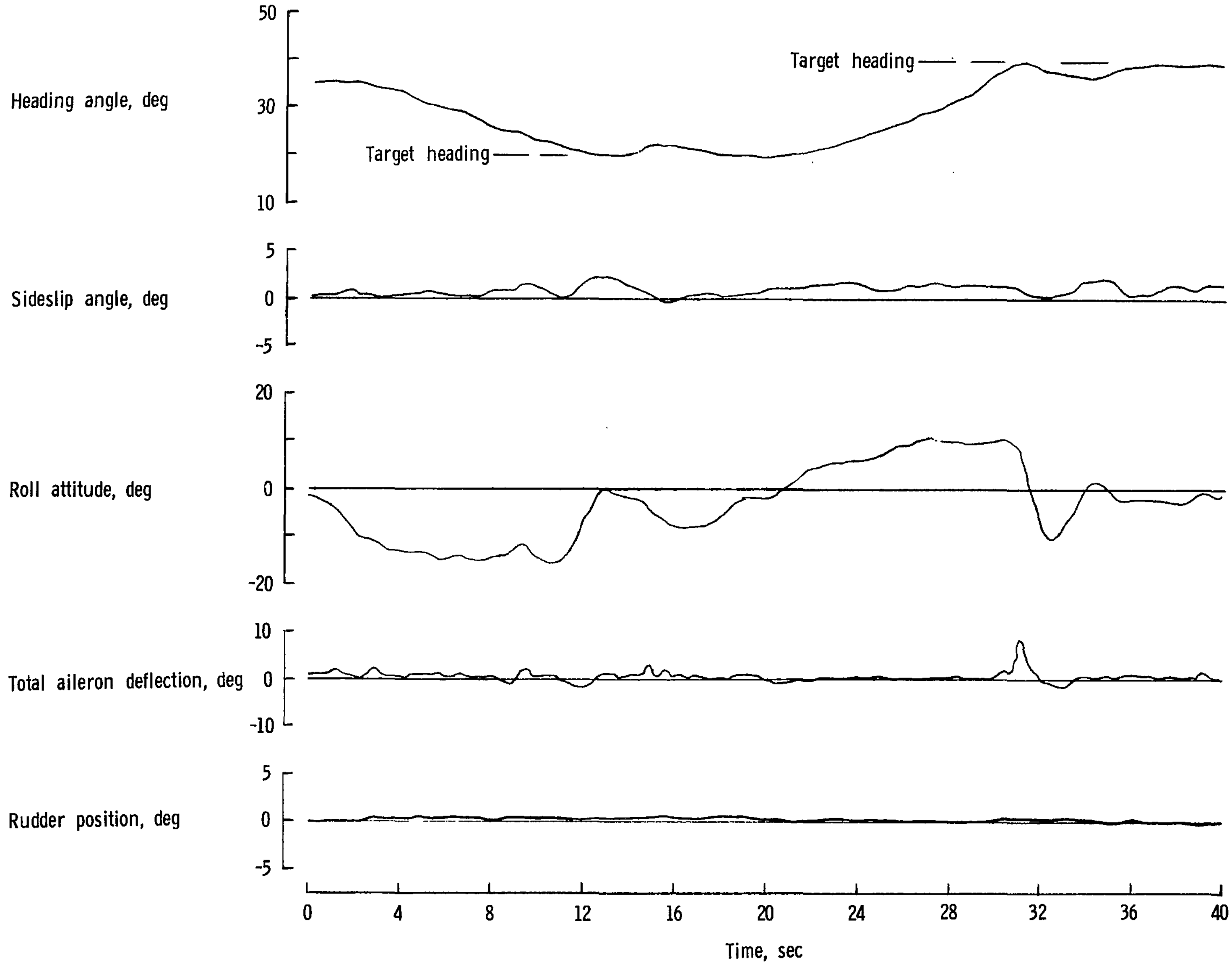
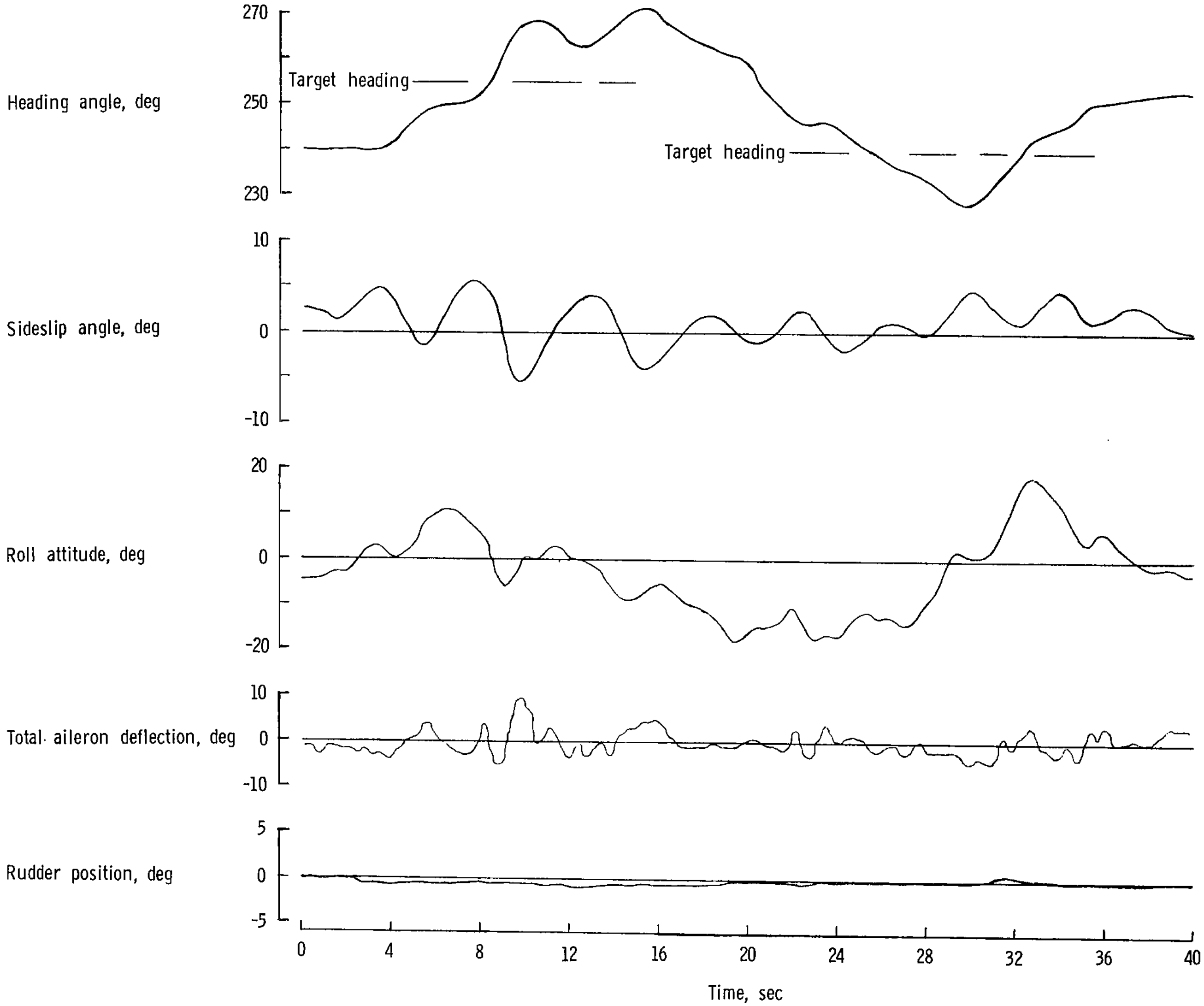


Figure 8.- Lateral upset at 110 knots. $\theta_j = 65^o$; $\alpha = 8^o$; altitude, 1500 meters.



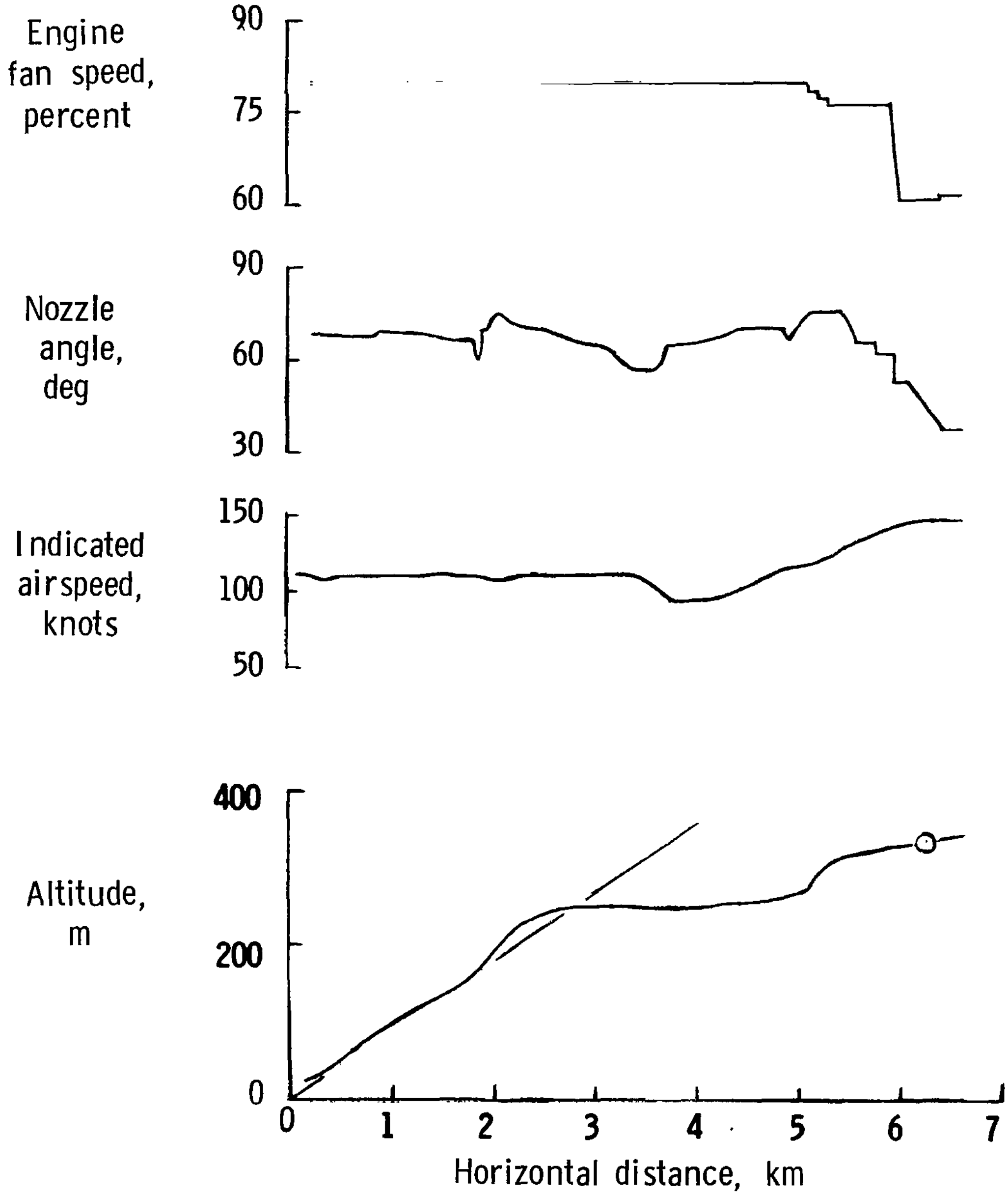
(a) 110 knots.

Figure 9.- Attempts at precision-heading changes.



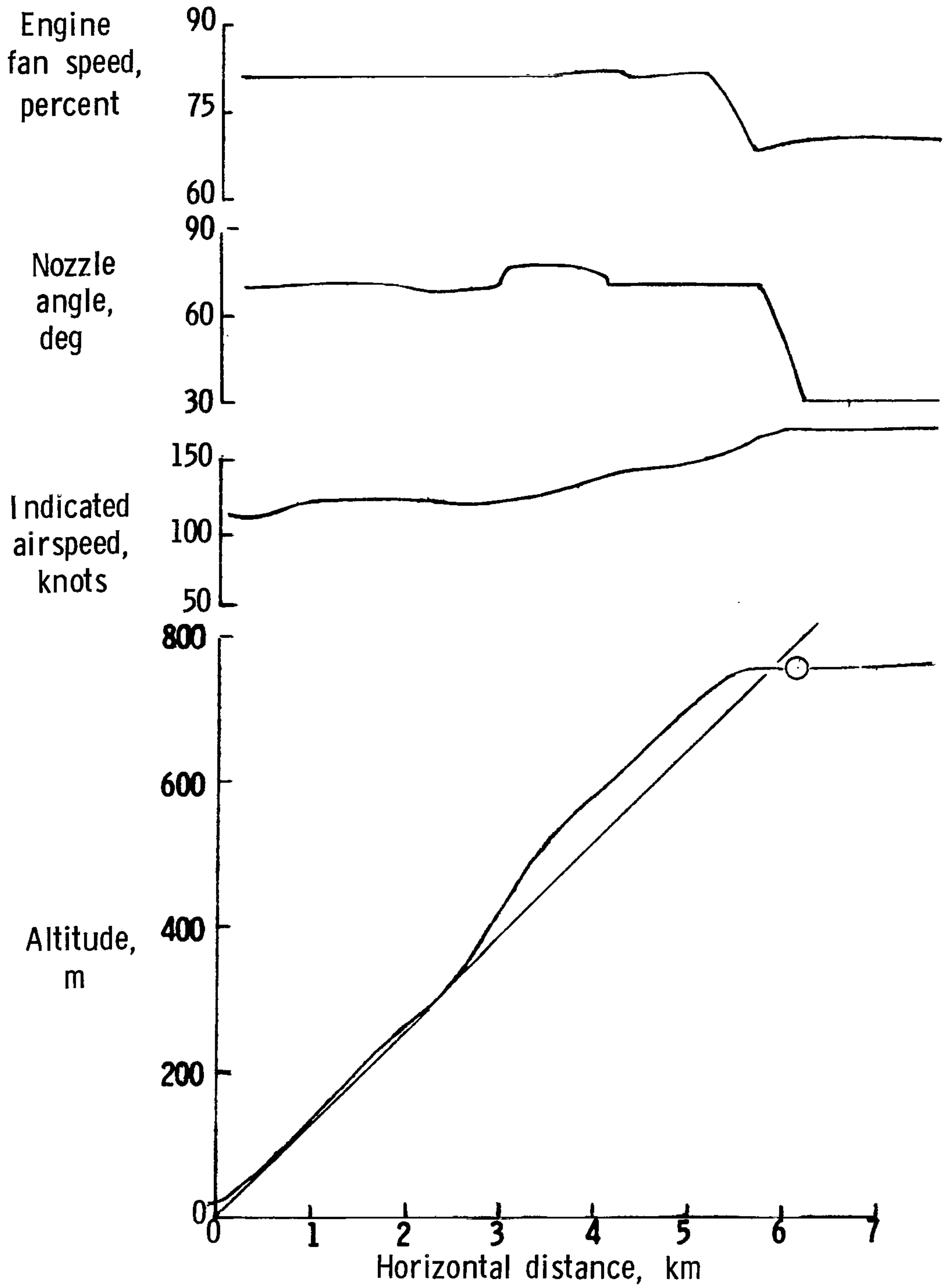
(b) 65 knots.

Figure 9.- Concluded.



(a) Early conversion; glide-slope angle, 5°; airspeed, 110 knots.

Figure 10.- Level-flight conversions.



(b) Late conversion; glide-slope angle, 7°; airspeed, 110 knots.

Figure 10.- Concluded.

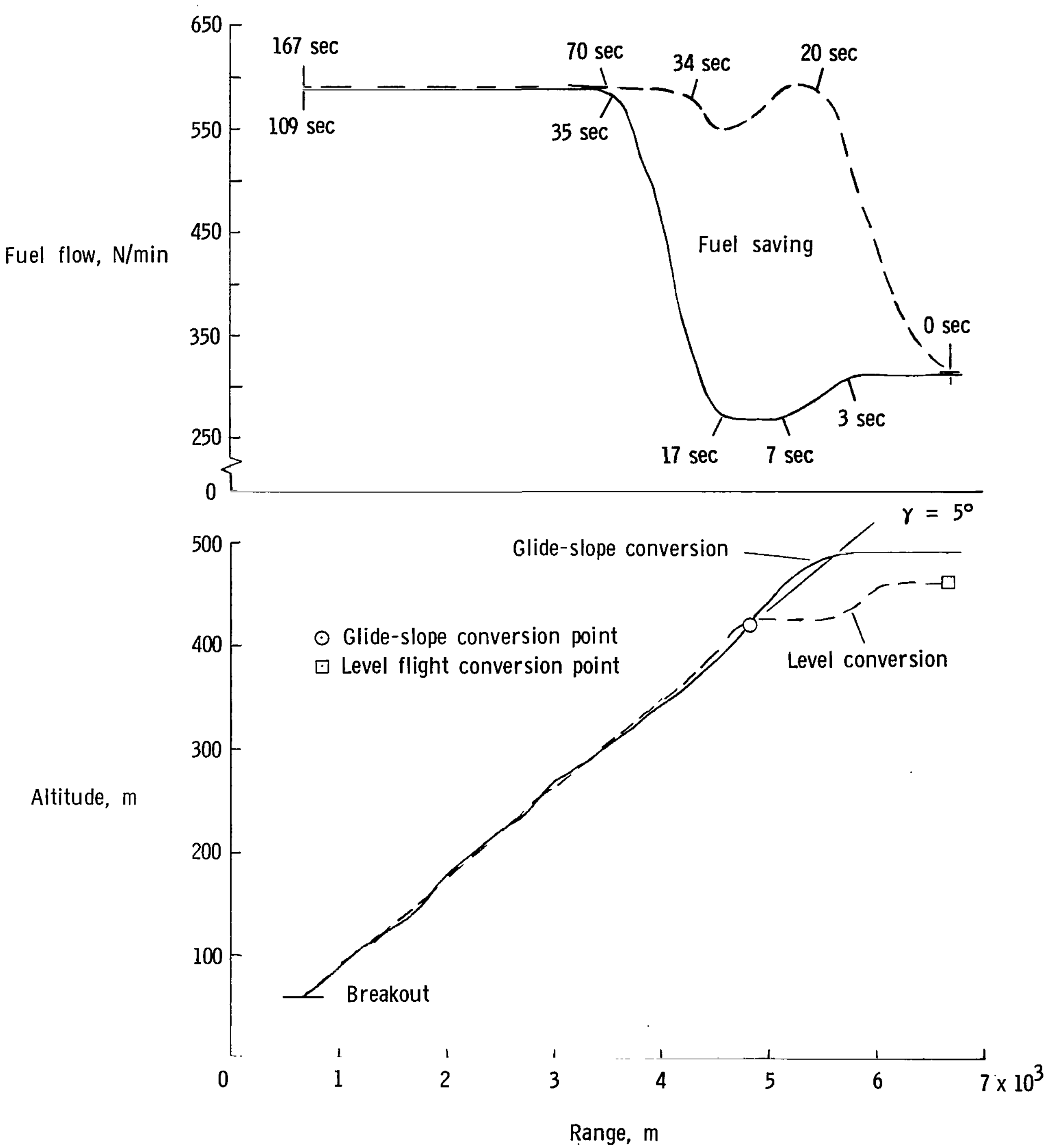


Figure 11.- Comparison of fuel usage during 5°, 65-knot approaches with different conversion points.

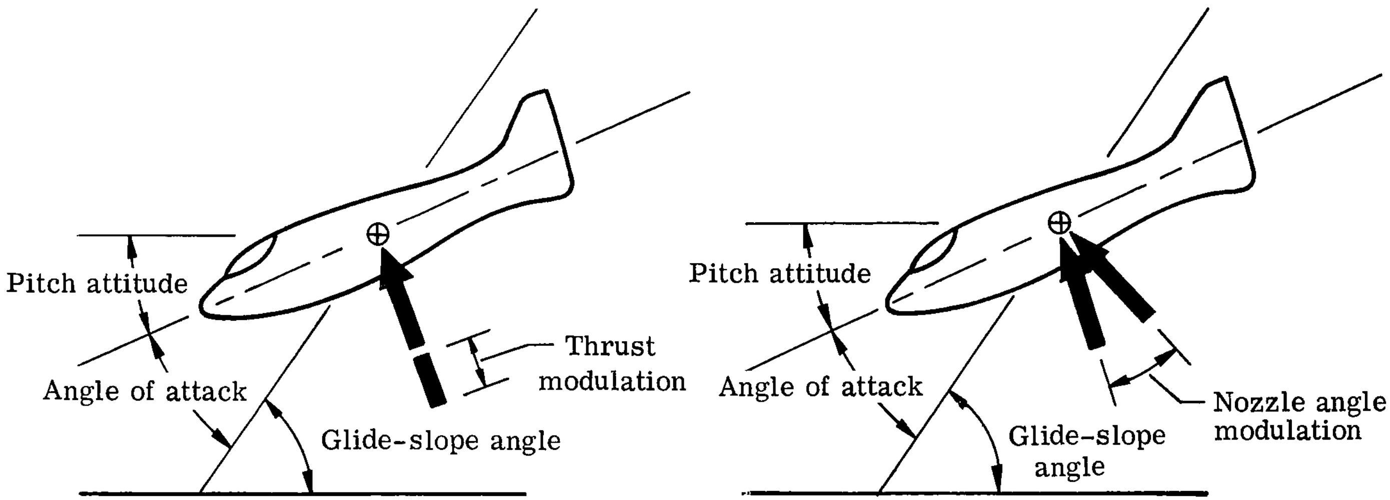


Figure 12.- Glide-slope control methods tested.

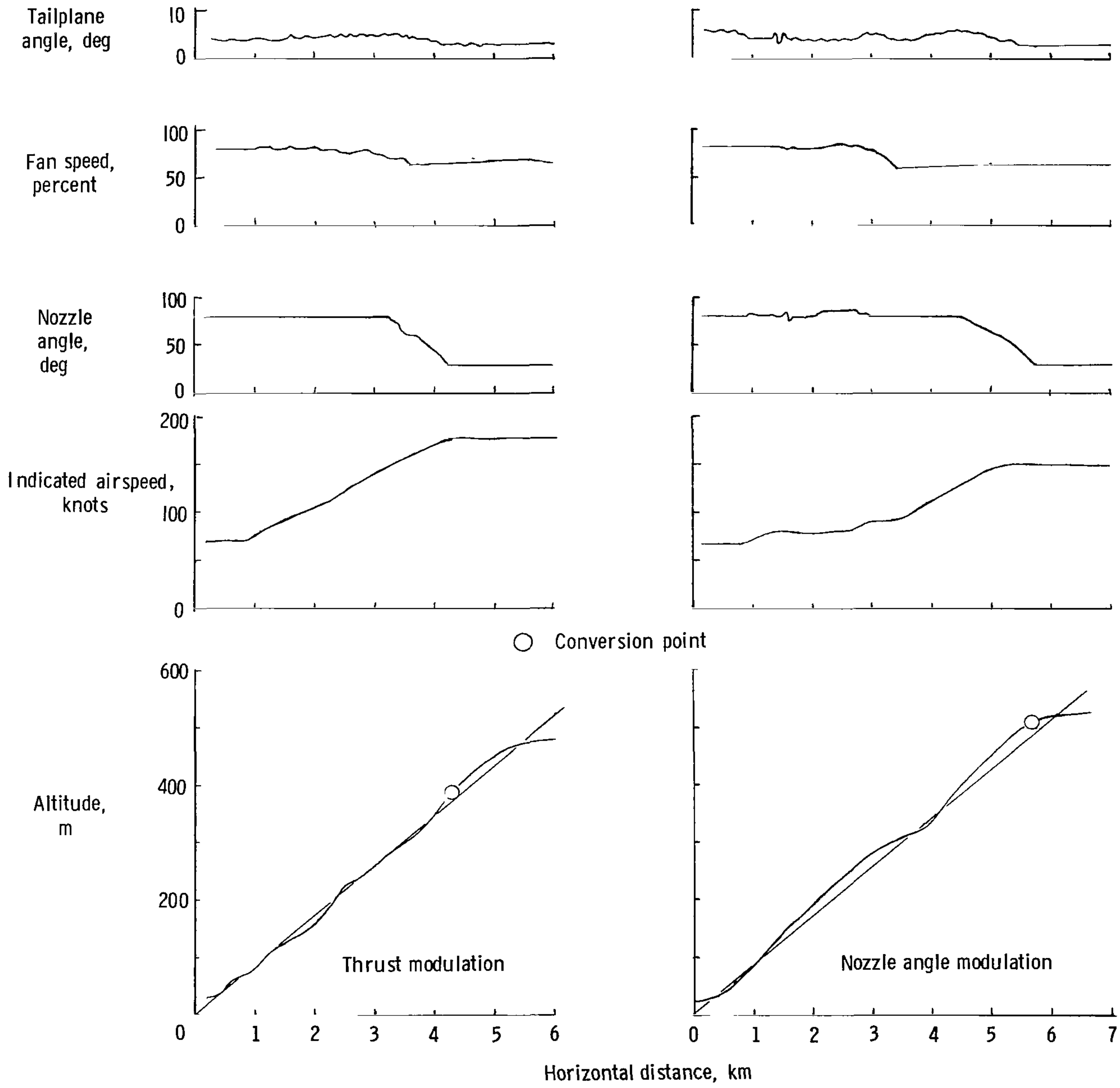


Figure 13.- Comparison of glide-slope control techniques. $\gamma = 5^{\circ}$.

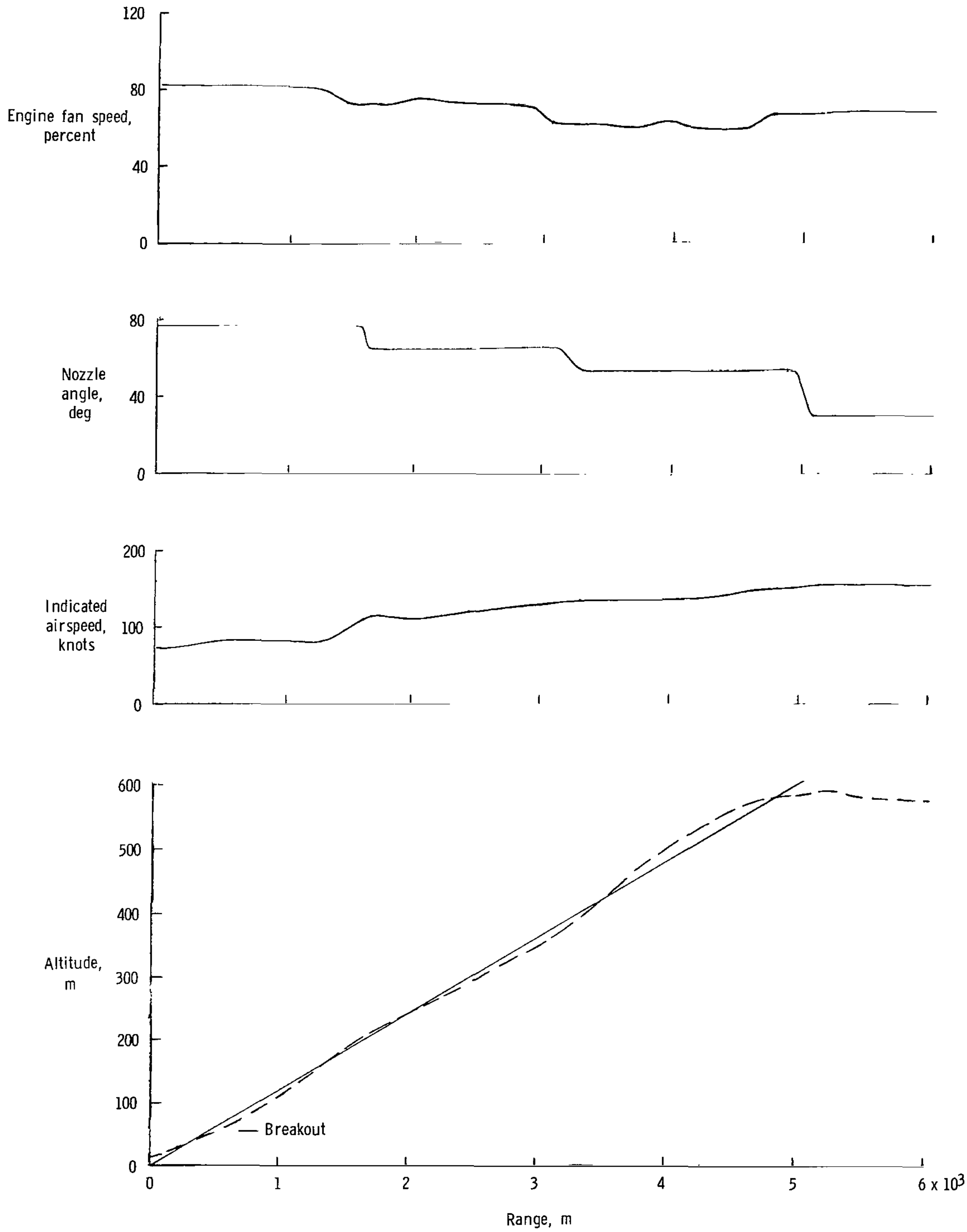


Figure 14.- Decelerating approach on 7° glide slope.

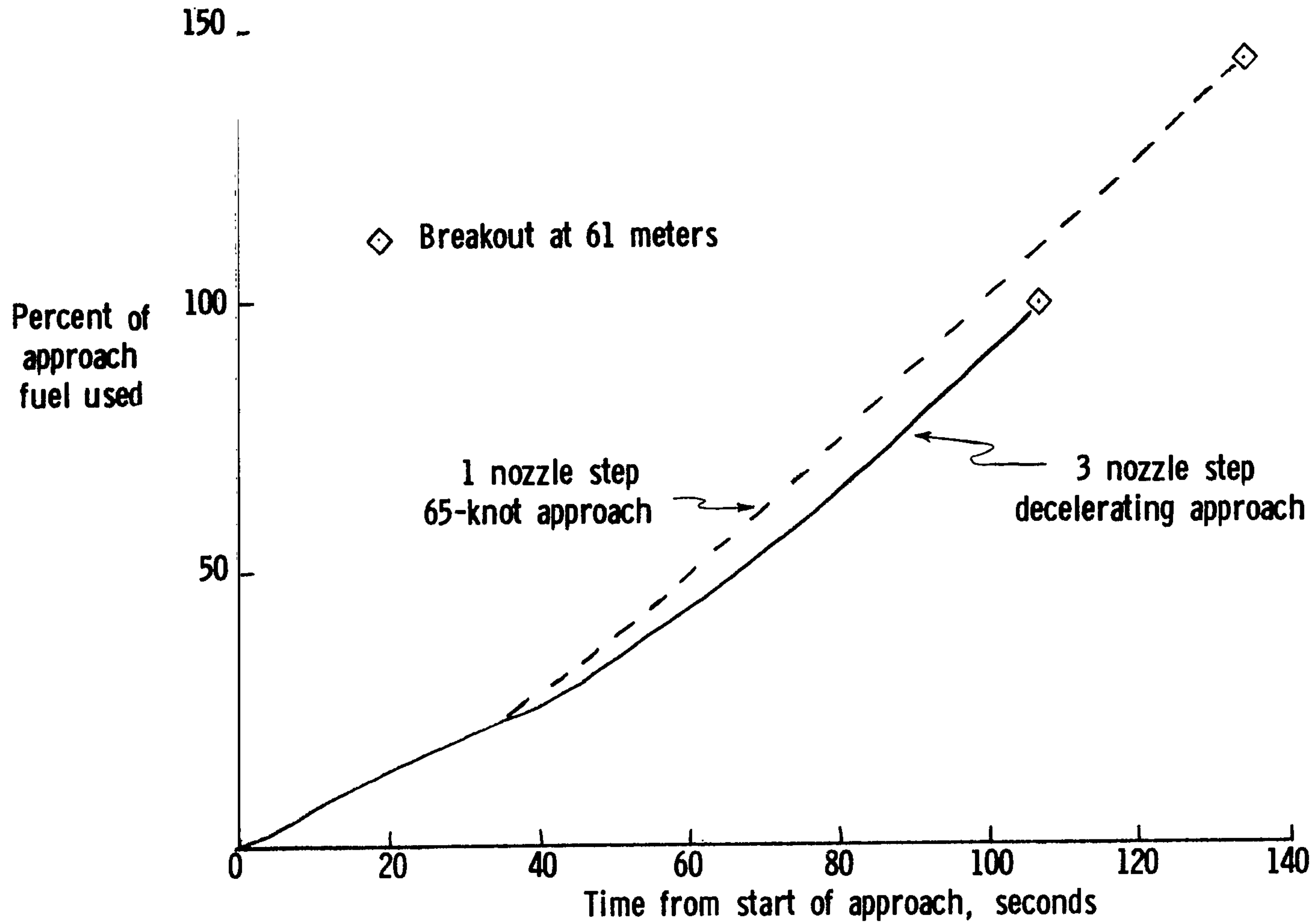


Figure 15.- Comparison of fuel used on approach. 7° glide-slope angle; 160 knots; range of 6100 meters.

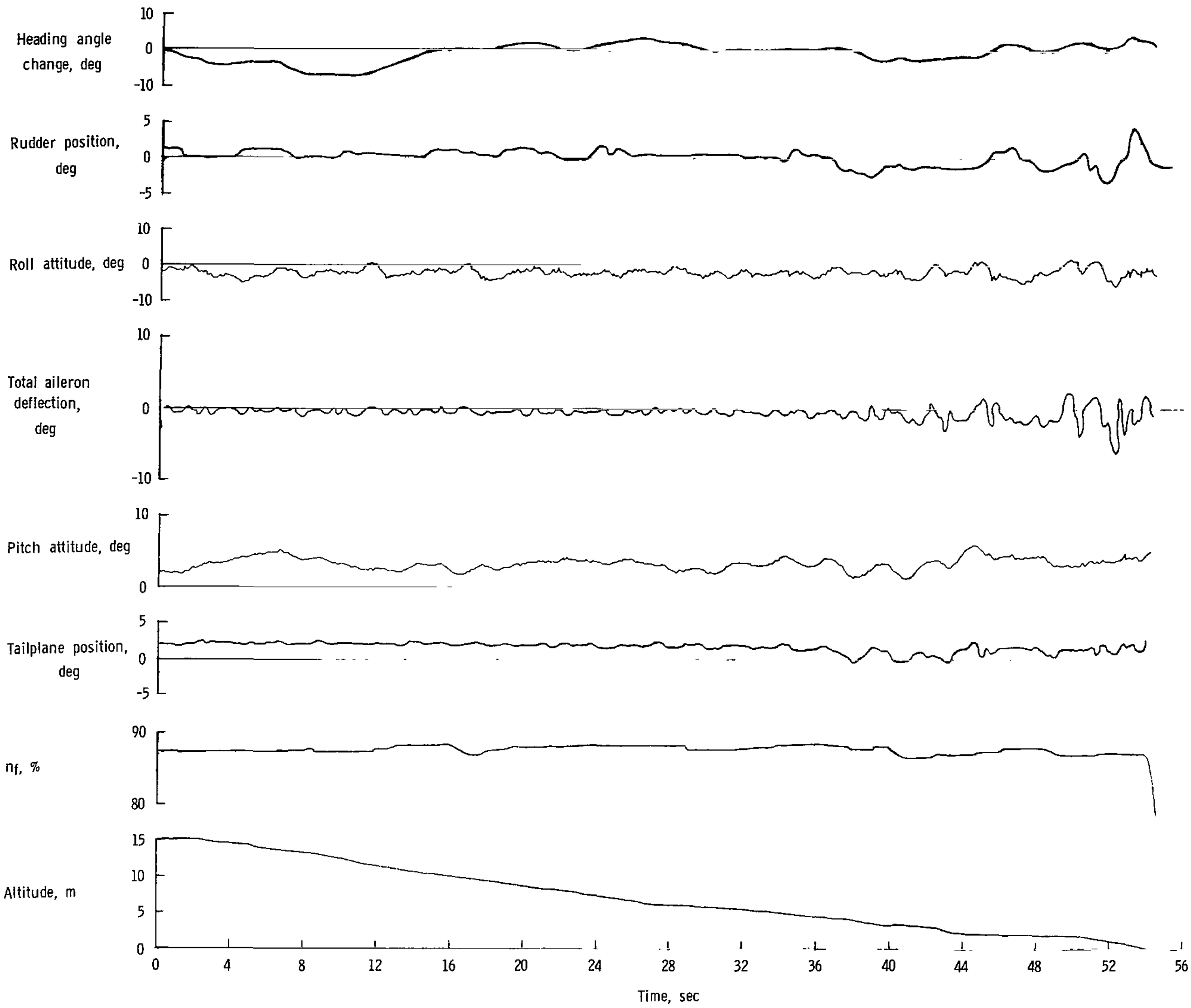


Figure 16.- Pilot control activity during hover letdown and vertical landing. 2 knots headwind at height of 7 meters.

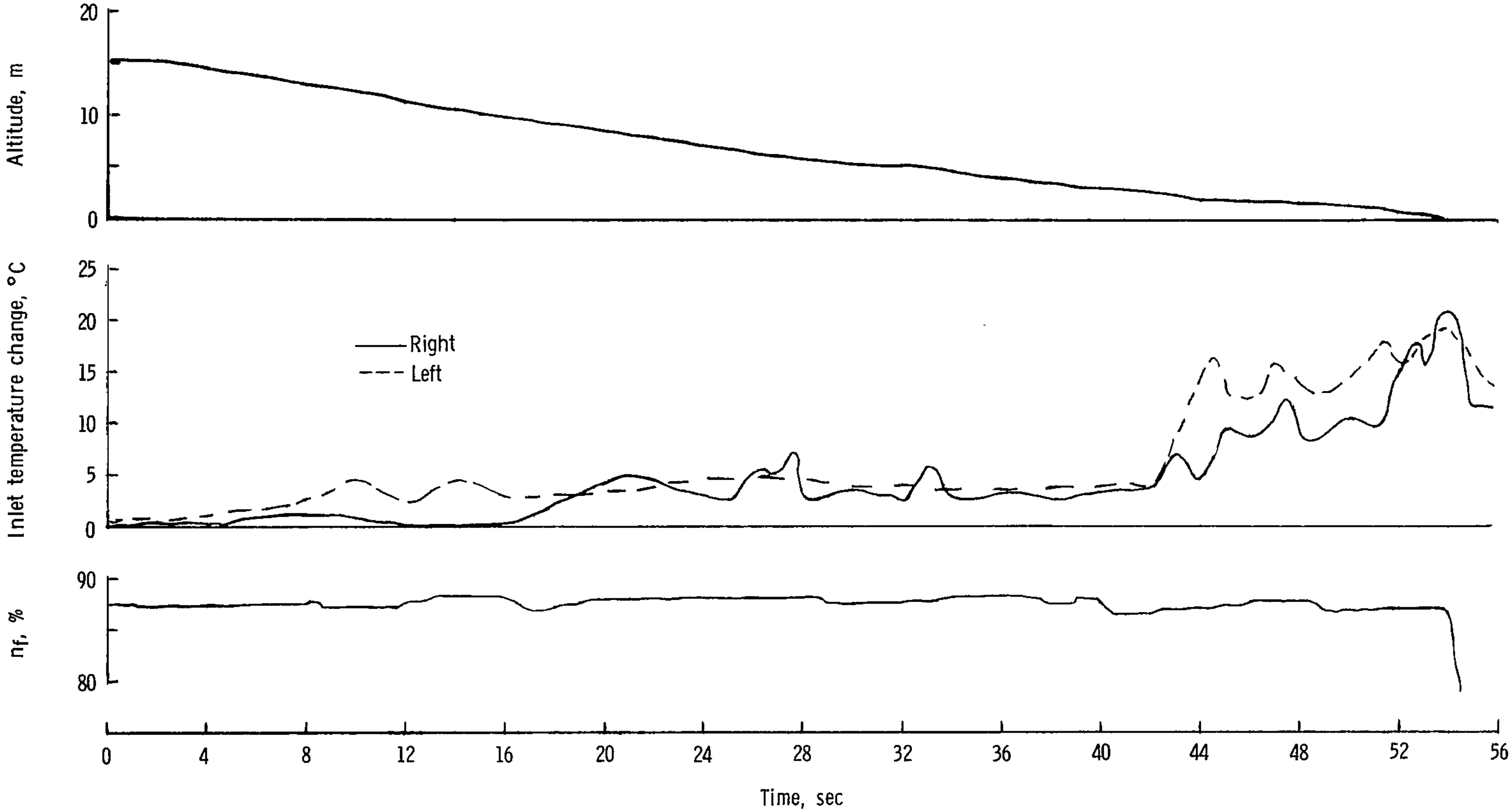


Figure 17.- Vertical-landing hot-gas reingestion.

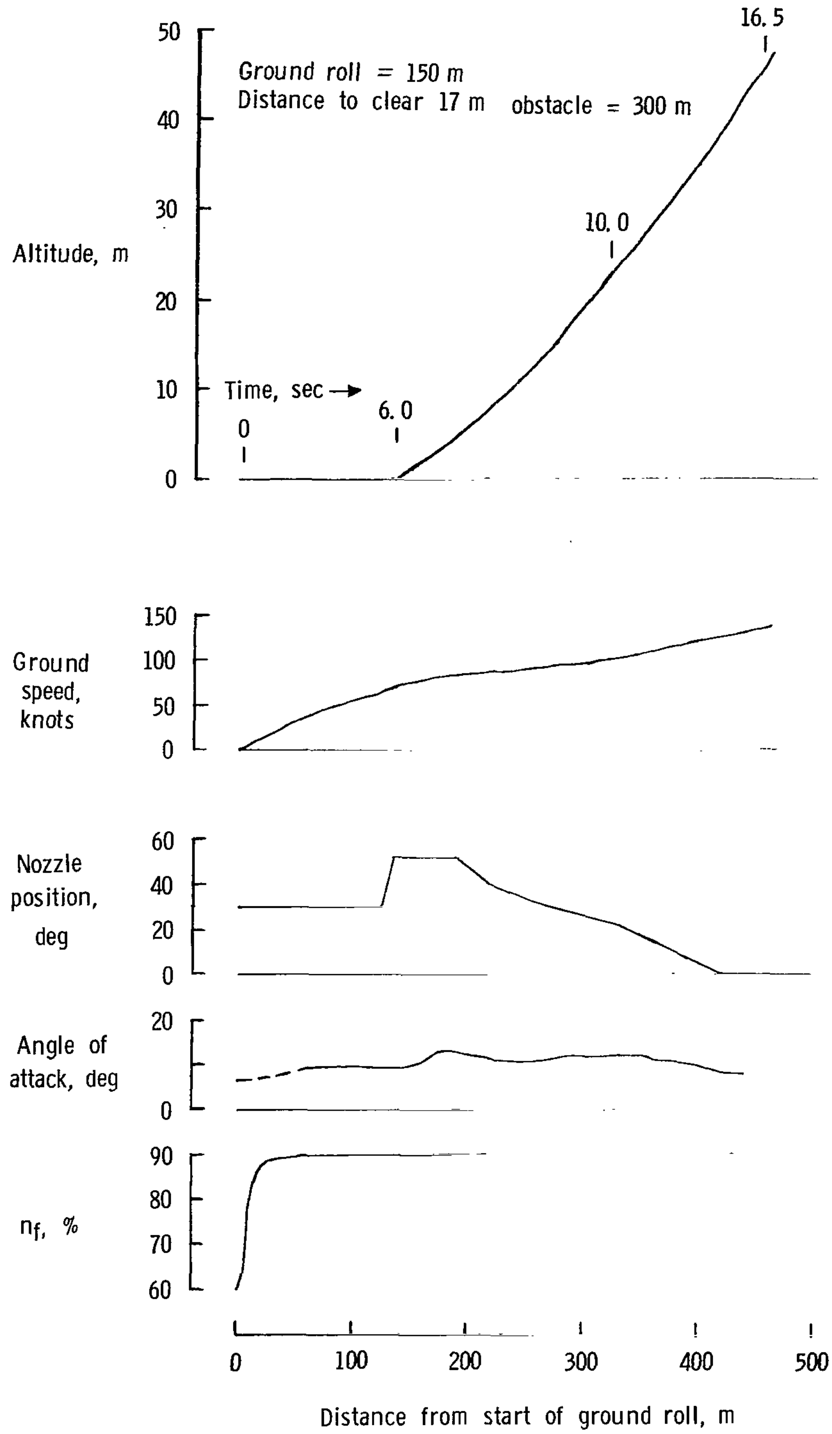


Figure 18.- Typical short take-off performance data.

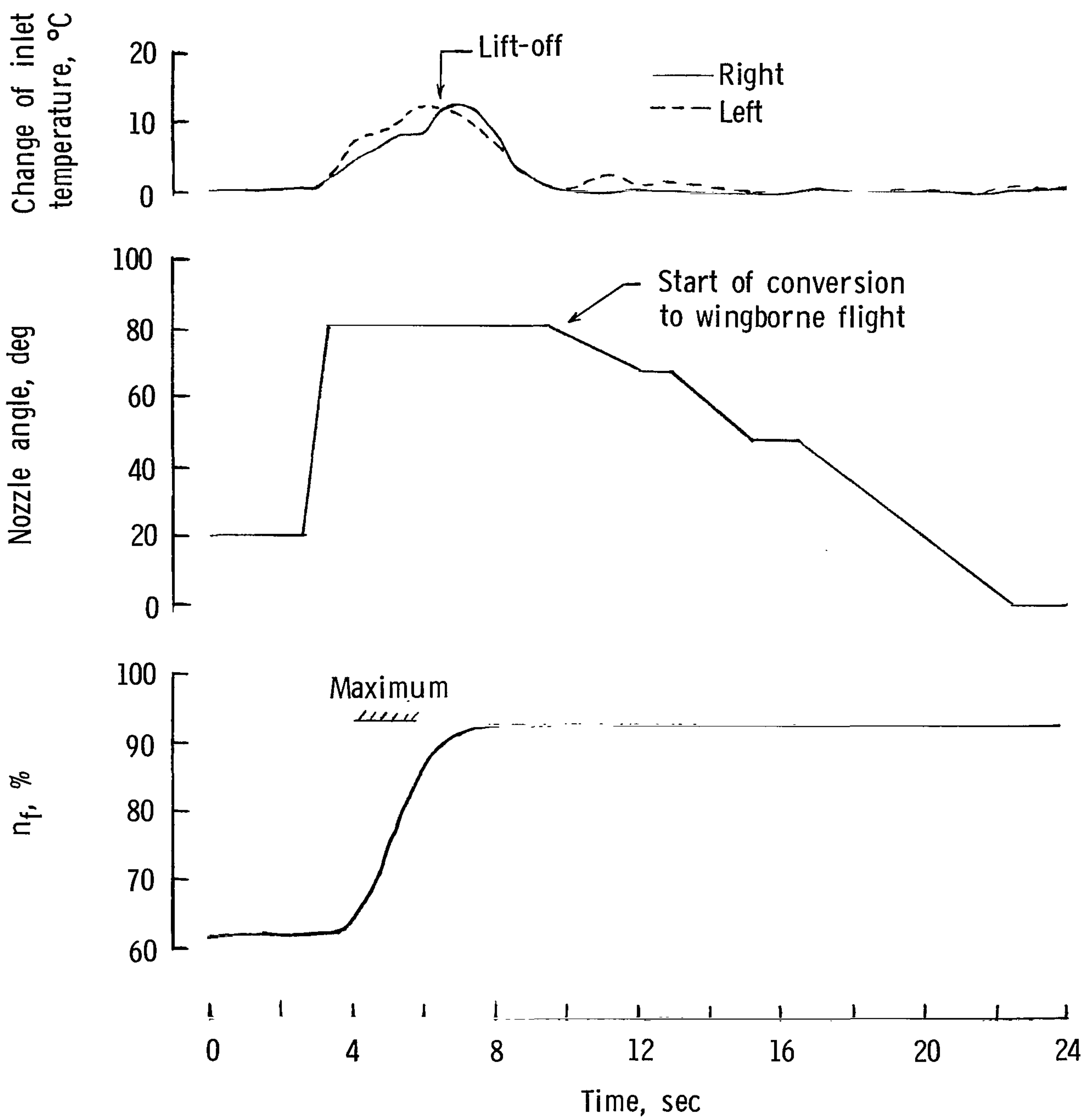
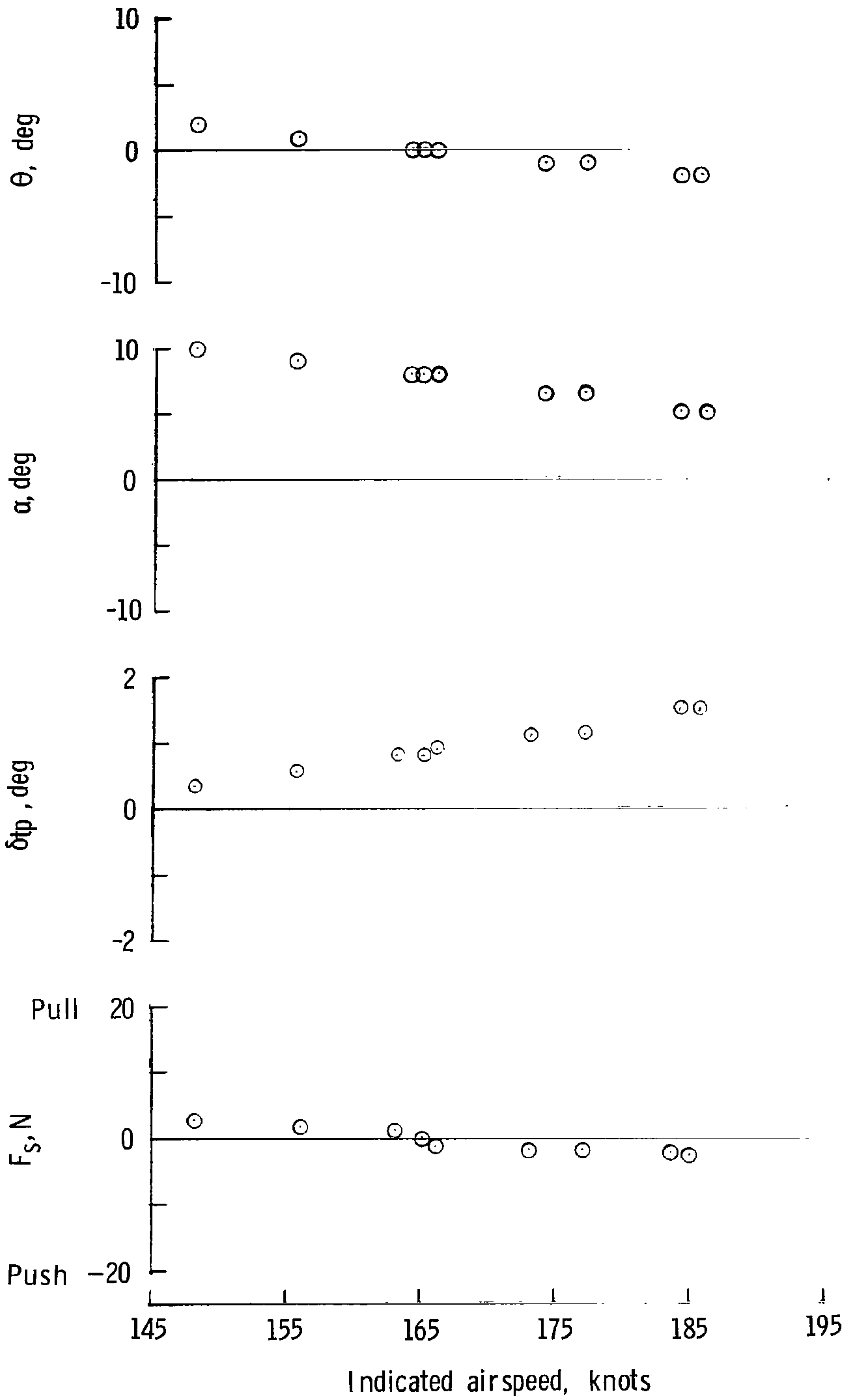
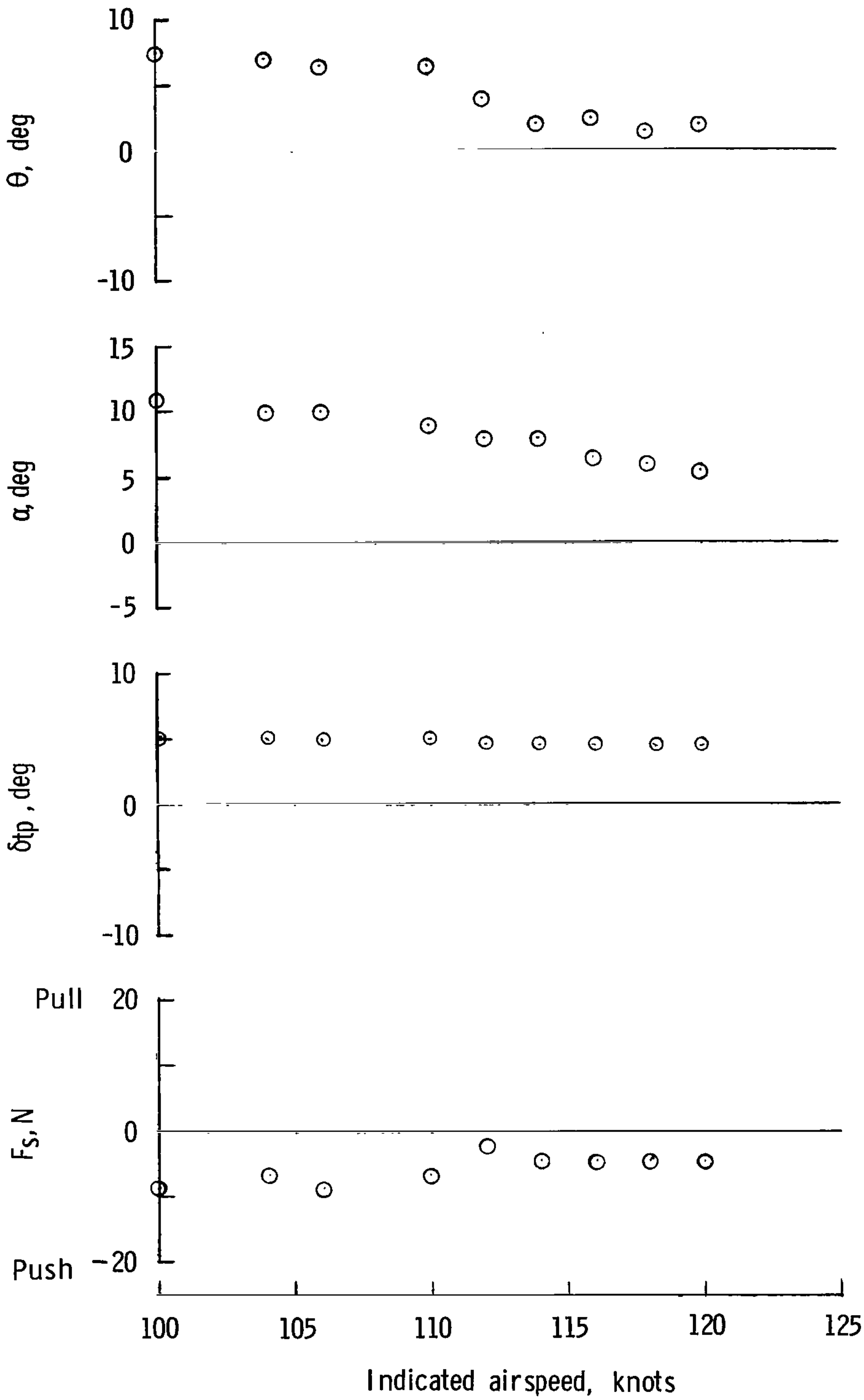


Figure 19.- Vertical take-off hot-gas reingestion. 6 to 12 knots headwind.



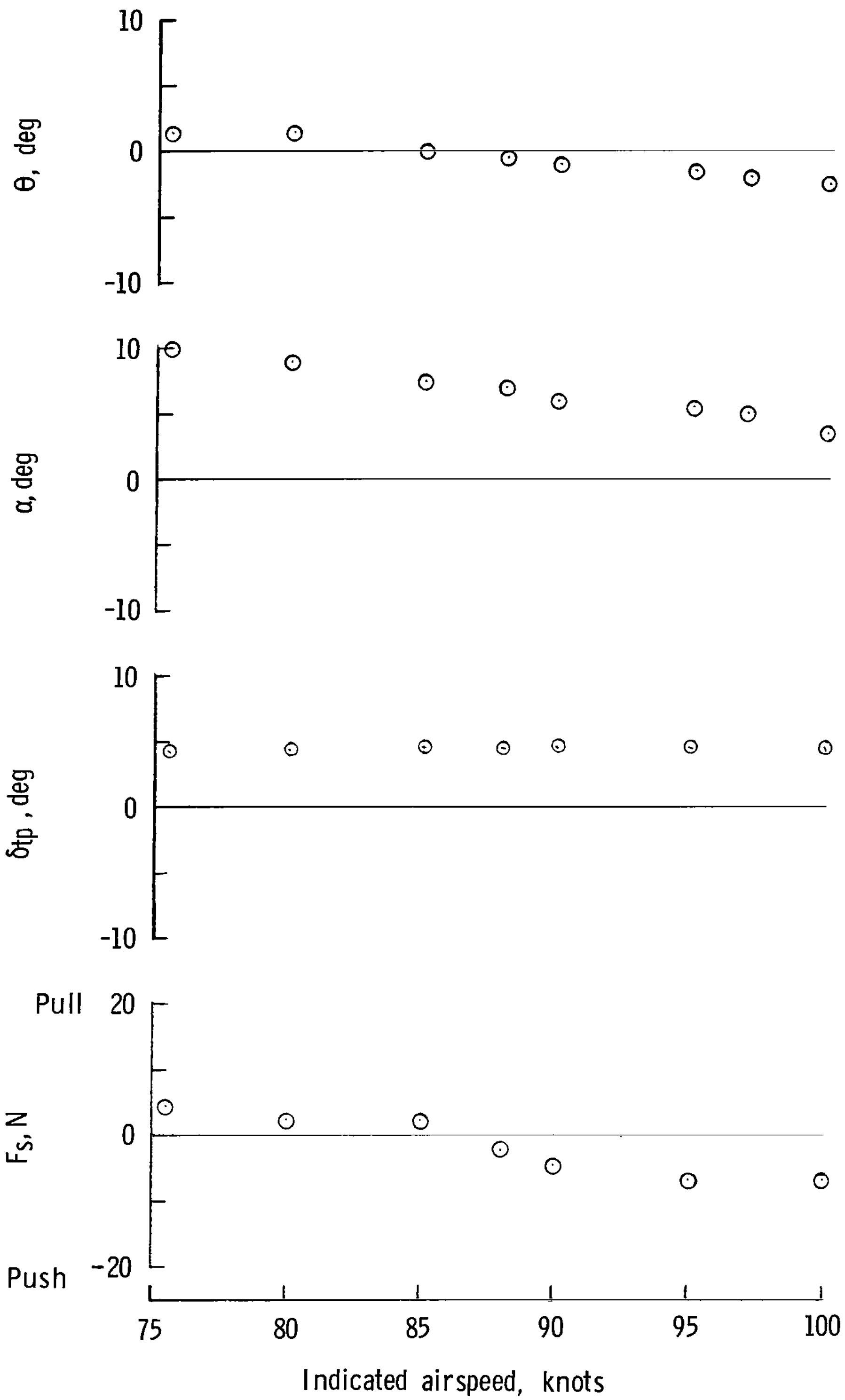
(a) 165 knots.

Figure 20.- Static longitudinal stability.



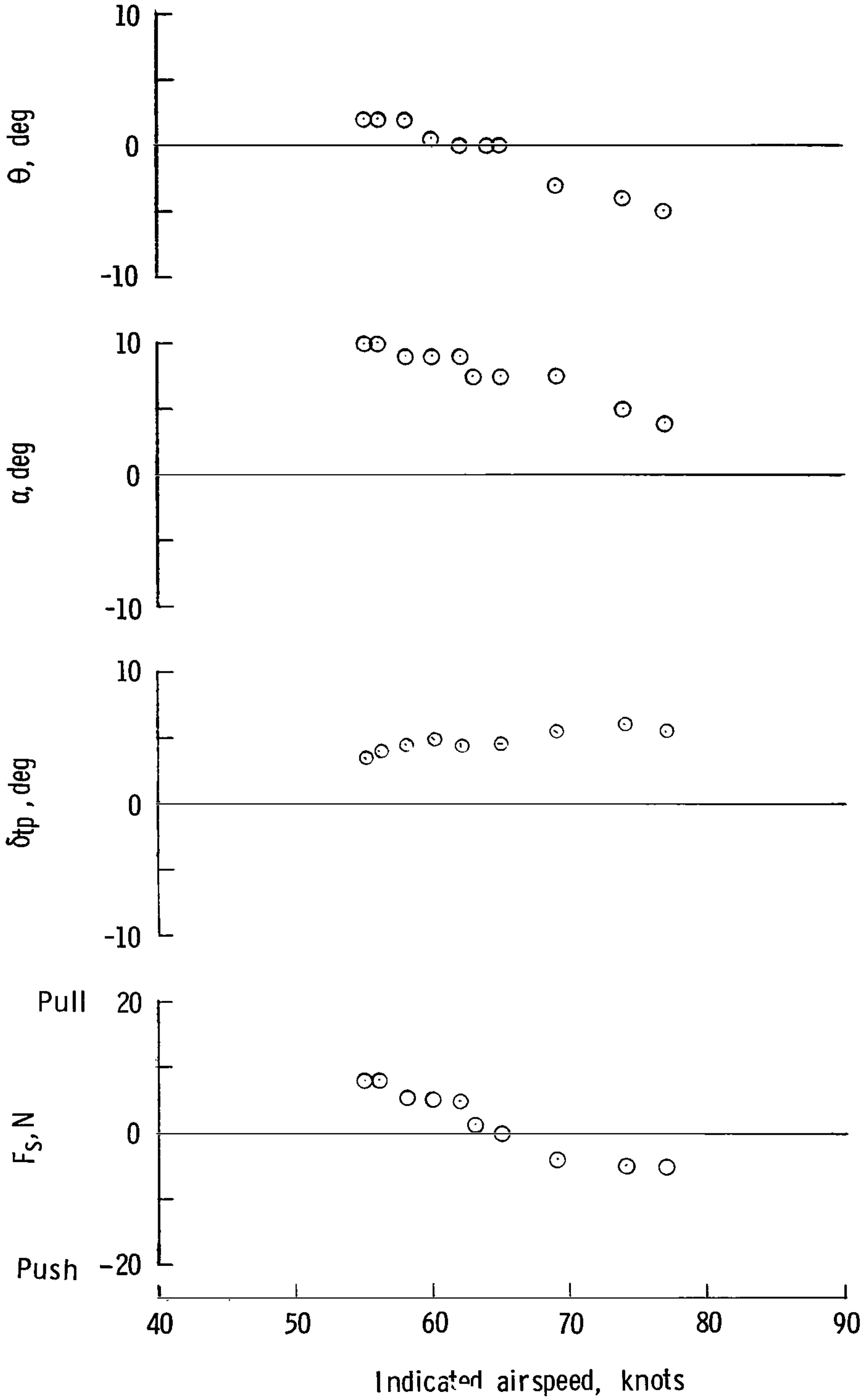
(b) 110 knots.

Figure 20.- Continued.



(c) 85 knots.

Figure 20.- Continued.



(d) 65 knots.

Figure 20.- Concluded.

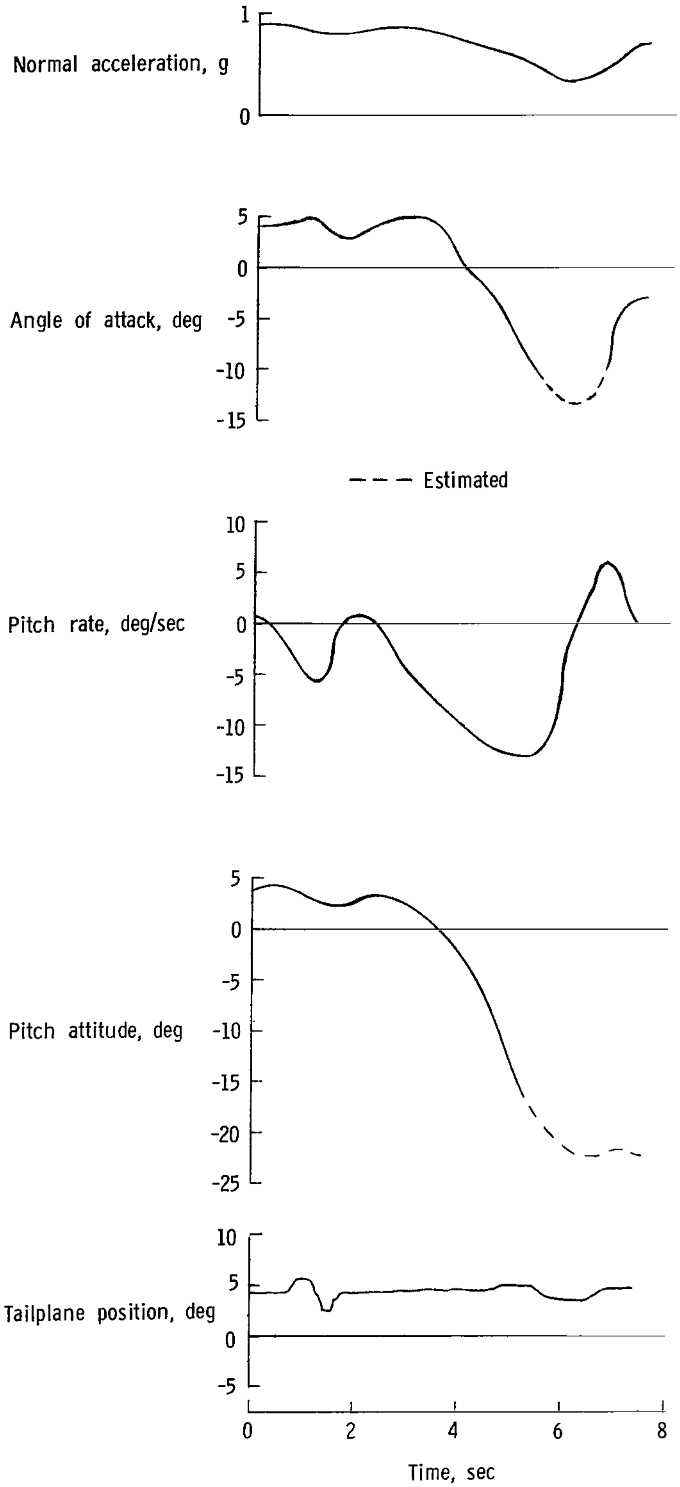


Figure 21.- Short period doublet. 85 knots.

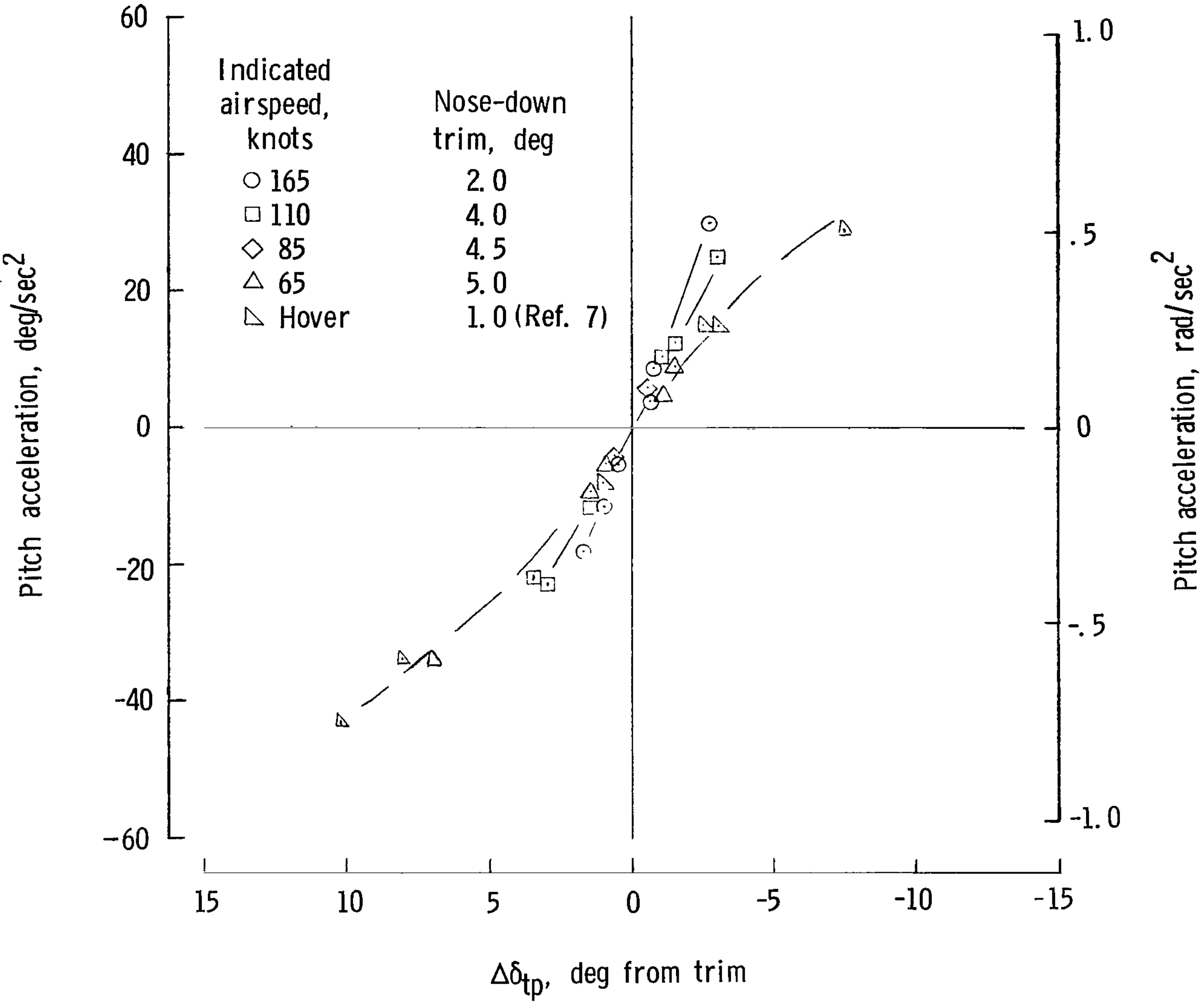
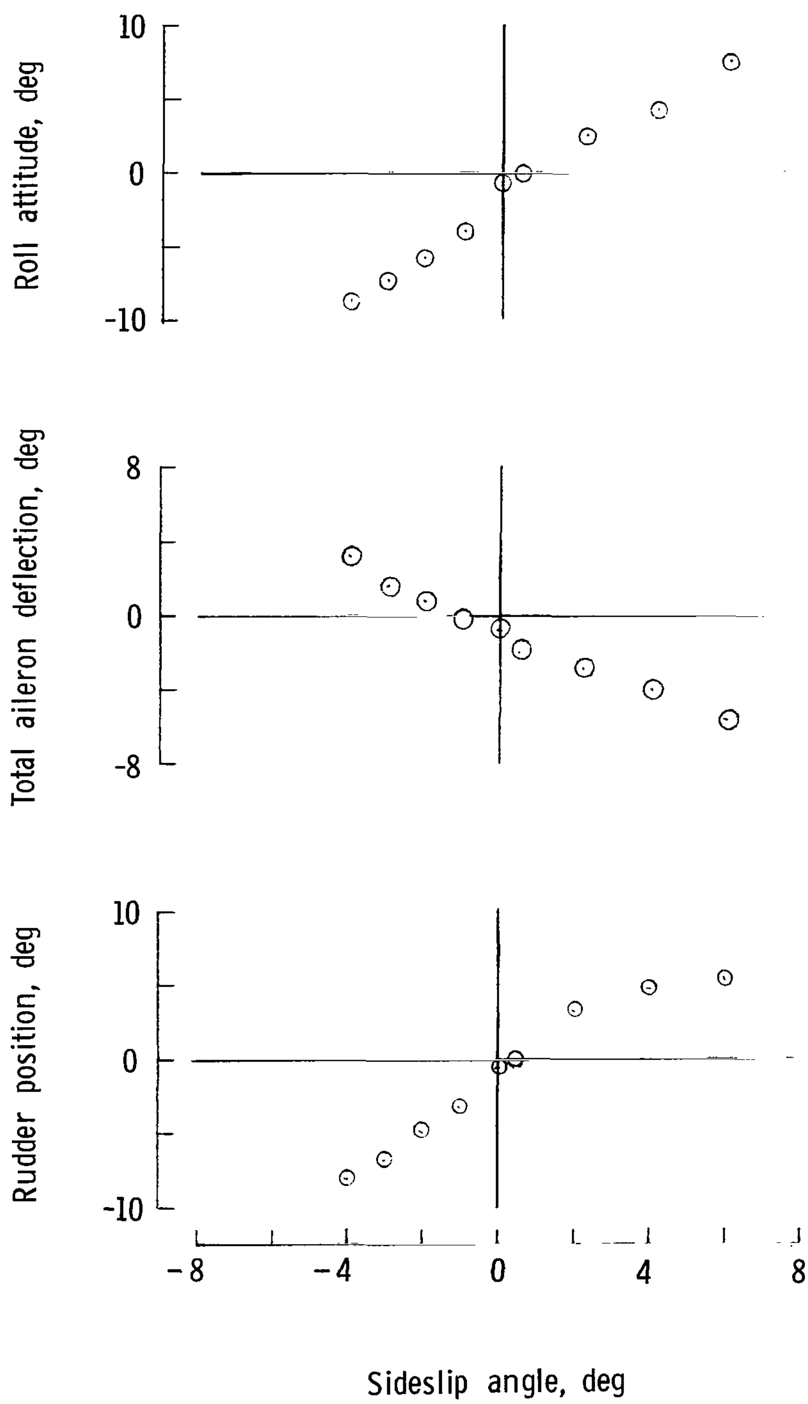
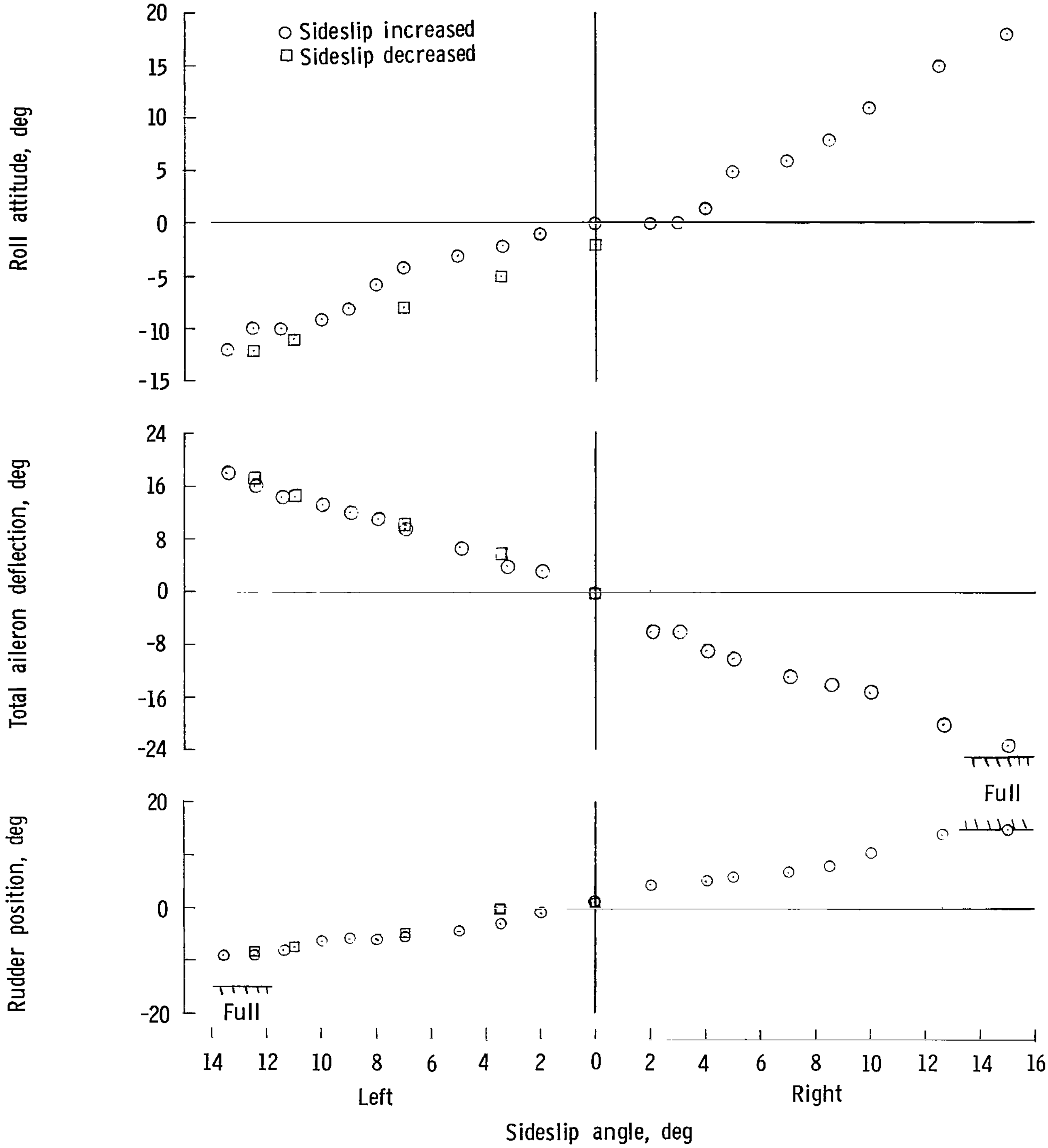


Figure 22.- Longitudinal control power.



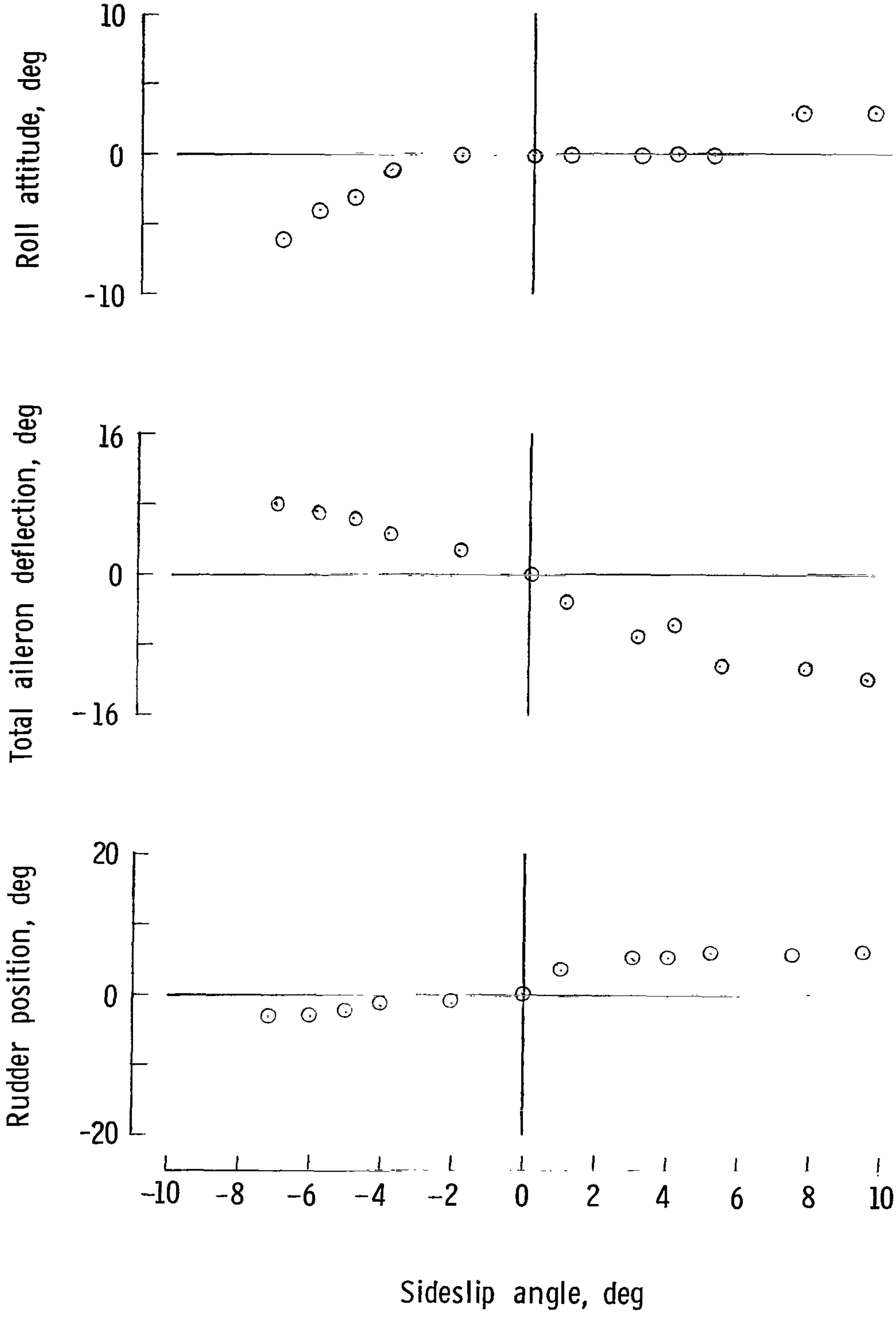
(a) 165 knots.

Figure 23.- Steady sideslip. $\alpha = 6^{\circ}$.



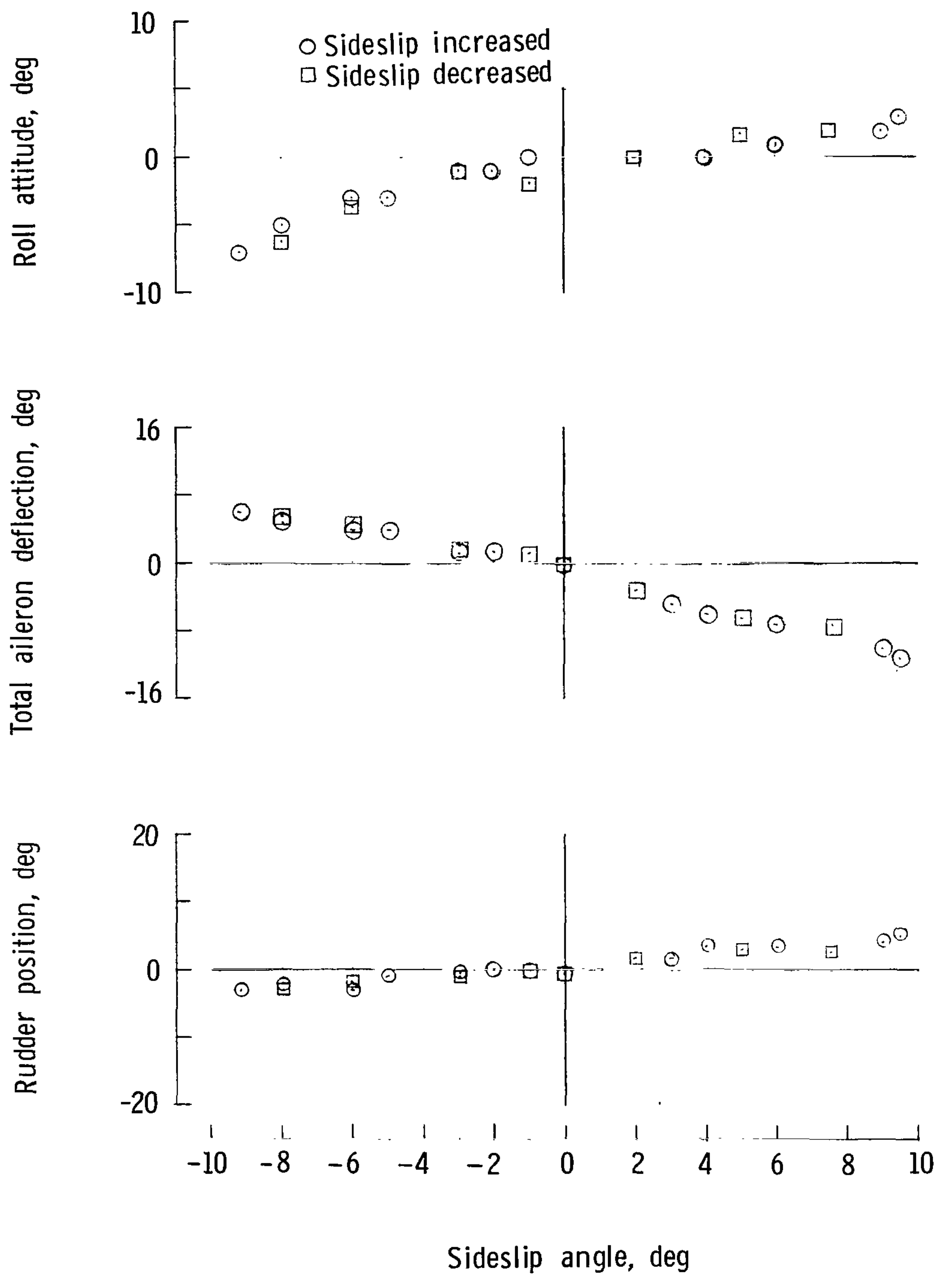
(b) 110 knots.

Figure 23.- Continued.



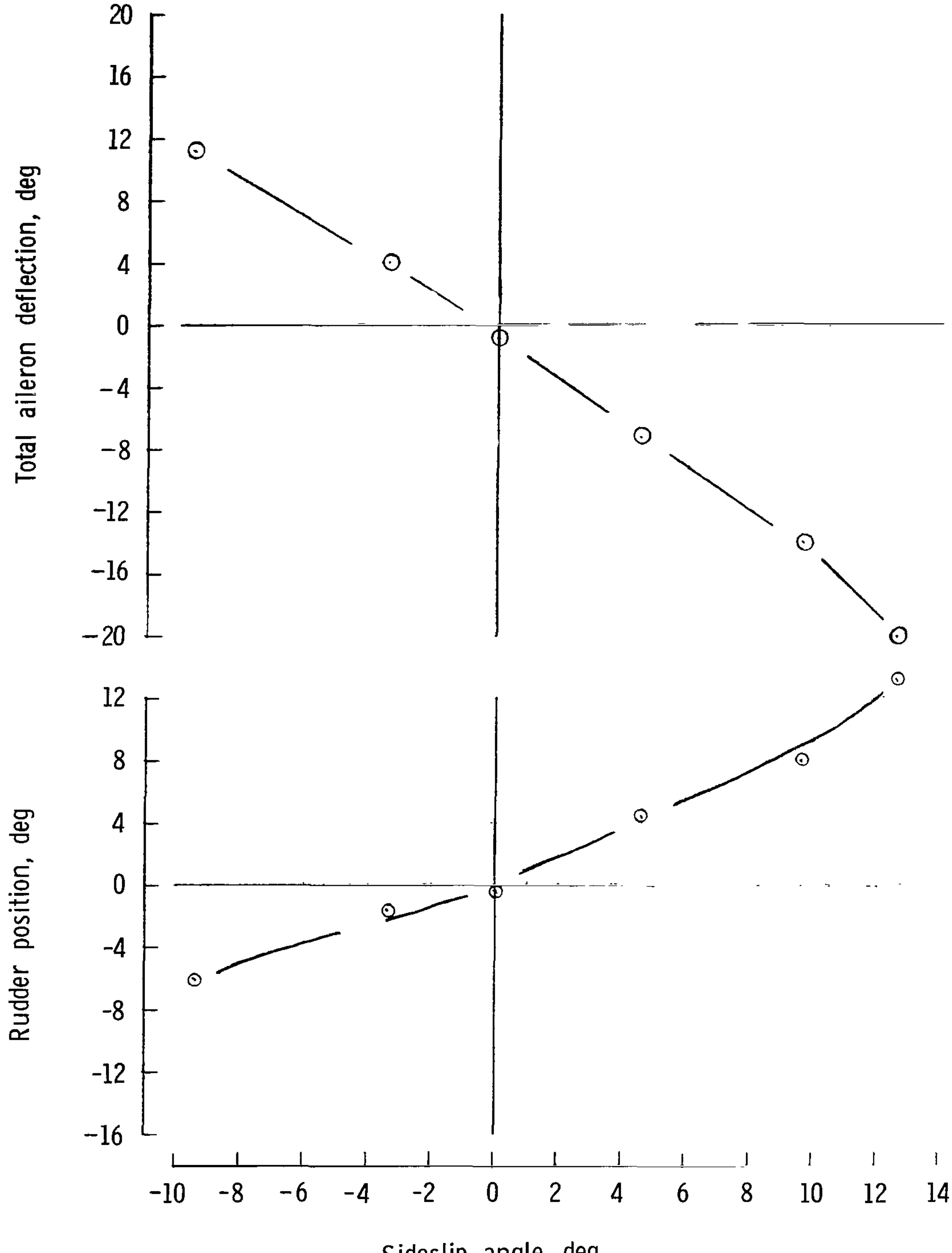
(c) 85 knots.

Figure 23.- Continued.



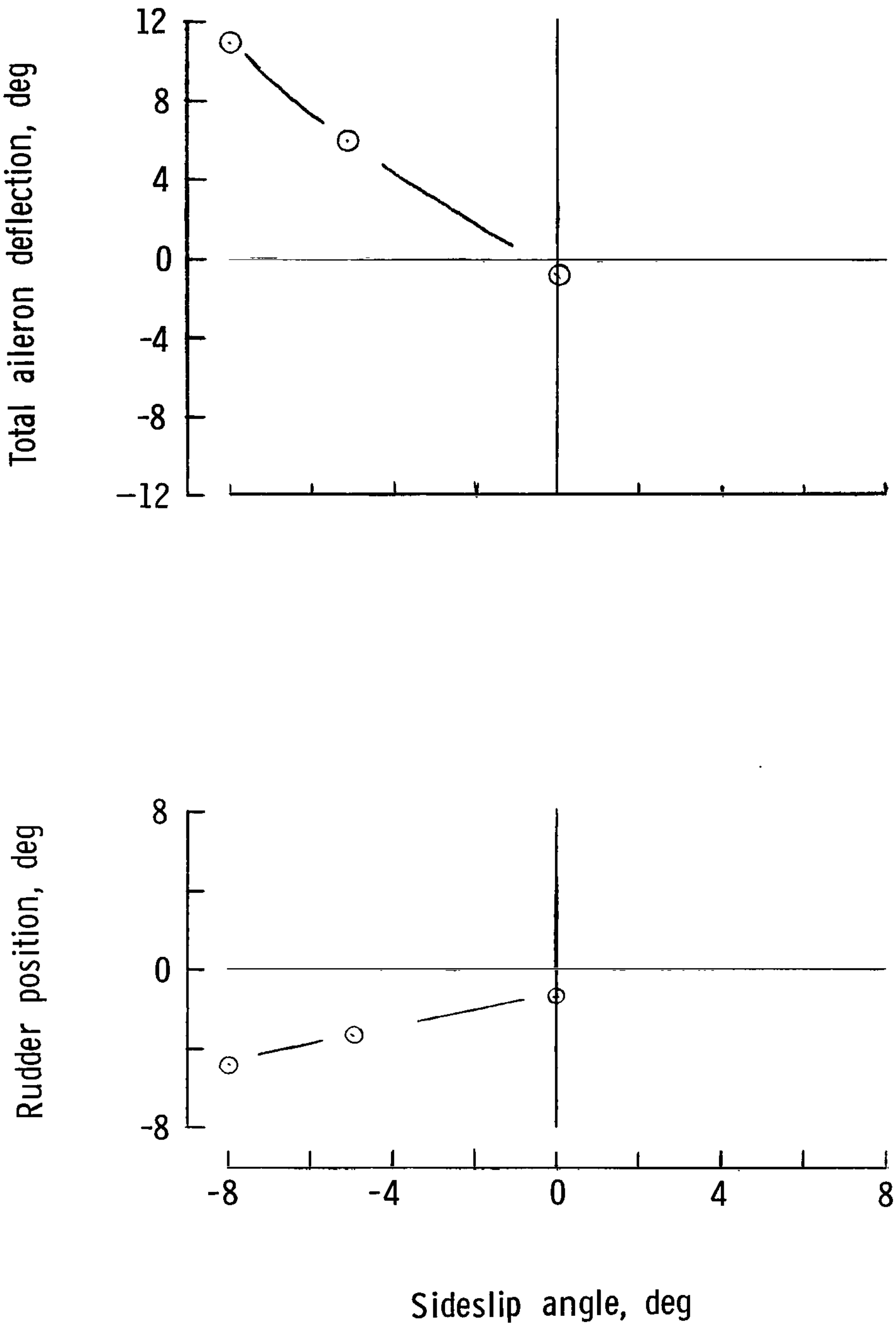
(d) 65 knots.

Figure 23.- Concluded.



(a) 110 knots.

Figure 24.- Wings level sideslip.



(b) 85 knots.

Figure 24.- Concluded.

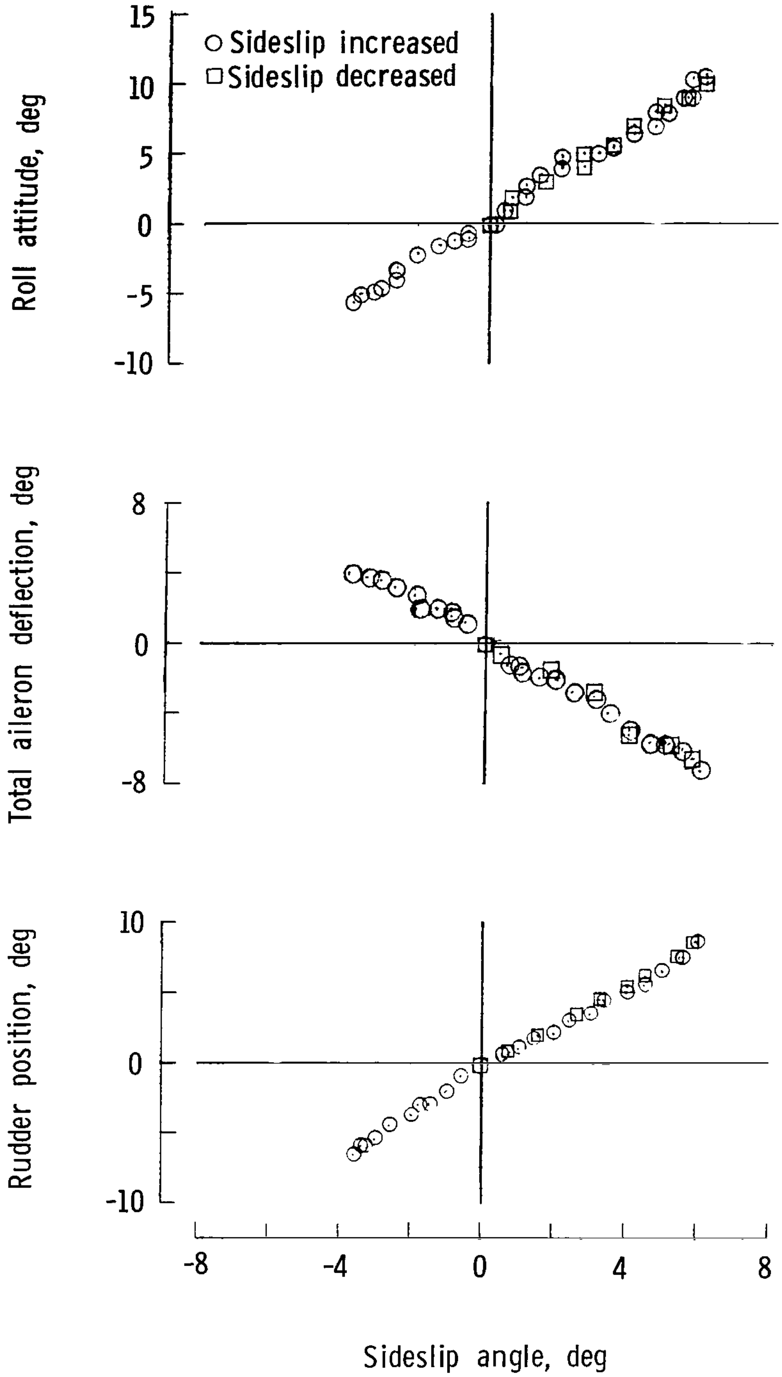
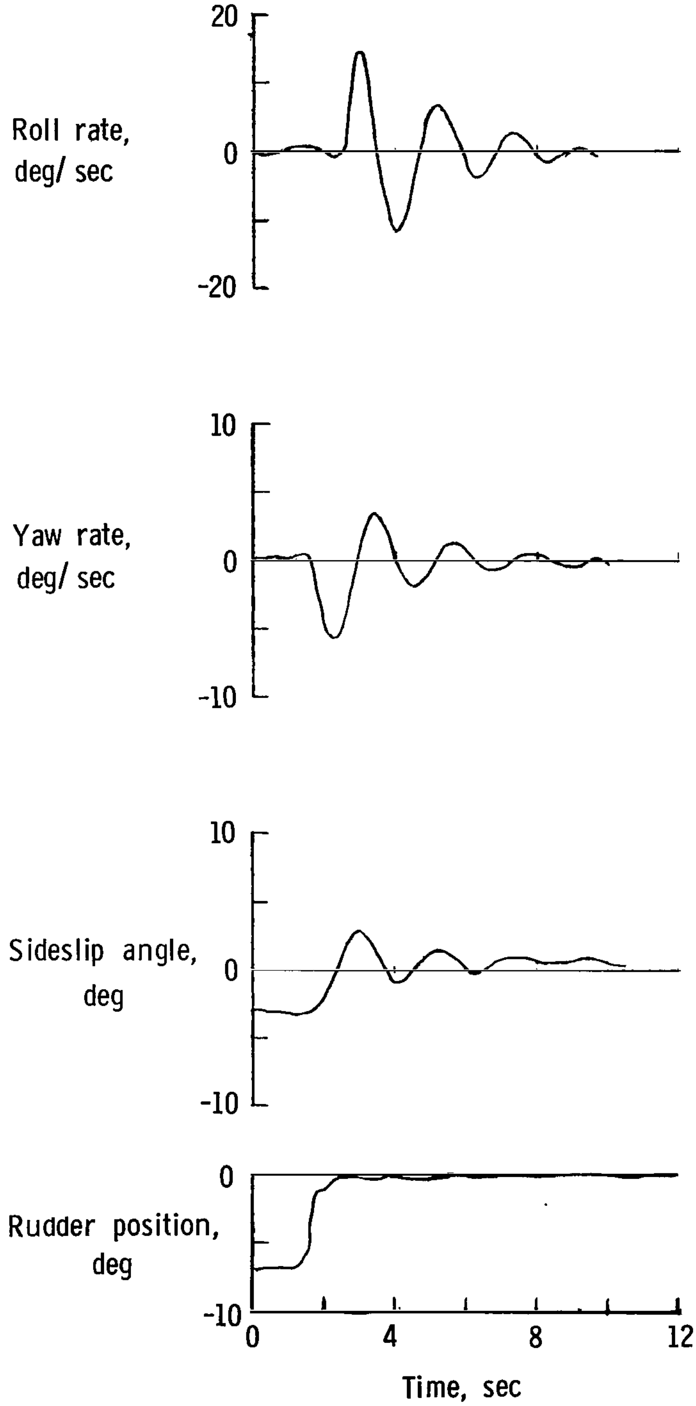
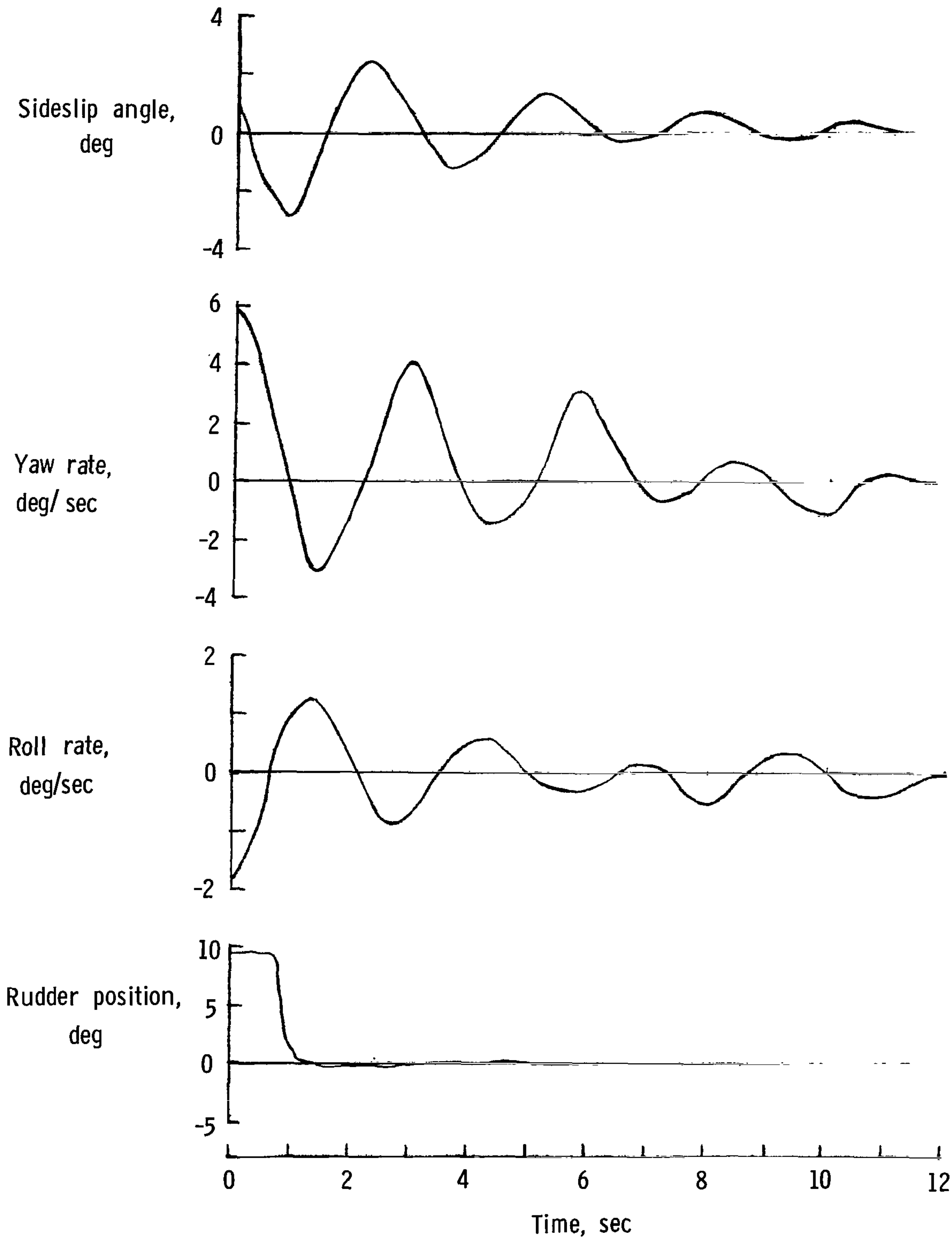


Figure 25.- Steady sideslip at 240 knots. $\alpha = 8^{\circ}$.



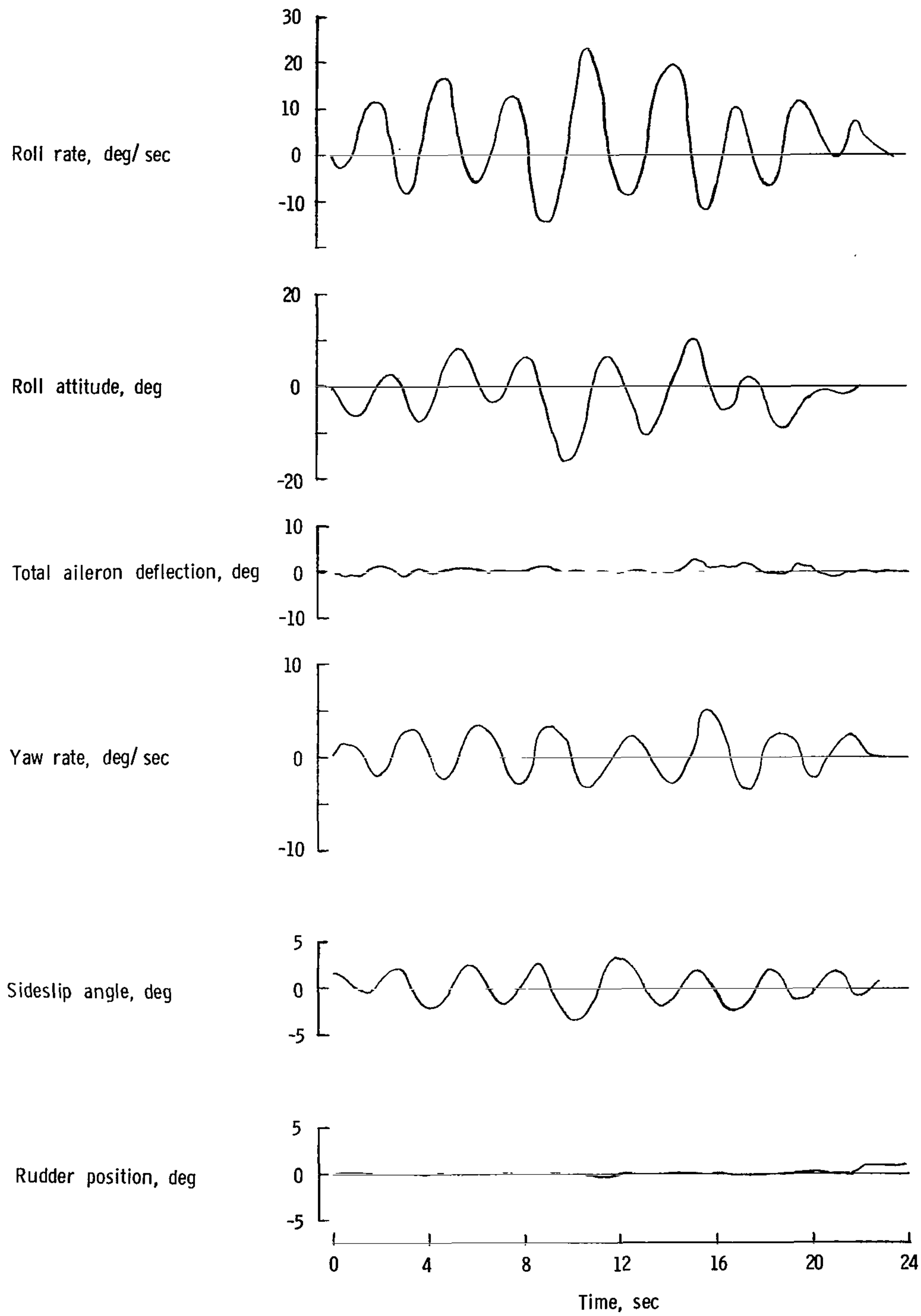
(a) 240 knots. h = 3400 m.

Figure 26.- Dutch roll motion.



(b) 165 knots. h = 1800 m.

Figure 26.- Continued.



(c) 110 knots.

Figure 26.- Concluded.

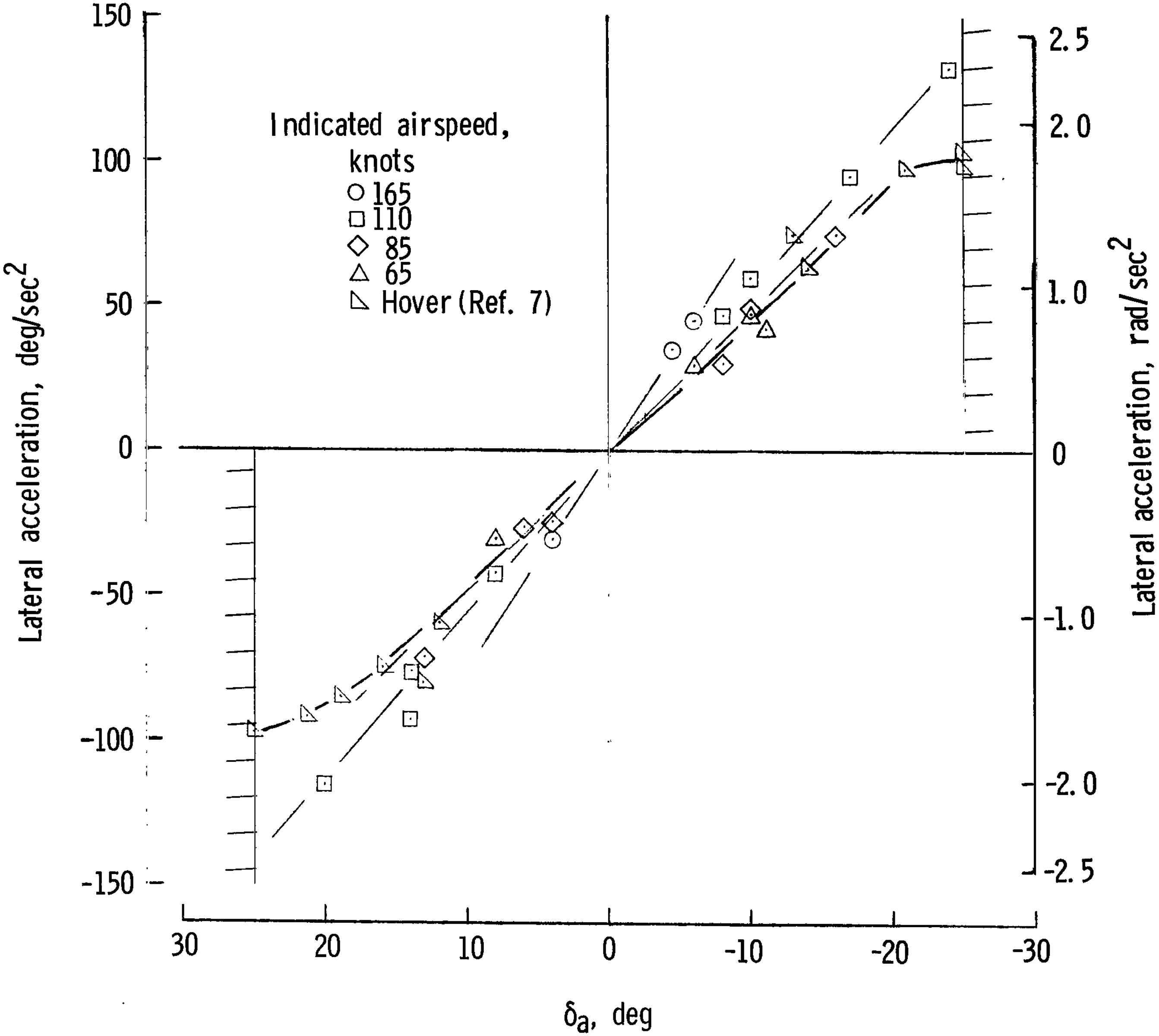


Figure 27.- Control power.

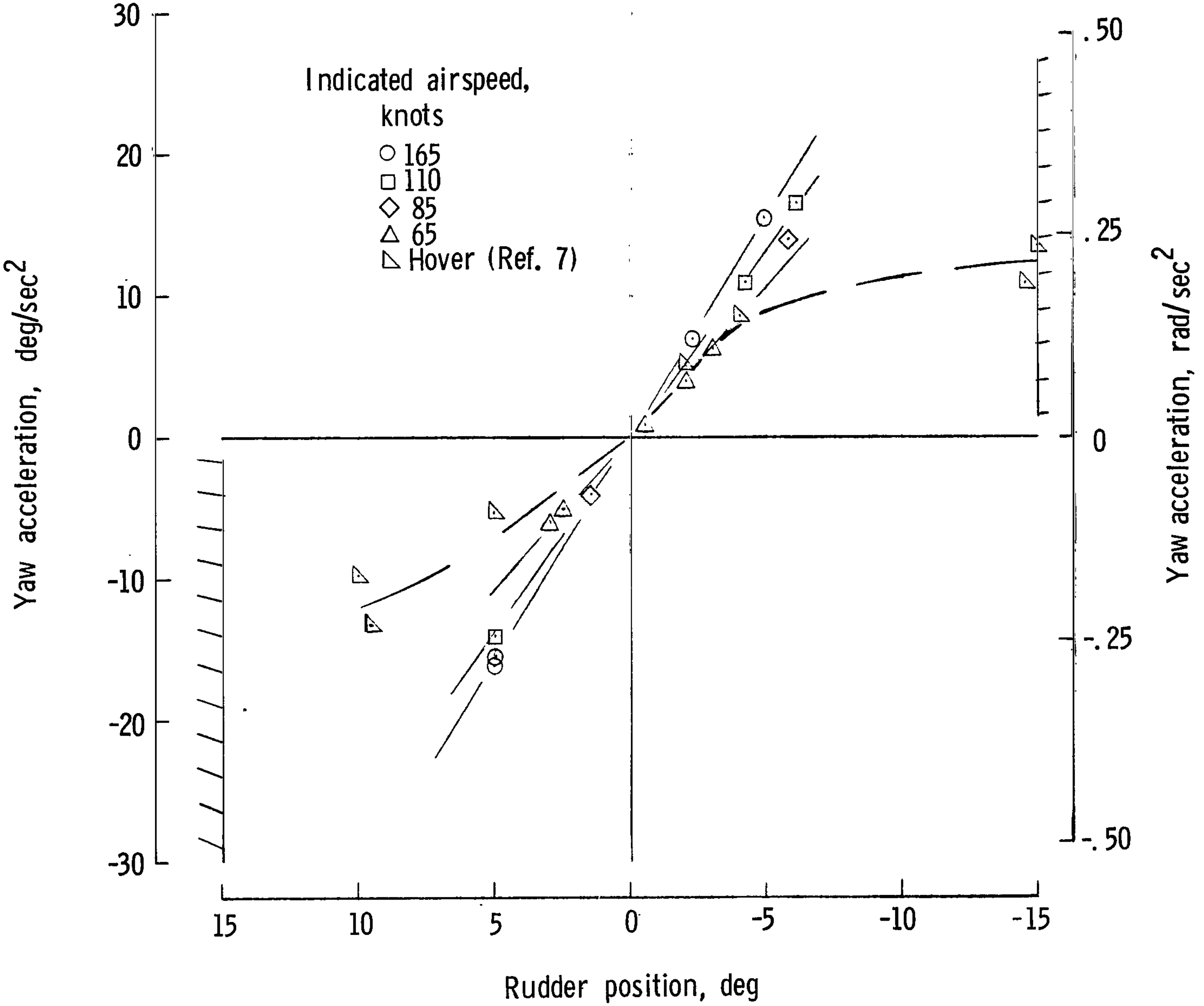


Figure 28.- Directional control power.

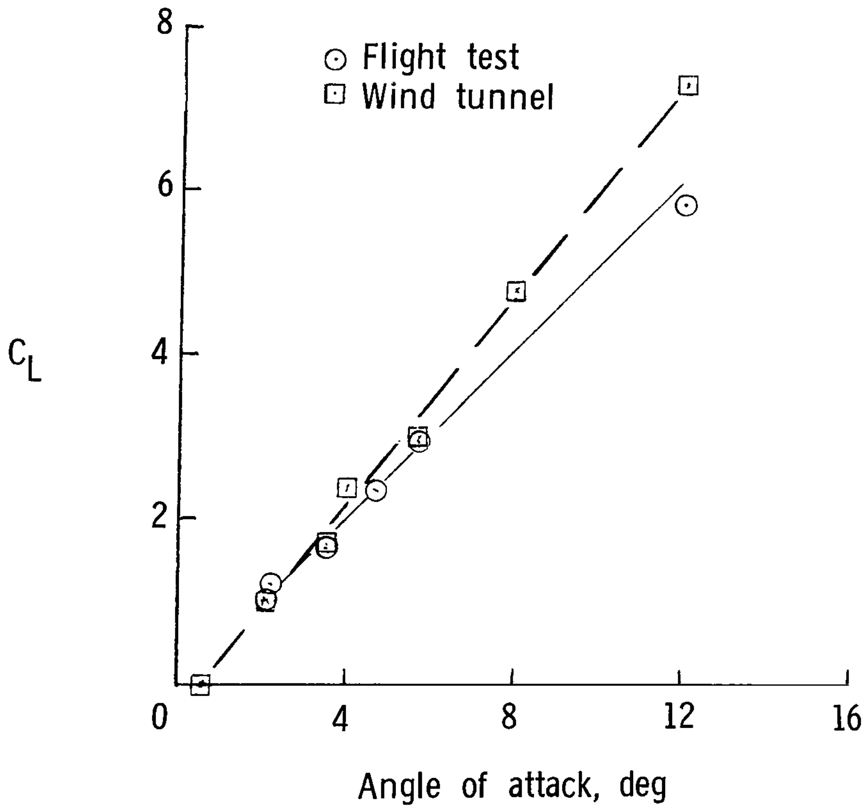


Figure 29.- Variation of trimmed lift coefficient with angle of attack. Clean aircraft; 0° nozzle angle.

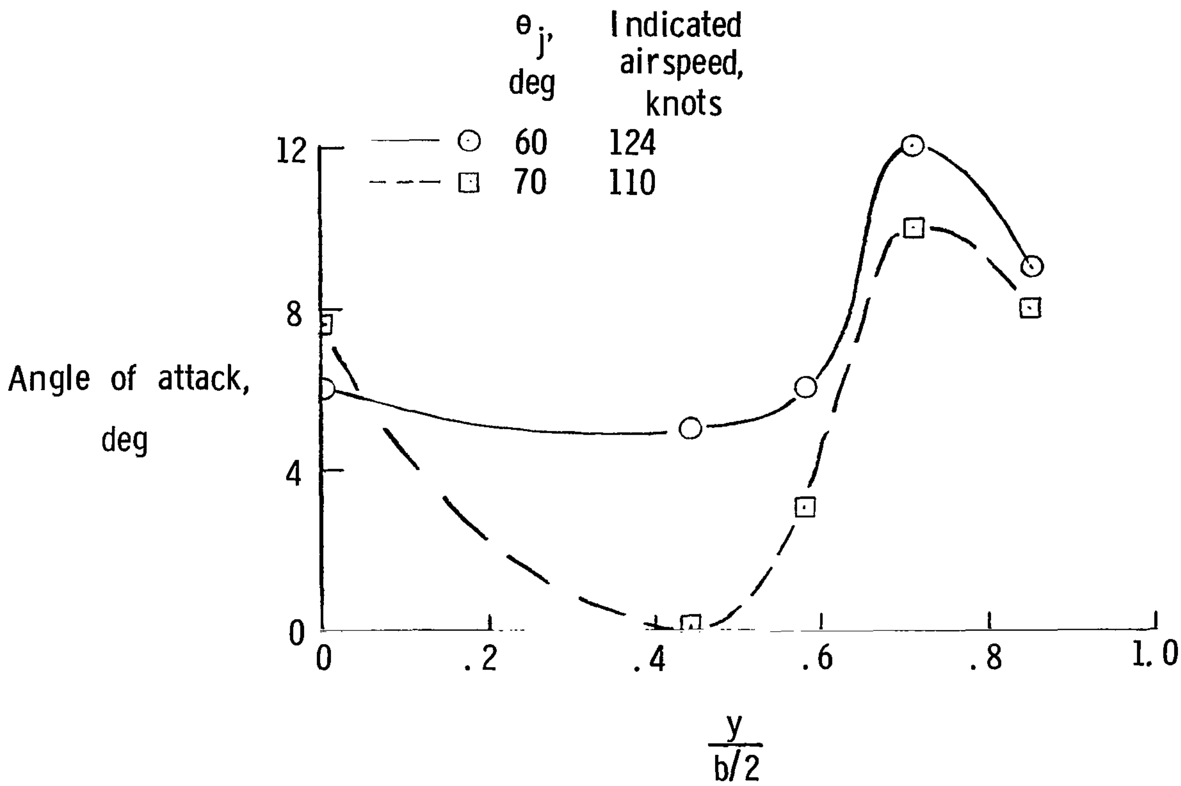


Figure 30.- Variation of angle of attack with spanwise location.

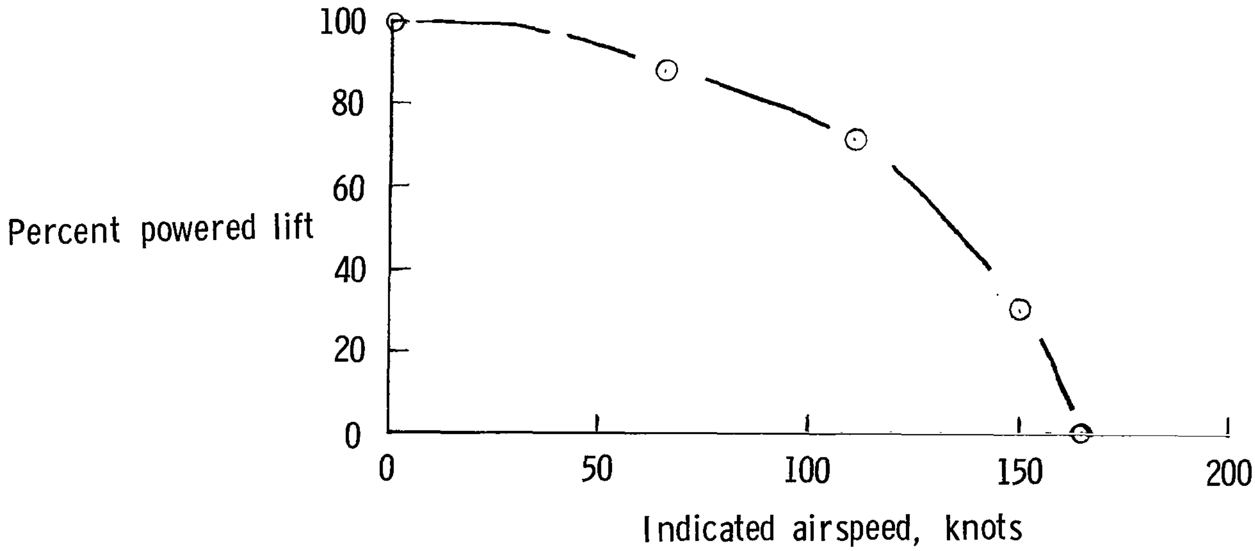


Figure 31.- Variation of powered lift with indicated airspeed. $\alpha = 6^{o}$; $h = 0$ to 500 m; glide-slope angle $\approx 5^{o}$.

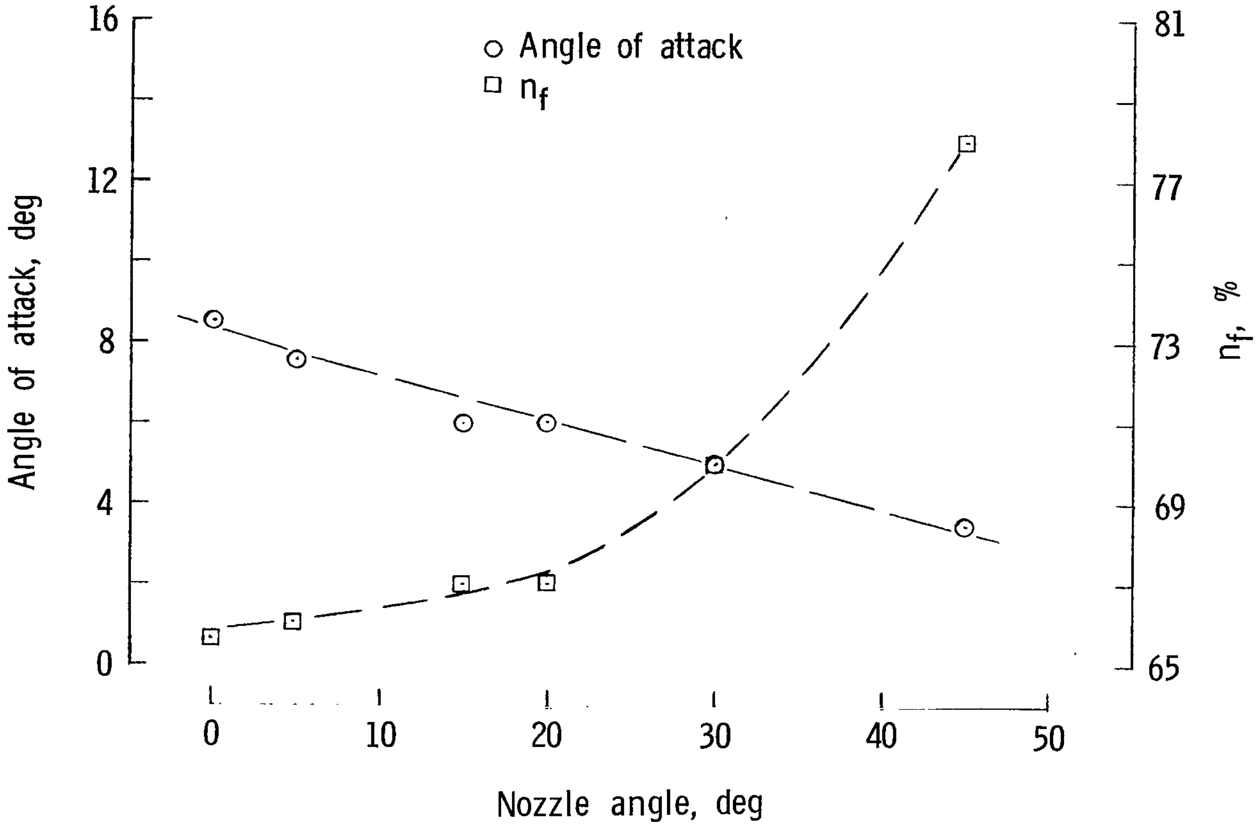


Figure 32.- Trim angle-of-attack and engine-speed data at 155 knots in level flight.

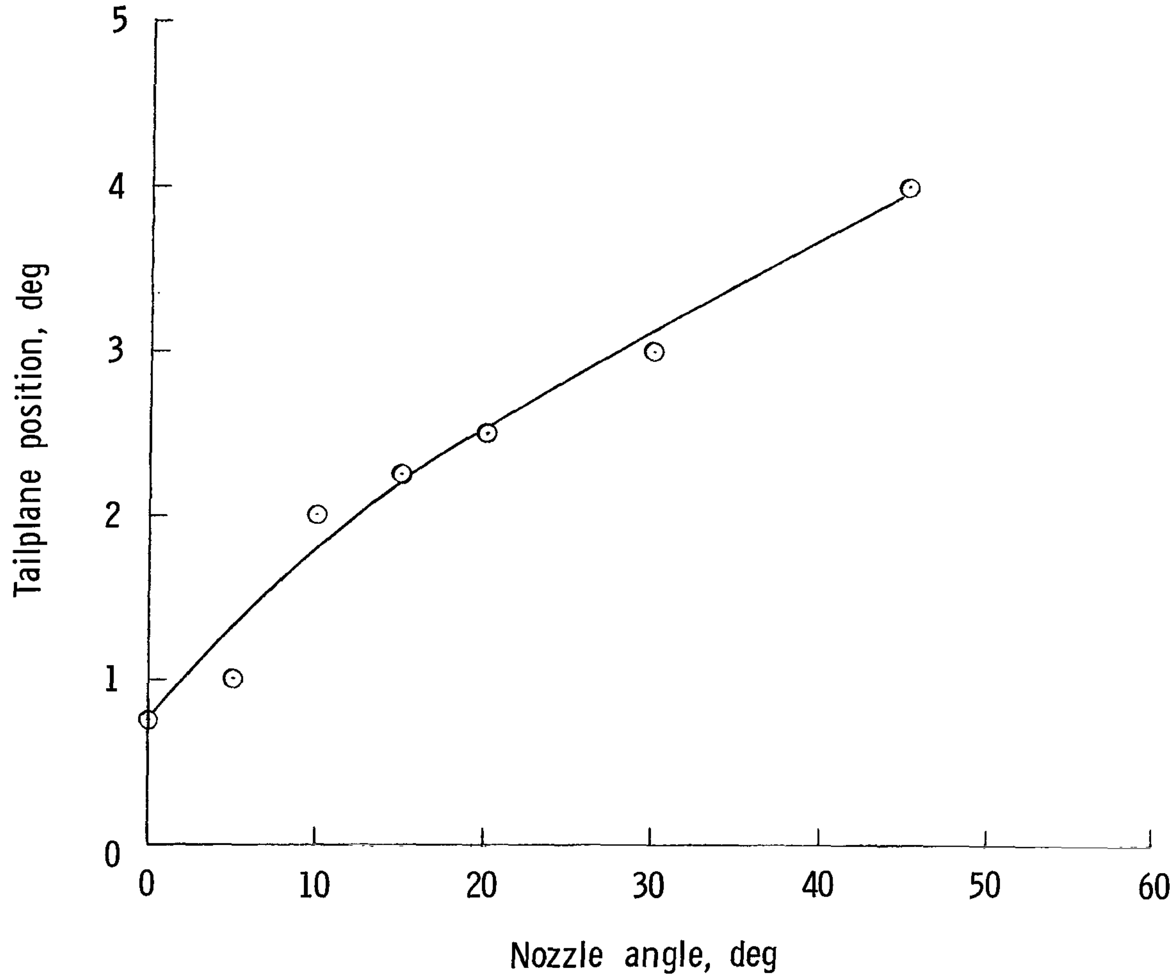


Figure 33.- Trim tailplane data at 155 knots in level flight.

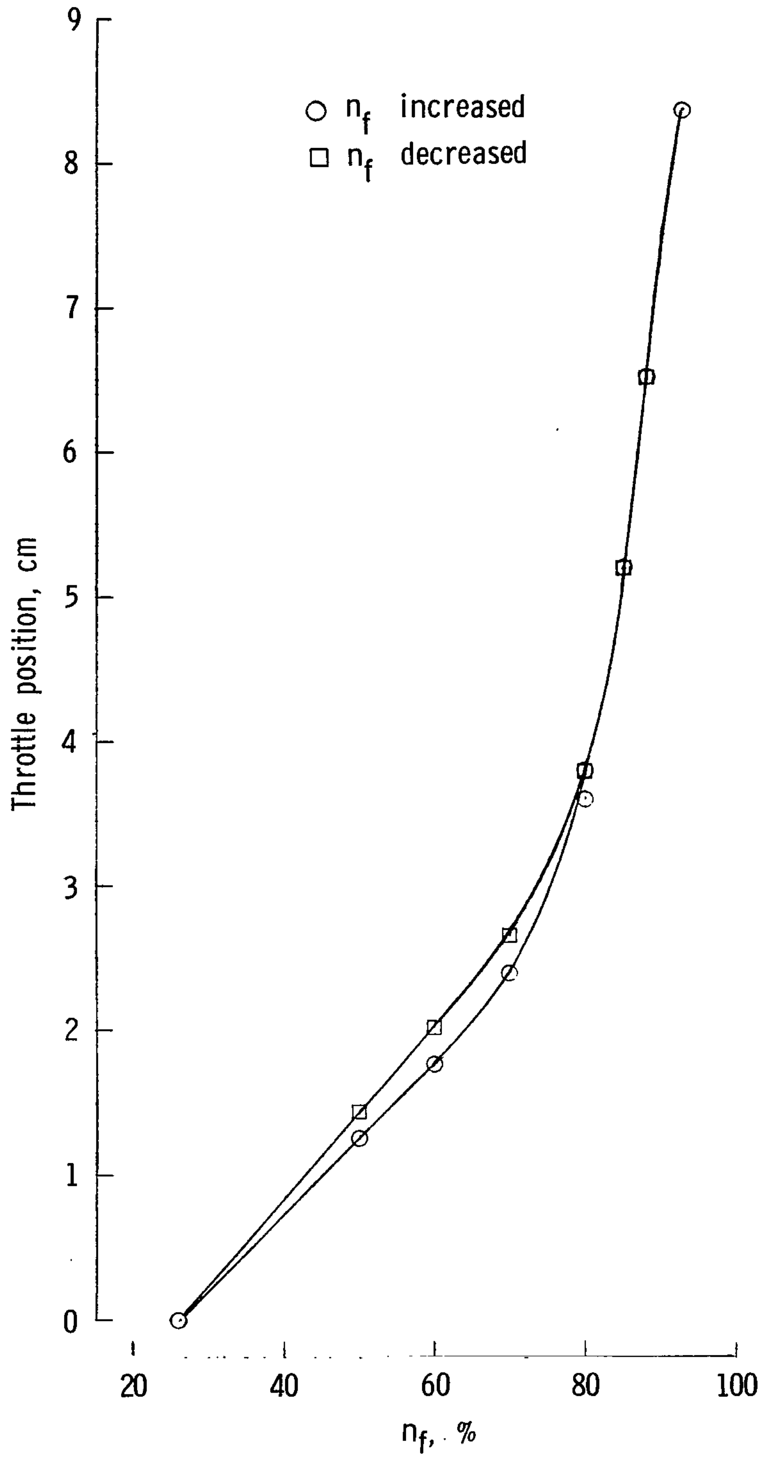


Figure 34.- Throttle characteristics.

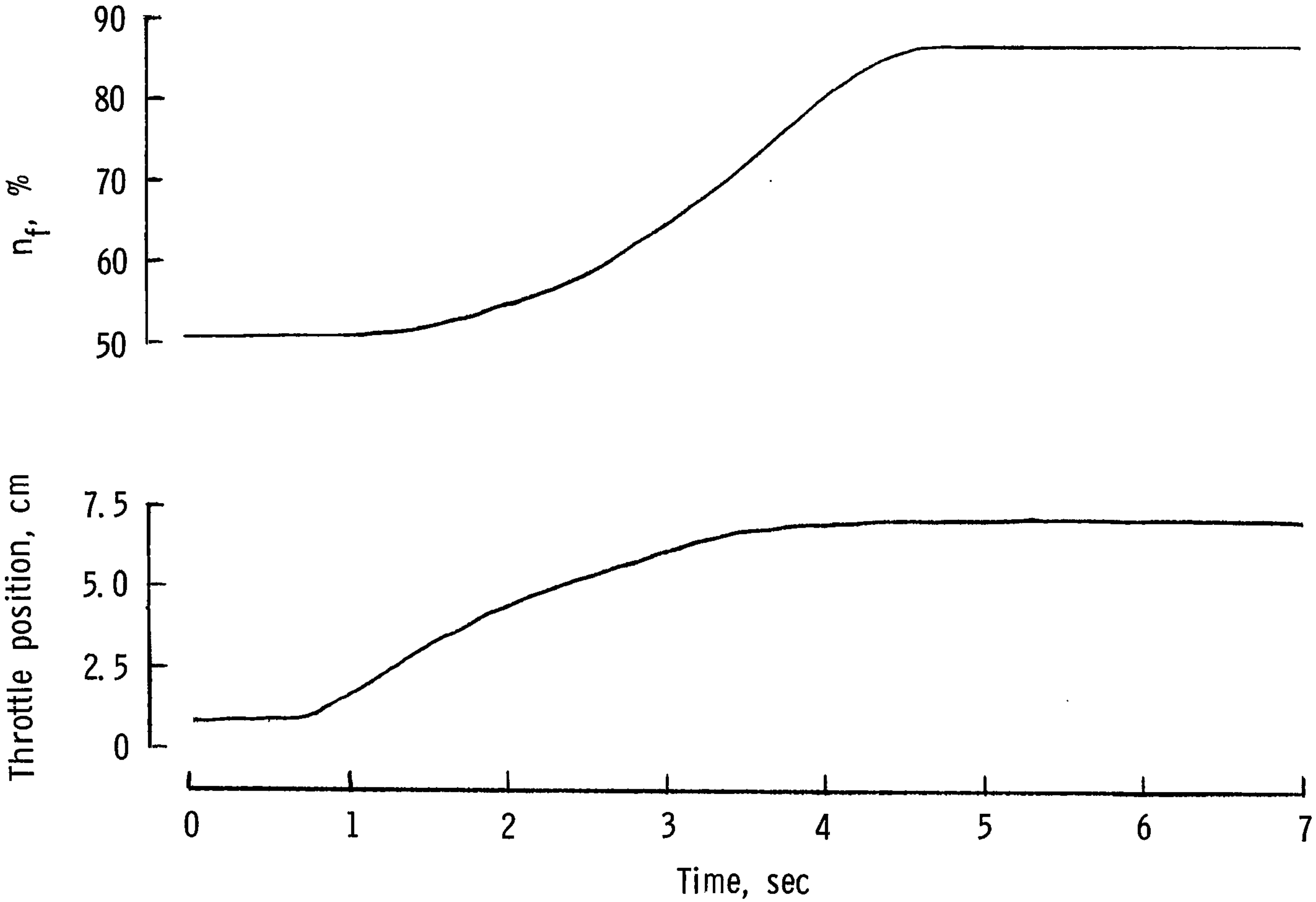


Figure 35.- Engine response characteristics. h = 10 000 meters.

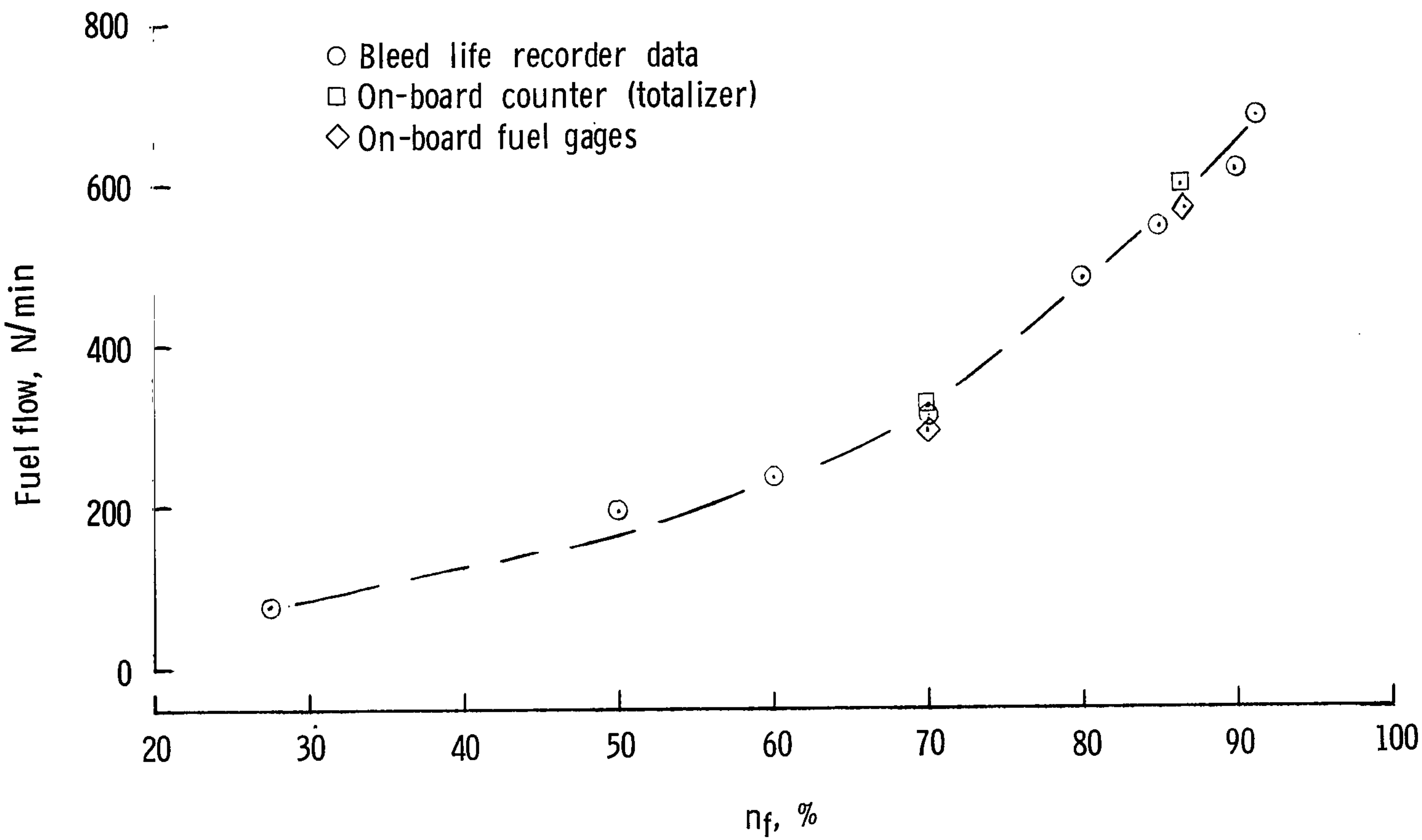


Figure 36.- Engine fuel flow during ground runup.

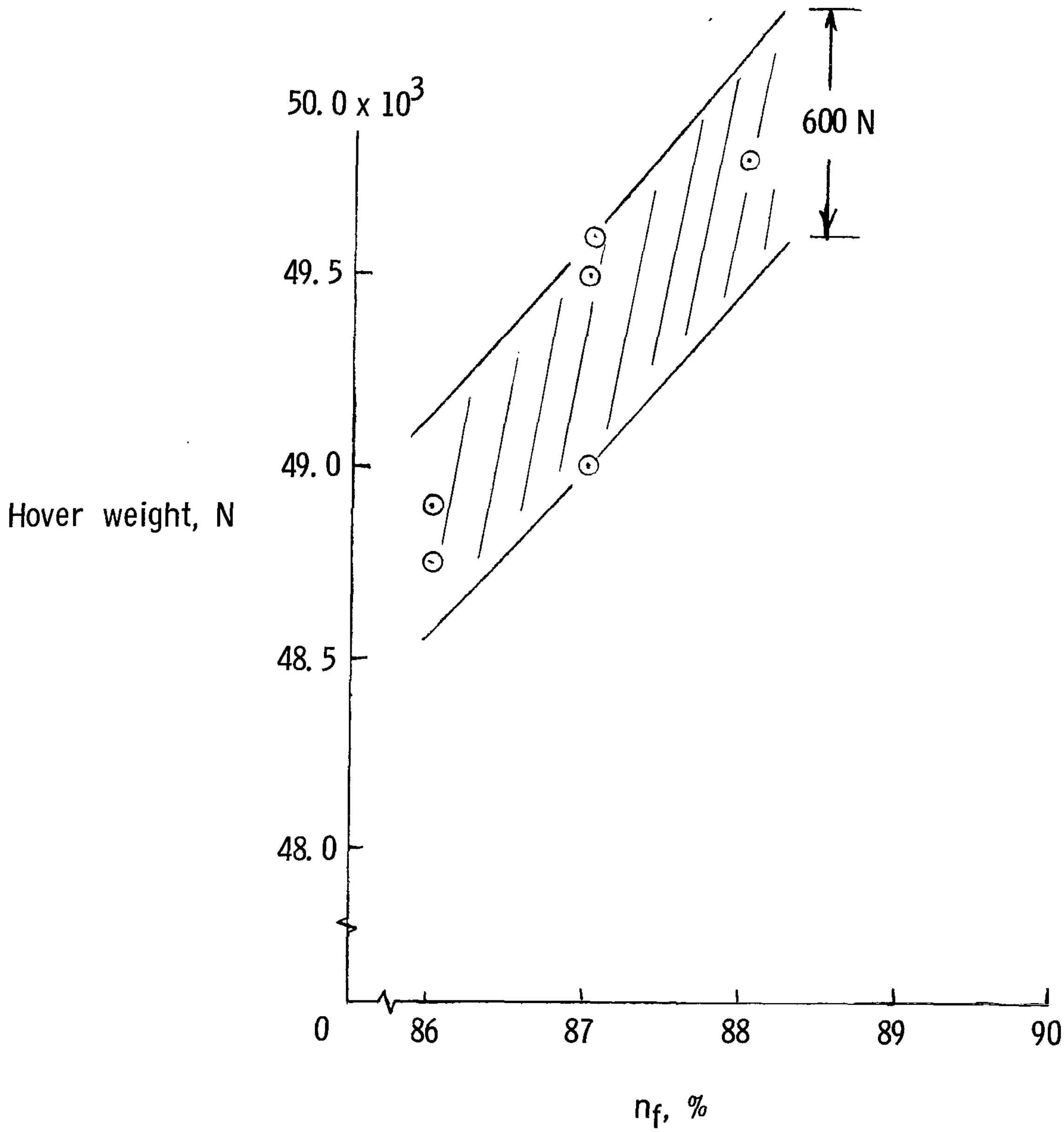


Figure 37.- Hover weight as function of fan speed. $\theta_j = 81^o$; all data corrected for standard conditions.

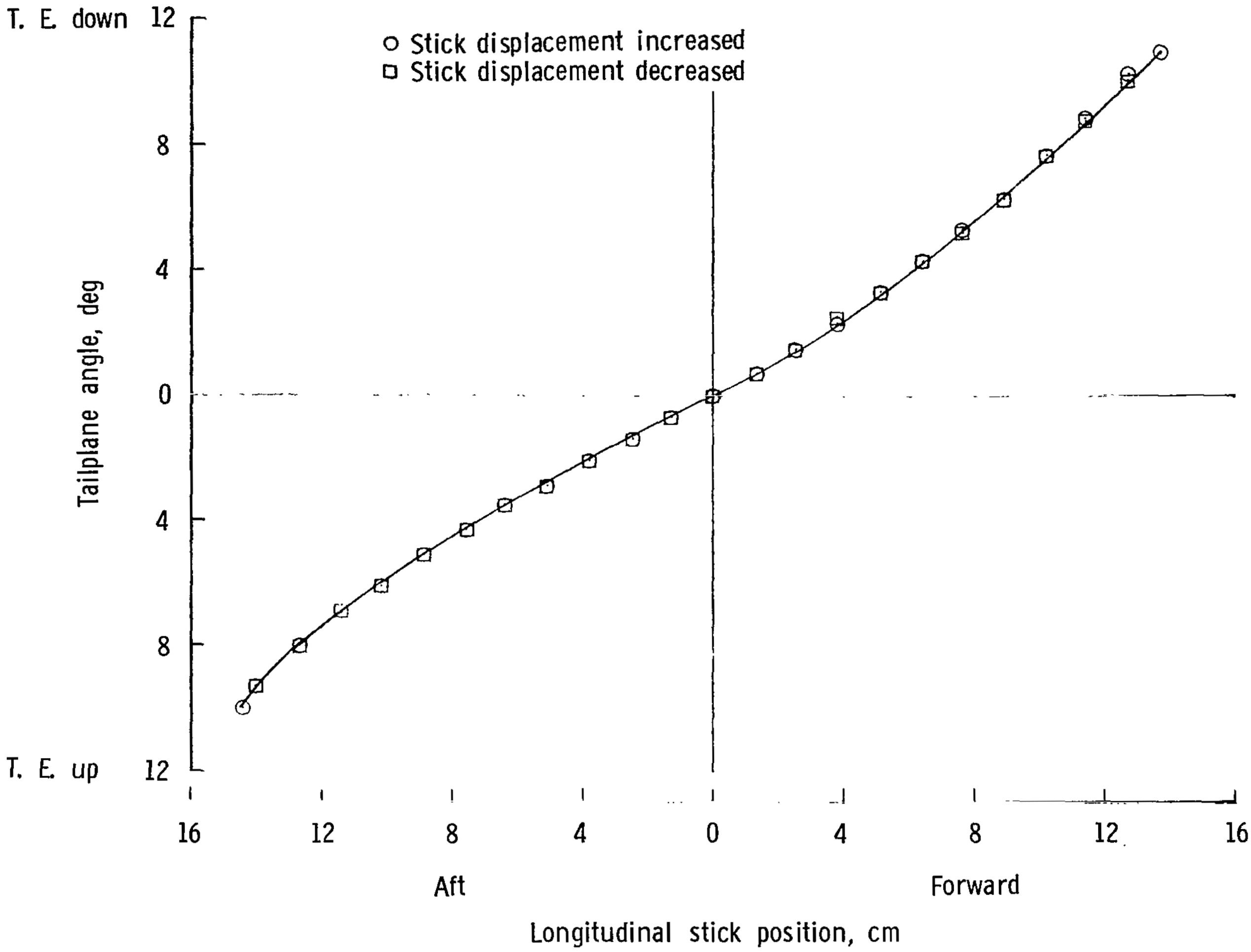


Figure 38.- Longitudinal control deflections.

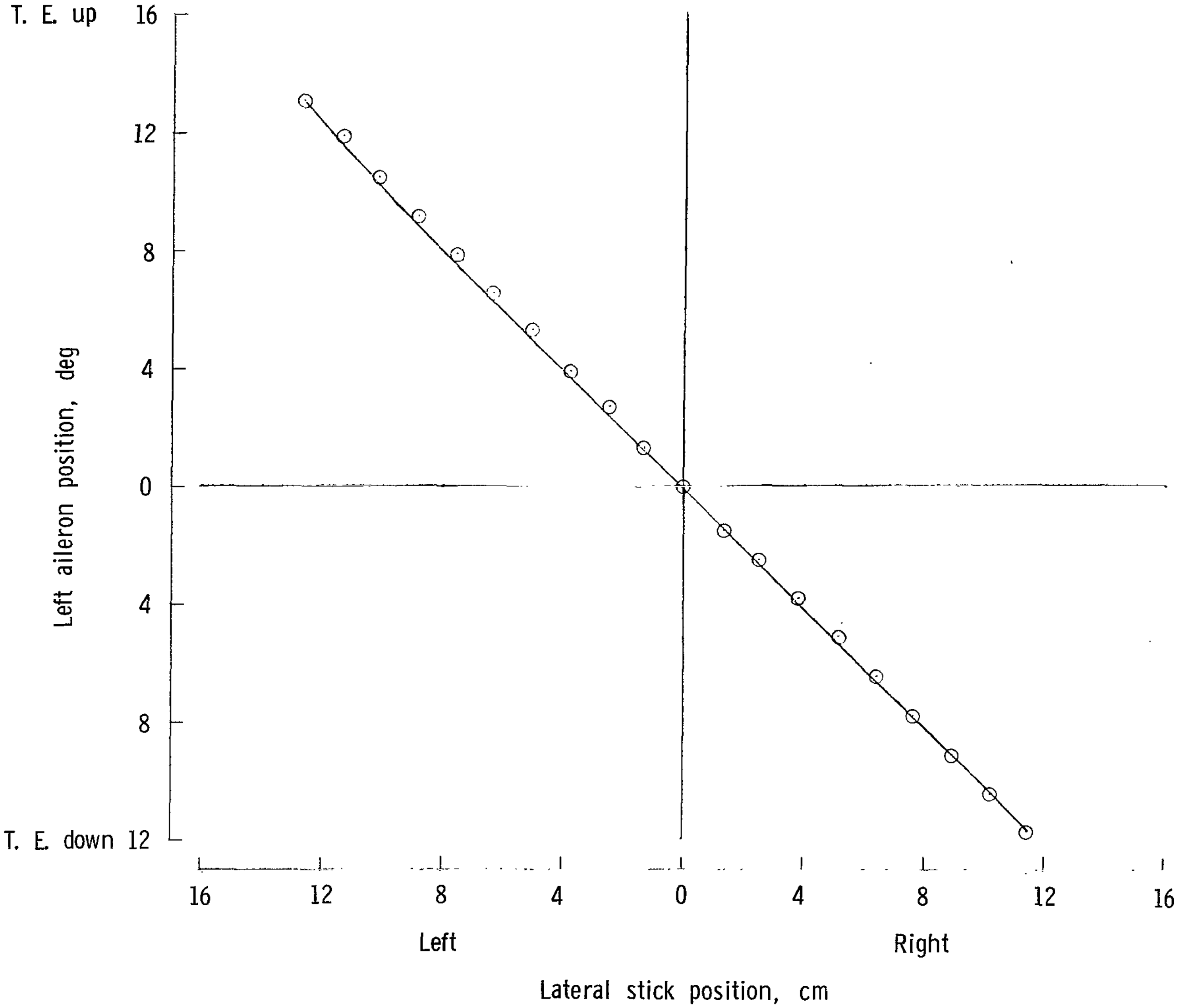


Figure 39.- Lateral control deflections.

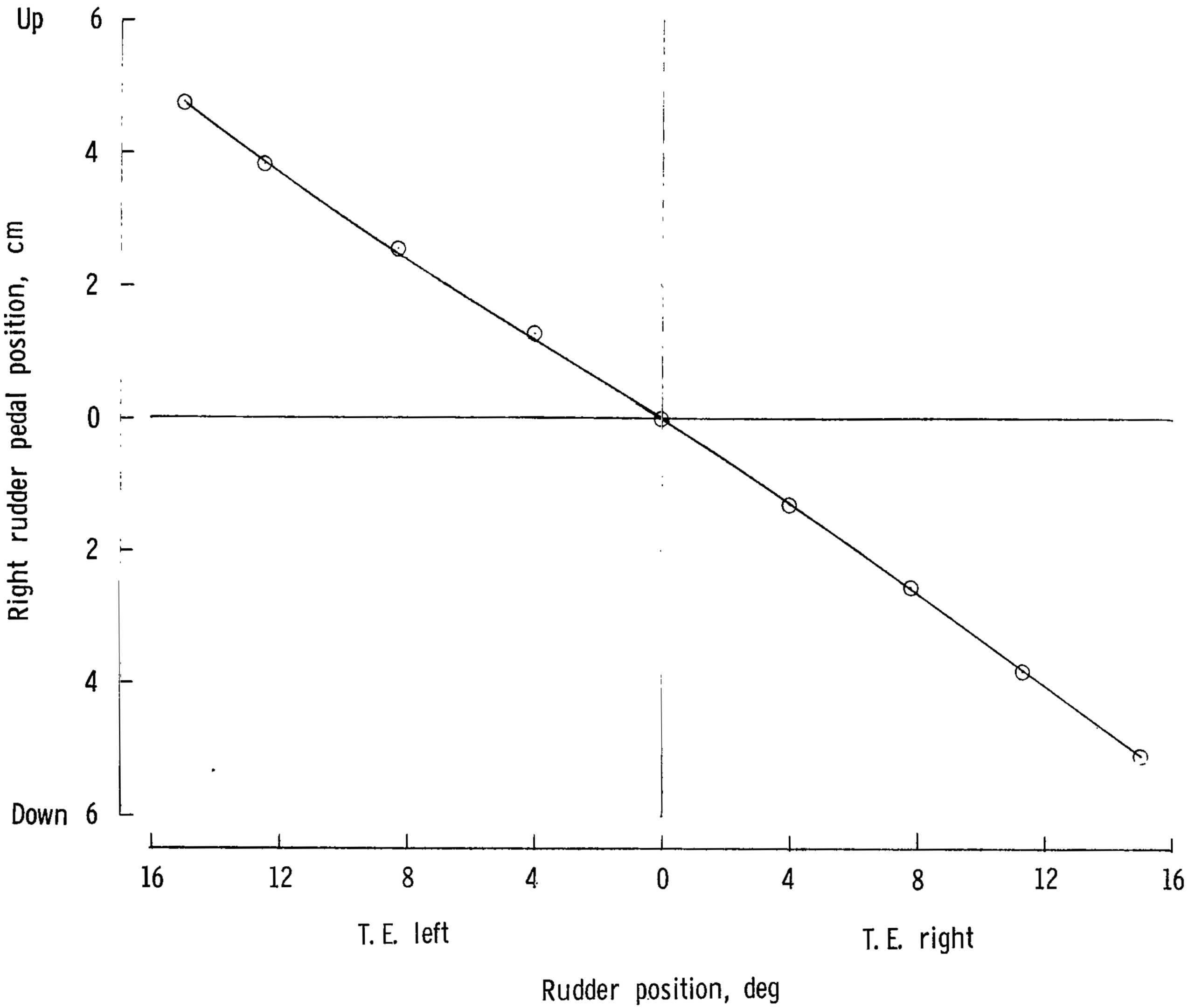


Figure 40.- Directional control deflections.

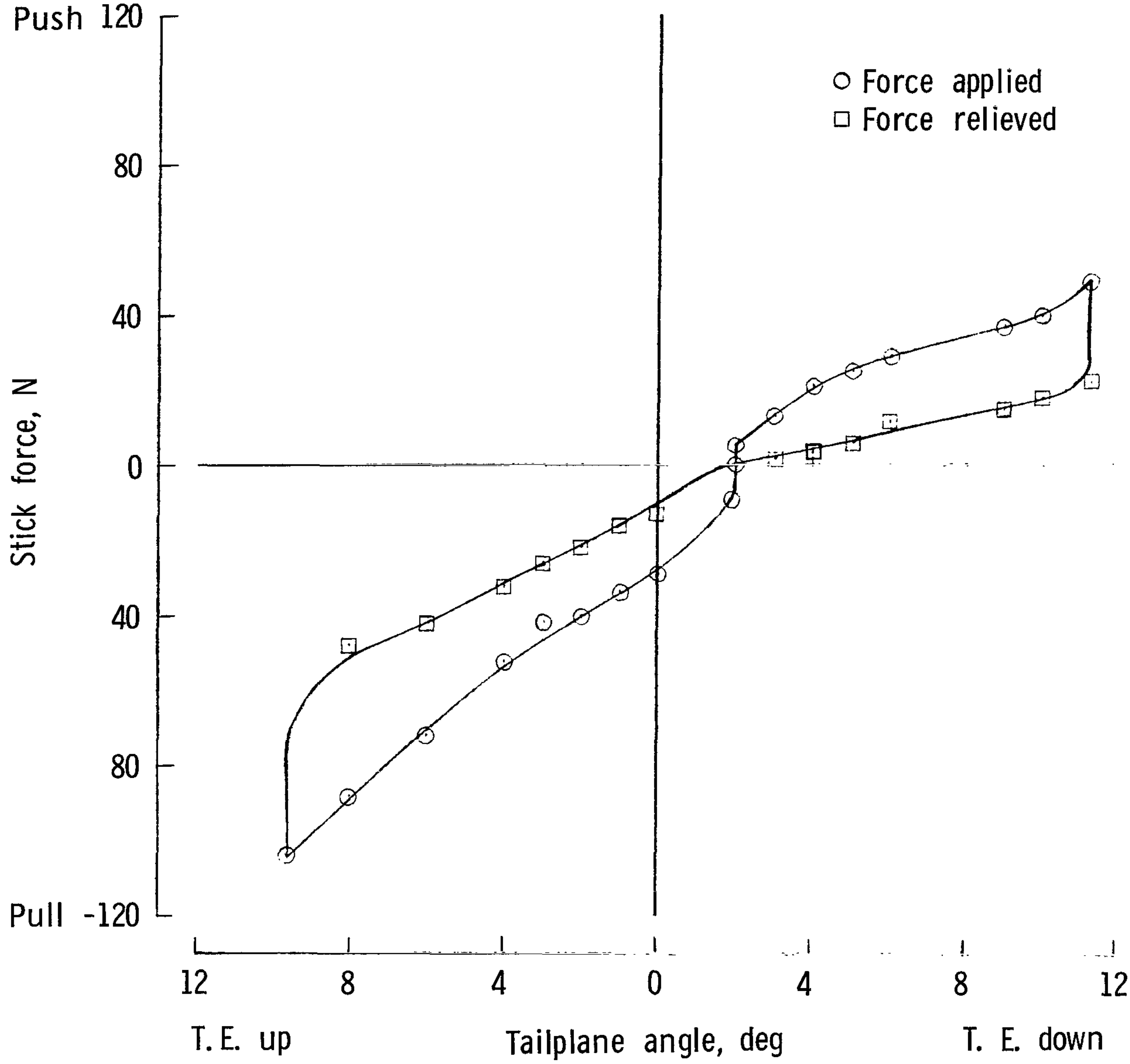


Figure 41.- Longitudinal static stick-force characteristics.

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