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RESEARCH MEMORANDUM

FLIGHT TESTS OF A DELTA-WING VERTICALLY RISING AIRPLANE MODEL POWERED BY A DUCTED FAN

By Powell M. Lovell, Jr.

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Langley Field, Va.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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FLIGHT TESTS OF A DELTA-WING VERTICALLY RISING AIRPLANE MODEL POWERED BY A DUCTED FAN

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SUMMARY

An experimental investigation has been conducted to determine the dynamic stability and control characteristics of a delta-wing vertically rising airplane model powered by a ducted fan. In addition to conventional flap-type control surfaces on the wings and vertical tail, the model had jet-reaction control provided by movable eyelids at the rear of the tail pipe and by air bled from the main duct and exhausted through movable nozzles near the wing tips. The investigation included take-offs and landings, hovering flight, and the transition from hovering to unstalled forward flight.

In hovering flight, the model could be flown smoothly and easily without any automatic stabilization. The jet-reaction controls were powerful and enabled the pilots to maneuver the model rapidly to various positions within the hovering test area. Take-offs could be made easily and landings on a predetermined spot could be made accurately.

About half the transition flights made without automatic stabilization devices were unsuccessful because the model diverged in roll and yaw at angles of attack between about 50° and 60° despite the efforts of the pilots to stop it. In some cases, however, it was possible to make the transition when the model happened to be flying very steadily as it passed through the critical angle-of-attack range.

The use of artificial damping in roll greatly improved the lateral stability and made the model easy to fly throughout the entire speed range. The use of artificial damping in yaw, directional stability, or dihedral effect, however, did not provide sufficient improvement in the critical angle-of-attack range to eliminate the occurrence of divergences during the transition.

INTRODUCTION

An investigation has been conducted to determine the dynamic stability and control characteristics of a jet-powered delta-wing vertically rising airplane model. A ducted-fan powerplant was used because there was no hot-jet powerplant of sufficiently small size and adequate reliability available. When the test results are interpreted, it should be borne in mind that the gyroscopic effects which a jet engine may have on the stability and control characteristics of a vertically rising airplane were not simulated because the two motors of the model powerplant turned in opposite directions and the gyroscopic forces were canceled.

The investigation consisted entirely of flight tests and covered take-offs and landings, hovering flight, and the transition from hovering to unstalled forward flight. In the transition flights, which covered a range of angle of attack from about 90° to 10°, the effects of various artificial lateral-stability devices were determined. The results of the investigation were obtained both from the pilots' observations and opinions of the stability and controllability of the model and from time histories of the motions of the model prepared from motion-picture records of the flights.

NOMENCLATURE AND SYMBOLS

In order to avoid confusion in terminology which might arise because of the large range of operating attitudes of the model, it should be explained that the controls and motions of the model are referred to in conventional terms relative to the body system of axes; that is, the rudder on the vertical tail and the deflection of the jet to left or right by the eyelid produced yaw about the normal body axis; differential deflection of the elevons and the jet nozzles in the wing produced roll about the fuselage axis; and simultaneous up or down deflections of the elevons and deflection of the jet up or down by the eyelid produced pitch about the spanwise axis. Figure 1 shows the axes and the positive directions of the linear and angular displacements.

The symbols used in the present paper are as follows:

θ angle of pitch of fuselage axis relative to horizontal, deg (For this report the angle of attack and angle of pitch are the same.)

ψ angle of yaw, positive for right yaw; measured from the vertical in plane shown by rear camera, deg

ϕ angle of bank, deg

t	time, sec
δ_a	deflection of controls to produce roll control
δ_r	deflection of controls to produce yaw control
δ_e	deflection of controls to produce pitch control

APPARATUS AND TESTS

Model

Photographs of the model showing the powerplant installation and controls are presented as figure 2, and a sketch showing some of the more important dimensions is shown as figure 3. The geometric characteristics of the model are presented in table I. A multiple-exposure photograph showing the model in various stages of a transition flight is presented as figure 4.

The model was powered by two 5-horsepower electric motors turning 14.25-inch-diameter oppositely rotating propellers in a duct 4 feet long. The duct was made of cellular plastic 0.25 inch thick covered both inside and outside with laminated-glass-fiber fabric. A rounded lip was provided on the forward end of the duct to increase the static thrust of the ducted fan. It is not known exactly how much increase was provided by this lip but tests of another ducted fan indicate than an increase in thrust of 60 percent over that of a ducted fan with a sharp lip might be expected.

The model had modified delta-wing and vertical-tail surfaces with conventional flap-type elevon and rudder controls for use in forward flight. Pitch and yaw controls for hovering flight were provided by eyelids at the rear of the fuselage which deflected the jet. Roll control was provided by air routed from the main duct through the wings to differentially moving nozzles near the wing tips. About 10 percent of the air was bled off from the main duct to the nozzles.

In most flights, the jet-reaction controls were operated by the flicker-type (full-on or off) pneumatic actuators used on all models by the Langley free-flight tunnel section. These actuators were equipped with an integrating-type trimmer which trimmed the control a small amount in the direction the control was moved each time a control deflection was applied. With actuators of this type, a model becomes accurately trimmed after flying a short time in a given flight condition.

In some of the transition flights, various artificial stabilizing devices were used to move the controls automatically in proportion to the rate of roll, rate of yaw, or to the sideslip angle. The sensing elements for the rate-of-roll and rate-of-yaw devices were rate gyroscopes which, in response to rate of roll or rate of yaw, provided signals to proportional control actuators which moved the controls to oppose the rolling or yawing motion. A pilot-operated override was provided in the gyroscope-operated devices so that the pilot could have all the available control power at his command. The operation of these devices was such that they provided damping in roll or yaw regardless of the attitude of the model. The override cut out the damping action and applied all available control in the direction desired by the pilot. If there had not been an override, the damping devices would have applied controls to oppose those applied by the pilot and would thus reduce the control effectiveness available to the pilot. The sensing elements for the angle-of-sideslip stabilizing devices were air-flow valves operated by a vane mounted on a boom extending from the nose of the model which provided signals to the proportional control actuators that moved the controls in response to an angle of sideslip.

Inasmuch as only a small amount of excess thrust was available, it was necessary to keep the weight of the model to a minimum to avoid overheating of the electric-drive motors. In some cases, therefore, various items of equipment unnecessary for a given test were removed. For the take-off, hovering, and landing tests, the flap-type control actuators were removed; for the transition tests, the landing-gear shock struts were removed. The weight of the model for the transition tests was 45.2 pounds and for the take-off, landing, and hovering tests, was 46.5 pounds.

Test Equipment and Setup

The take-off, landing, and hovering tests were conducted in a large building which provided protection from the random effects of outside air currents and thereby permitted the basic stability and control characteristics of the model to be determined more readily. The forward-flight tests were conducted in the Langley full-scale tunnel.

Essentially the same test setup was used in all tests. This setup is illustrated for the forward-flight tests in figure 5. The sketch shows the pitch pilot, the safety-cable operator, and a power and camera operator on a balcony at the side of the test section. The roll pilot was located in an enclosure in the lower rear part of the test section, and the yaw pilot and a second camera operator were at the top rear of the test section. The three pilots were located at positions which gave them a good vantage point for observing and controlling the particular phase of the motion with which they were concerned. In the hovering tests, which were made in a different facility, the pilots and operators were also stationed at various positions around the test area to give them a good vantage point for observing and flying the model.

A safety cable was used for catching the model to prevent crashes in case of a power or control failure or in the event that the pilots lost control of the model. This cable was attached to the top of the fuselage at the front motor mount and was then run over a pulley at the ceiling of the test chamber and to the safety-cable operator who adjusted the length of the cable to keep it slack during flight.

The power and control cable consisted of plastic tubes, which provided air for the electro-pneumatic control actuators, and electric wires, which supplied power for the motors and carried the remote control signals to the control actuators. This cable was led from the power sources and suspended from the ceiling from a point near the safety cable pulley. It was then taped to the safety cable from about 15 feet above the model down to the model.

Tests

The investigation consisted of flight tests to determine the stability and control characteristics of the model in vertical take-offs and landings in still air, in hovering flight in still air, and in forward flight. The test results were obtained both from the pilots' observations and opinions of the behavior of the model and from motion-picture records of the motions of the model.

In take-offs, landings, and hovering flight, the eyelids were deflected $\pm 4^\circ$ from the trim position for both yaw and pitch control and the roll nozzles were deflected $\pm 60^\circ$. For forward flight, the eyelids were deflected $\pm 11^\circ$ for elevator control and $\pm 8^\circ$ for rudder control and the roll nozzles were deflected $\pm 60^\circ$. In all the forward-flight tests, the elevons were deflected $\pm 18^\circ$ for roll control. In the few forward-flight tests in which the elevons and rudder were used for longitudinal and directional control, the elevons were deflected $\pm 13^\circ$ and the rudder was deflected $\pm 18^\circ$.

The take-off tests were made by increasing the power to the model fairly rapidly until it took off. After the take-off, power was reduced until the model stabilized at a height of about 10 feet above the ground.

Landing tests were started with the model in steady hovering flight at a height of about 10 feet above the ground. The power was reduced slightly so that the model descended slowly until the landing gear was about 6 inches above the ground. At this point the power was cut off abruptly and the model dropped to the ground.

The hovering-flight tests were made at a height of about 15 to 20 feet above the ground in order to study the basic stability and control characteristics of the model when it was high enough to eliminate any possible effects of ground proximity. In these tests the ease with which the model could be flown in steady hovering flight and maneuvered from one position to another was studied.

The transition-flight tests were started with the model in hovering flight in the test section of the full-scale tunnel and, as the airspeed was increased, the controls were operated so that the model tilted progressively into the wind to maintain its fore-and-aft position in the test section. These flights corresponded to very slow constant-altitude transitions and covered a range of angle of attack from the hovering attitude of about 83° to an angle of attack of about 10°. Since small corrections or adjustments to the tunnel airspeed could not be made quickly, the pitch pilot and power operator had to make adjustments continually in order to hold the model in the center of the test section. Flights were also made in which the airspeed was held constant at intermediate speeds so that the stability and control characteristics at constant speeds could be studied. Constant speeds less than 25 miles per hour could not be maintained, however, because of speed control limitations in the drive system of the Langley full-scale tunnel.

Artificial stability devices which provided damping in roll, damping in yaw, effective dihedral, and directional stability were used one at a time in the tests. The control surfaces were moved approximately 3° per degree per second for the damping parameters and 3° per degree of sideslip for the directional stability and effective dihedral parameters. The exact amount of each of the stability parameters added artificially is not known because no force tests have been made to determine the control effectiveness.

RESULTS AND DISCUSSION

The results of the investigation are illustrated more graphically by motion pictures of the flights of the model than is possible in a written presentation. For this reason a motion-picture film supplement to this paper has been prepared and is available on loan from the National Advisory Committee for Aeronautics, Washington, D. C.

When the test results are interpreted, it should be borne in mind that the gyroscopic effects which a jet engine may have on the stability and control characteristics of a vertically rising airplane were not simulated because the two motors of the model powerplant turned in opposite directions and the gyroscopic forces were canceled.

Basic Model

Hovering flight.- The model could be flown smoothly and easily in hovering flight and could be maneuvered to any desired position at will. Figure 6 shows time histories of three typical flights in which the model takes off, maneuvers away from the take-off position, hovers a short time, maneuvers back to the take-off position, and lands. The jet-reaction controls provided good controllability and, as is evident in the time histories, the model could be moved fairly rapidly from one position to another and restored quickly to a steady-flight condition.

The motions of the model in pitch and yaw were very steady. Since the stability was not studied in detail, it is not known whether the model had unstable pitching and yawing oscillations such as had been experienced previously with propeller-driven models. It was clear, however, that the model did not tend to start an oscillation as quickly as the propeller-driven models and was consequently easier for the pilots to fly. The rolling motions, as would be expected, seemed about neutrally stable. The model seemed easier to fly in roll than the propeller-driven models previously tested because the random torque fluctuations which had been experienced with the unshrouded propellers of propeller-driven models were much less severe with the shrouded propellers of the present model.

Take-offs and landings.- Take-offs could be made very easily; in fact, they were easier to perform than for any of the propeller-driven vertically rising airplane models tested by the Langley free-flight tunnel section. The time histories of figure 6 show that the model took off vertically with very little control required. For all these take-offs, the controls were trimmed for hovering flight before the start of the tests.

The take-offs were smoother when the angle (pitch or yaw) at which the model rested on the ground was the same as the angle for hovering flight. Occasionally, because of improper inflation of the pneumatic shock struts, these angles were not identical and the model would slide sideways about one-half a span before leaving the ground. This sideways motion could not be stopped by use of the controls until the model left the ground. It was not particularly objectionable to the pilots but it did cause them to have to maneuver the model back to the desired flight path. The climb to the hovering altitude appeared rougher than for those take-offs in which the angle at which the model rested on the ground was the same as the angle for hovering flight.

The model could be landed fairly gently on a predetermined spot on the ground with little difficulty. No decrease in stability or controllability was noticed when the model neared the ground.

Forward flight.- The forward flights made in the test section of the Langley full-scale tunnel which represented slow, constant-altitude transitions covered a range of angle of attack from about 90° down to 10°. Some preliminary flights were made with both the jet-reaction controls and the flap-type controls operating for roll, pitch, and yaw. These tests showed that for the high-speed portion of the transition the use of both sets of control resulted in excessive control moments and consequently in overcontrolling. All later flights were therefore made with only the eyelids operating for yaw and pitch controls. Both the nozzles and elevons were used for roll control, however, because it was found that the nozzles alone did not provide sufficient rolling moment for control at the angles of attack at which the tendency toward the rolling and yawing divergence was encountered.

About half the forward flights made without automatic-stabilization devices were unsuccessful because the model diverged in roll and yaw at angles of attack between about 50° and 60° despite the efforts of the pilots to stop it. In all cases, the divergence started with the model rolling to the left about 20° or 30°, flying in a sideslipped attitude for a short time, and then diverging in yaw to the right. Figure 7 shows time histories of two transition flights which ended in such divergences. Since no accurate records of the rolling motions could be obtained from the motion pictures, these time histories are somewhat incomplete but they do illustrate the difficulty of controlling the motions since, at the time of the divergence, the control records indicate that the pilots were holding corrective control (right aileron and left rudder) as the model diverged. The roll records presented are only approximate. Their only purpose is to indicate the time at which the model started the rolling divergence. The divergence could not be studied in detail because of speed-control limitations in the Langley full-scale tunnel. The minimum steady airspeed available was 25 miles per hour which corresponded to an angle of attack of 33°; thus, when the airspeed reached the minimum steady-state value, the model had already passed through the critical angle-of-attack range.

The reasons for the divergence have not yet been definitely ascertained but some of the factors which probably contribute to the divergence are known. A rapid change in roll trim between hovering and low-speed forward flight existed which may have been caused by asymmetry in the model or by a change in propeller torque due to increased inflow velocity as the model went into forward flight. The divergence in roll was undoubtedly aggravated by this change in roll trim, which caused difficulty in controlling the model because the pilot could not trim the controls quickly enough. Another contributing factor to the divergence might have been the negative dihedral effect. If the model possessed negative effective dihedral at these high angles of attack, any sideslip introduced by control deflections or by rolling of the model about its body axis would have caused it to tend to diverge in roll. The divergence in yaw following the roll could have been caused by static directional instability.

Force tests of a similar model have indicated the likelihood of static directional instability at very high angles of attack.

In some cases it was possible to complete the transition if the model happened to be flying very steadily as it passed through the critical angle-of-attack range in which the strong divergent tendency was encountered and if this critical range was passed through rapidly. Figure 8 shows a time history of a transition flight in which there was no divergence. Although this yaw record indicates that the model did not fly very smoothly in yaw at the higher speeds, the yaw pilot felt that the model was easy to control in this speed range.

In the unstalled flight range, the lateral motions of the model were easy to control and in most cases the roll pilot could quit controlling the model and the yaw pilot alone could control the lateral motions. The model tended to wander but the yaw pilot could stop it at any time he desired. The lateral motions could not be controlled satisfactorily with the roll controls alone in the unstalled flight range because of the adverse aileron yawing moments.

The pitch and power controls were somewhat difficult to coordinate since variations in thrust also changed the pitching moment because the center of gravity was not on the thrust axis. Despite the coordination difficulty, however, the model could be flown smoothly in pitch at the higher speeds. At times the model seemed to have stability of angle of attack since, at constant tunnel airspeeds, it could be flown hands-off occasionally for a short period of time without any indication of a tendency to diverge.

Effect of Artificial Stabilizing Devices

Roll damper.- The roll damper which moved the elevons greatly improved the stability in both the critical angle-of-attack range (50° to 60°) and at high speeds so that all the transition flights attempted with this device installed were successful. Apparently the roll damper reduced the tendency of the model to sideslip by keeping it steady in roll about the body axis. During the high-speed portions of these flights, the roll pilot had to apply very little control; in fact, the record of figure 9 shows that the roll pilot did not have to apply any control after the model reached angles of attack below about 50°. The flights with the roll damper installed were much smoother than for any other condition covered in the investigation. The yaw record is similar to that made without any automatic stabilization but, in this case, the roll and yaw pilots found that, although a slight tendency to diverge was still evident, the model could be controlled fairly easily in the critical angle-of-attack range. The roll pilot was able to trim the model for level flight early in the flight and then could stop flying the model and let the yaw pilot alone control the lateral motions at high speeds. This procedure was followed in most of the flights because of the excessive roll control at high speeds.

Yaw damper.- When the yaw damper with a manual override was used to operate the yaw eyelid and the rudder was held fixed, the tendency toward a lateral divergence in the low-speed portion of the transition was reduced somewhat but was not eliminated. The model sometimes diverged at angles of attack of about 50° to 60° in spite of the pilot's efforts to control it. At high speeds the flights were much smoother than when no automatic stabilization was used. Apparently the stability of the Dutch-roll motion was increased by the yaw damper to such an extent that the motion was not excited so easily by the roll and yaw controls.

The use of the yaw damper operating the rudder (no override was used in this system) and manual control of the yaw eyelid did not cause any noticeable improvement in the divergent tendency during the low-speed portion of the transition, probably because of low rudder effectiveness in this high angle-of-attack range. The flights were smoother at high speeds, however, than when no automatic stabilization was used. This improvement at high speeds apparently resulted from the increase in damping of the Dutch-roll motion provided by the damper.

Artificial dihedral effect.- Additional effective dihedral was provided by a vane pick-up operating a proportional-control actuator which deflected the elevons differentially when the model sideslipped. No override was provided in this control system and the roll pilot had manual control only of the nozzles. With this system in operation, the lateral divergence in the transition range was not materially improved and the behavior at high speeds was made much worse than when no automatic stabilization was used. The flights were characterized by rolling oscillations between about $\pm 20^\circ$ angle of bank. At high speeds these oscillations became violent and were very difficult to control. Usually the oscillations at high speeds caused loss of control and the model had to be retrieved with the safety cable.

Artificial directional stability.- Additional directional stability was provided by the vane pick-up operating a proportional control actuator connected to the rudder. No override was provided with this system and the yaw pilot had manual control only of the yaw eyelid. The lateral divergent tendency at low speeds was not materially improved, probably because the vertical tail and rudder were blanketed by the wing so that the rudder was relatively ineffective. This system reduced the yawing motions at high speeds but it caused the rolling oscillation to become very pronounced at high speeds as was the case when artificial dihedral effect was used.

SUMMARY OF RESULTS

The results of a free-flight investigation of the stability and control characteristics of a delta-wing vertically rising airplane model powered by a ducted fan can be summarized as follows:

1. In hovering flight the model could be flown smoothly and easily without any automatic stabilization devices. The jet-reaction controls were powerful and enabled the pilots to maneuver the model to various positions within the hovering test area and to restore it to a steady-flight condition rapidly.

2. Take-offs could be made easily and landings on a predetermined spot could be made accurately.

3. The eyelid controls provided good pitch and yaw control throughout the entire speed range covered in the investigation. In order to maintain roll control in the transition range, however, the jet-reaction roll control had to be supplemented by the flap-type elevons.

4. Transition flights without automatic stabilization were difficult to accomplish because of a lateral divergence which occurred between angles of attack of about 50° to 60°. Only about half the forward flights without automatic stabilization were successful.

5. The use of a roll damper eliminated the lateral divergent tendency during the low-speed portion of the transition and also made the high-speed portion of the flights much smoother than in any other test condition. The use of artificial damping in yaw, directional stability, or dihedral effect, however, did not provide sufficient improvement in the critical angle-of-attack range to eliminate the occurrence of divergences during transition flights.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., February 2, 1955.

TABLE I.- GEOMETRIC CHARACTERISTICS OF MODEL

Weight, lb	
Hovering, take-offs, and landings	46.50
Forward flight	45.20
Wing (modified triangular plan form):	
Sweepback, deg	60
Airfoil section	NACA 65A006
Aspect ratio	1.65
Taper ratio (root to tip)	1.79
Area, sq in.	1765.00
Span, in.	54.00
Mean aerodynamic chord, in.	38.00
Span of elevon, in.	18.00
Chord of elevon, in.	5.25
Span of roll-control nozzles, in.	6.00
Chord of roll-control nozzles, in.	2.13
Overall length of model, in.	77.00
Vertical tail (modified triangular plan form):	
Sweepback, deg	50
Airfoil section	NACA 65A006
Aspect ratio	1.56
Taper ratio (root to tip)	2.94
Area, sq in.	574.3
Span, in.	22.50
Span of rudder, in.	19.50
Chord of rudder, in.	4.75
Fuselage:	
Duct length, in.	48.00
Inside diameter, in.	14.50
Outside diameter, in.	15.00

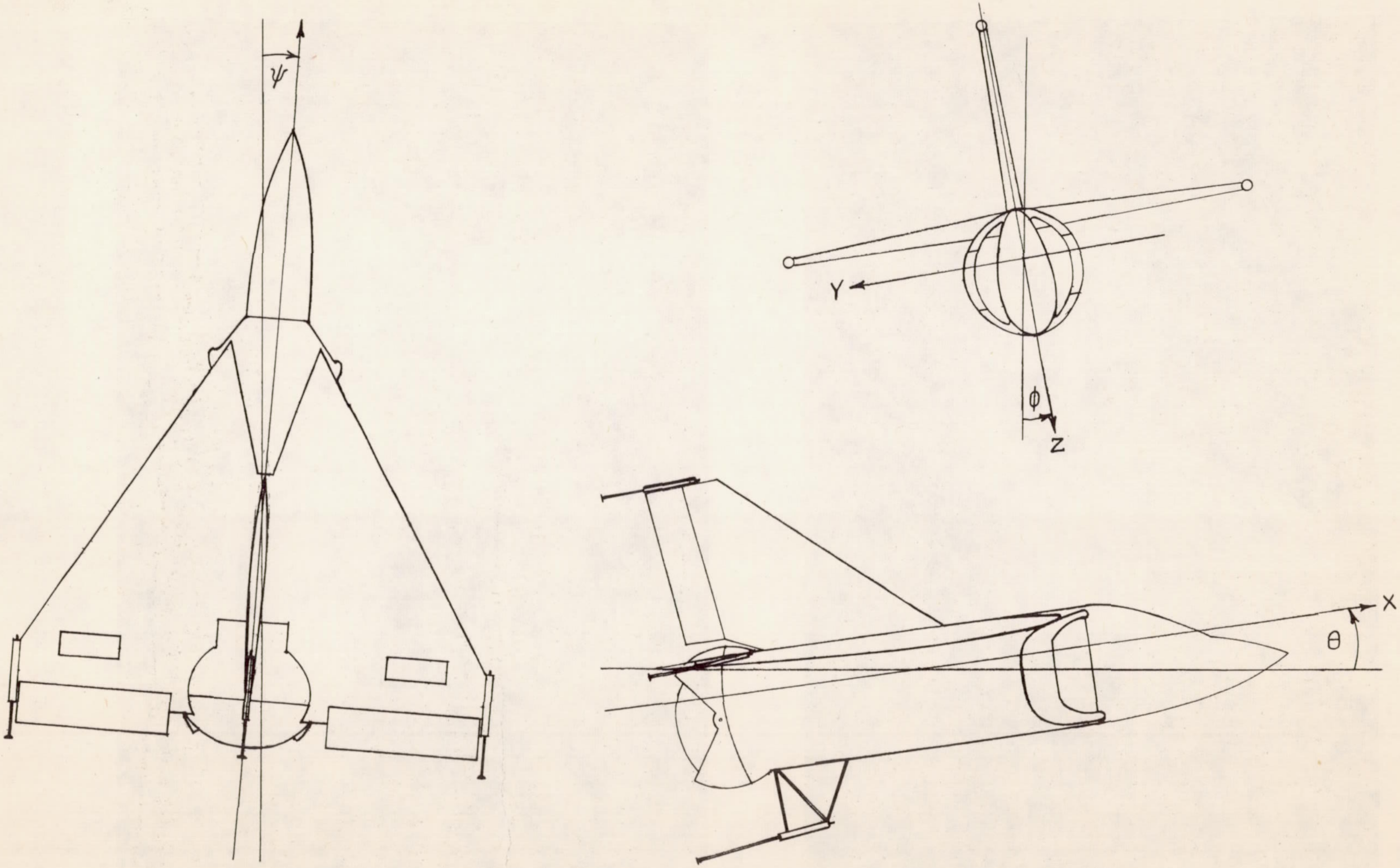
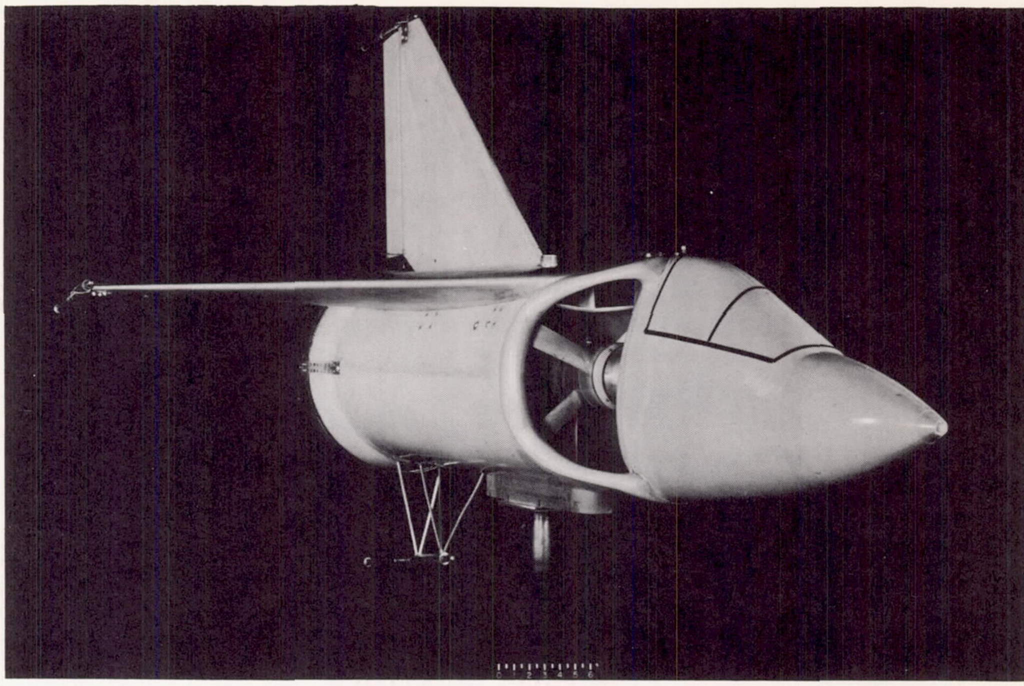


Figure 1.- The body system of axes. Arrows indicate positive directions of linear and angular displacements.



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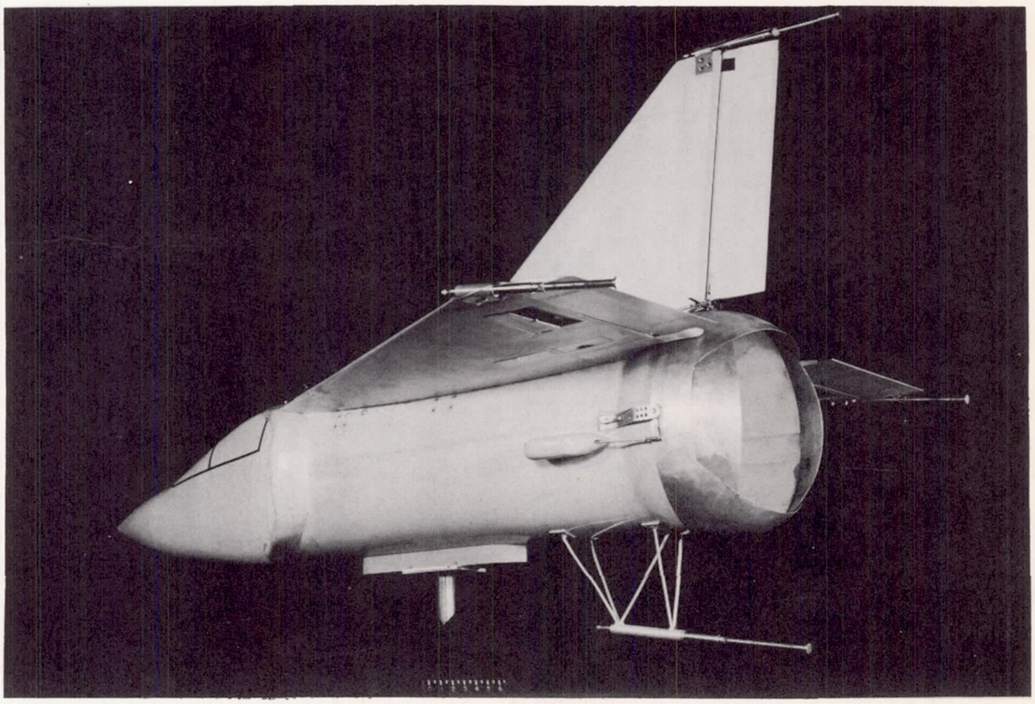

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Figure 2.- Photographs of delta-wing, ducted-fan powered model.

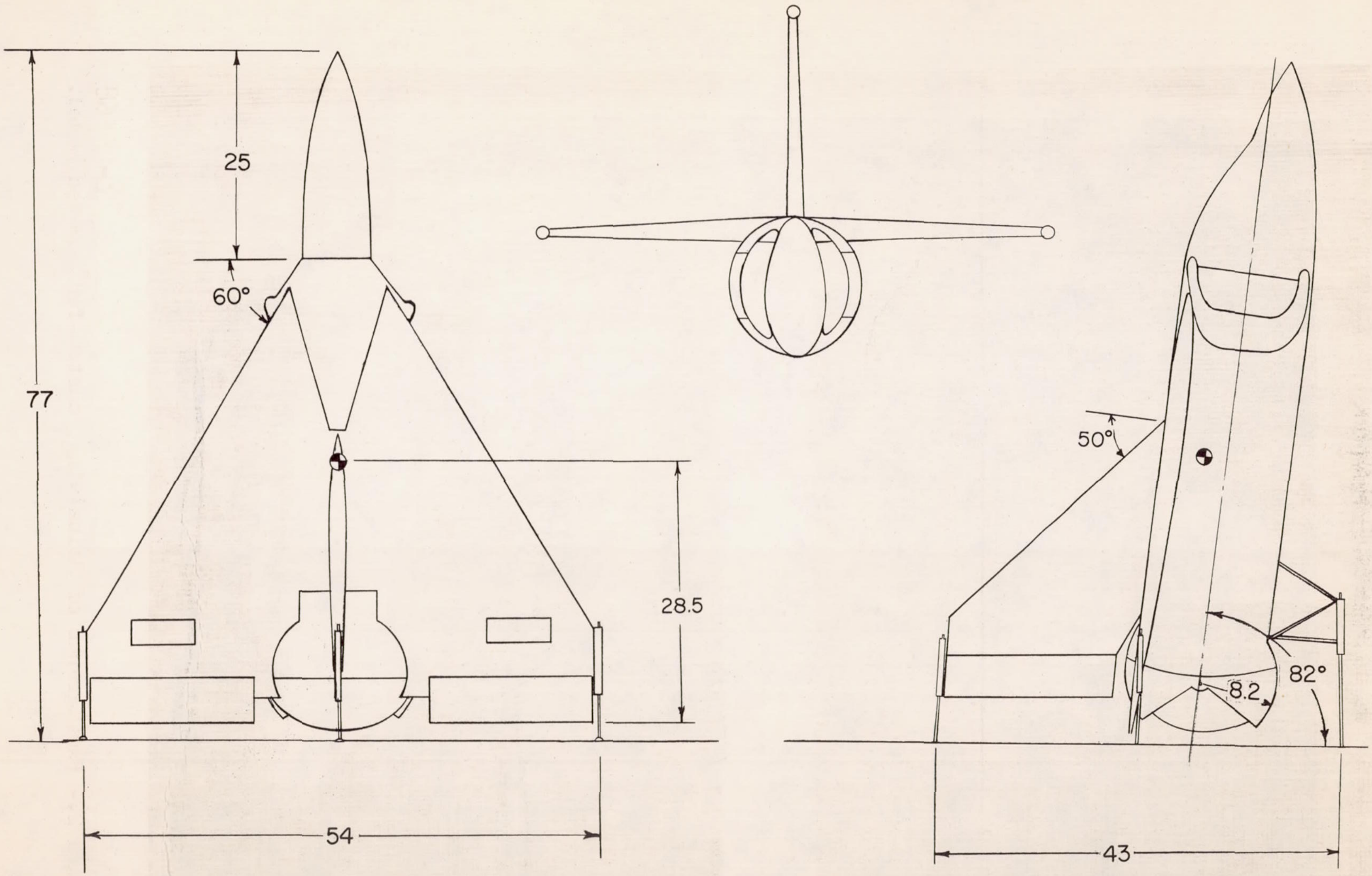

Figure 3.- Sketch showing the more important dimensions. All dimensions are in inches.

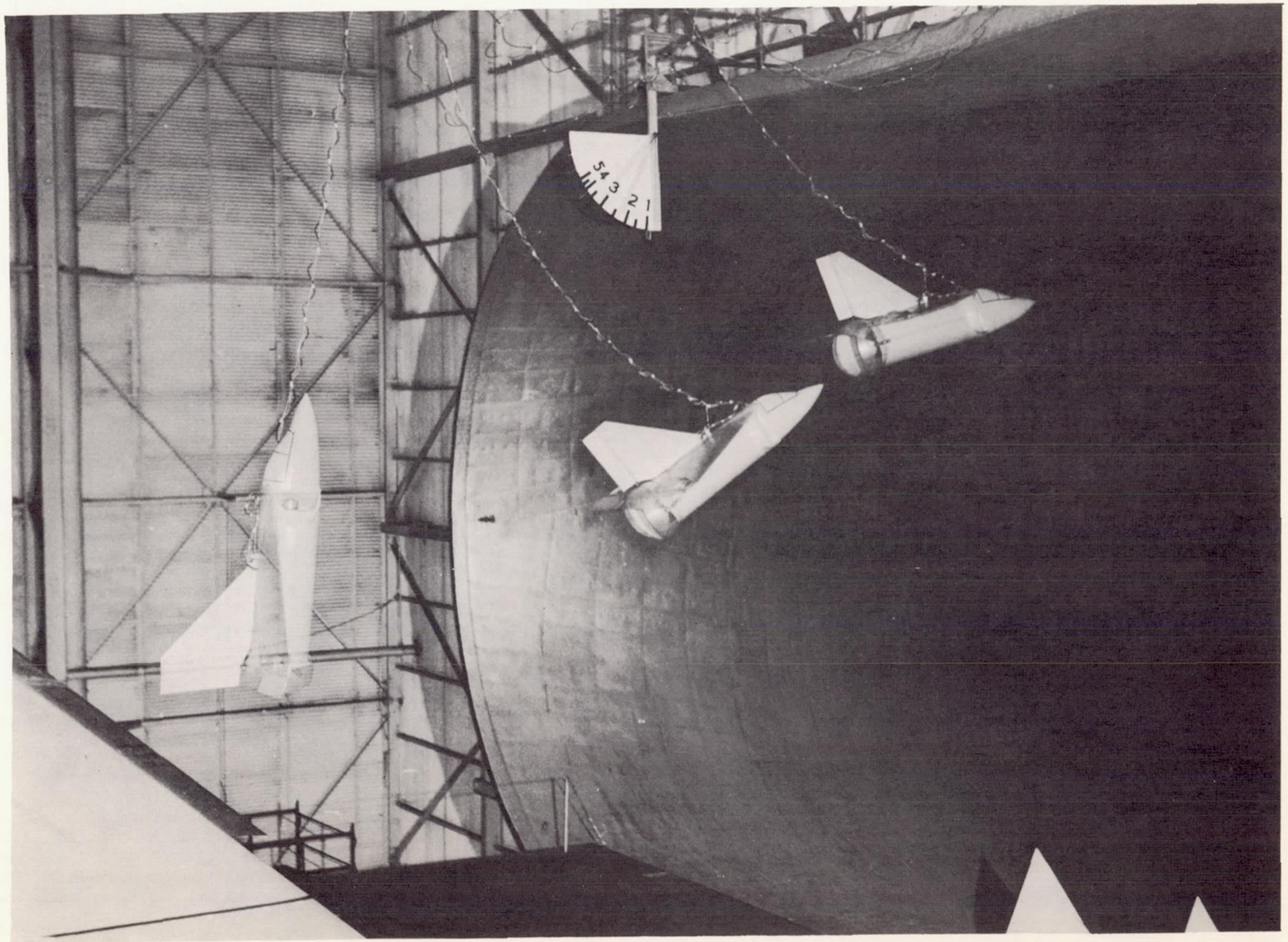

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Figure 4.- Multiple-exposure photograph of model in various stages of forward flight.

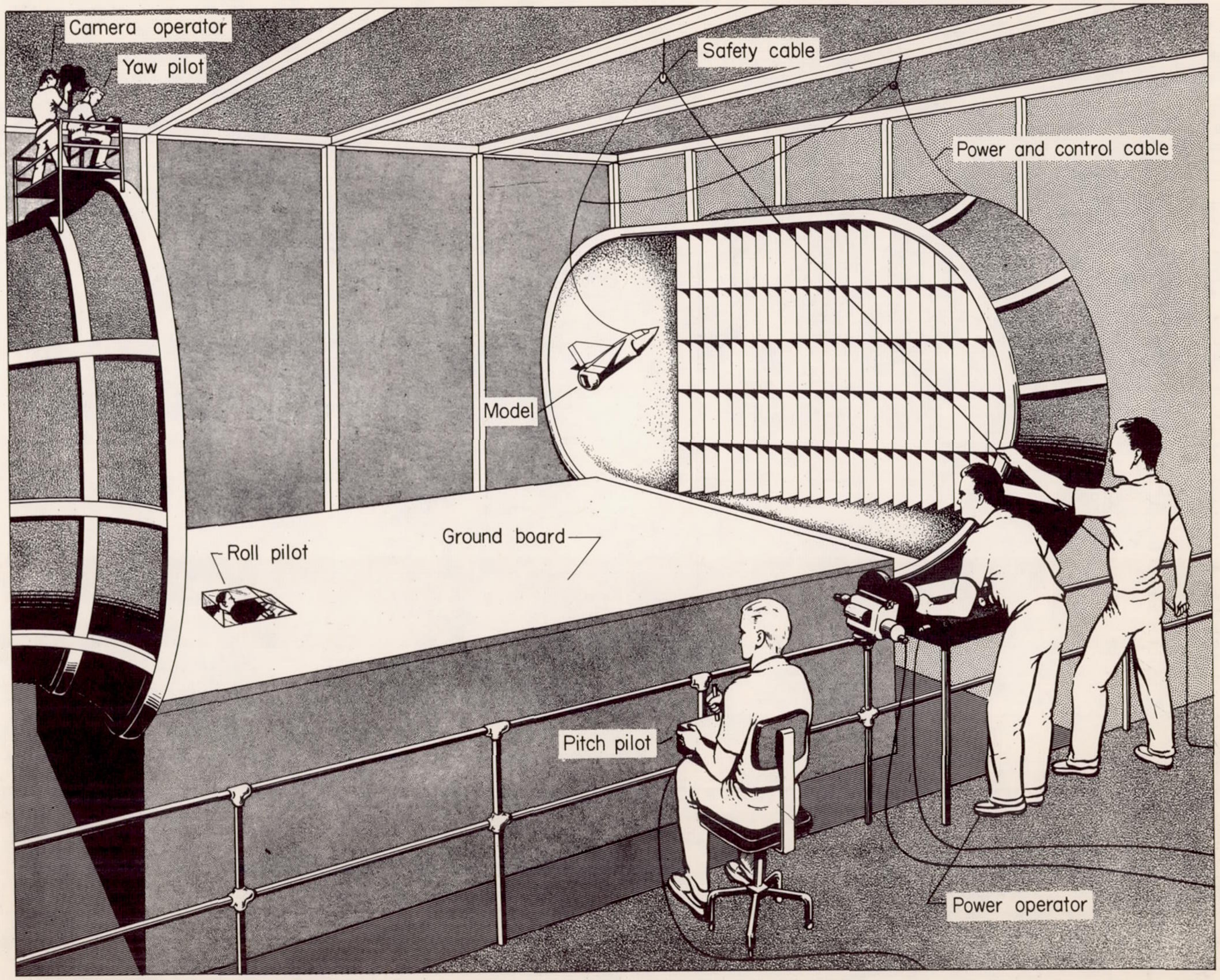

Figure 5.- Sketch of test setup for forward flight.

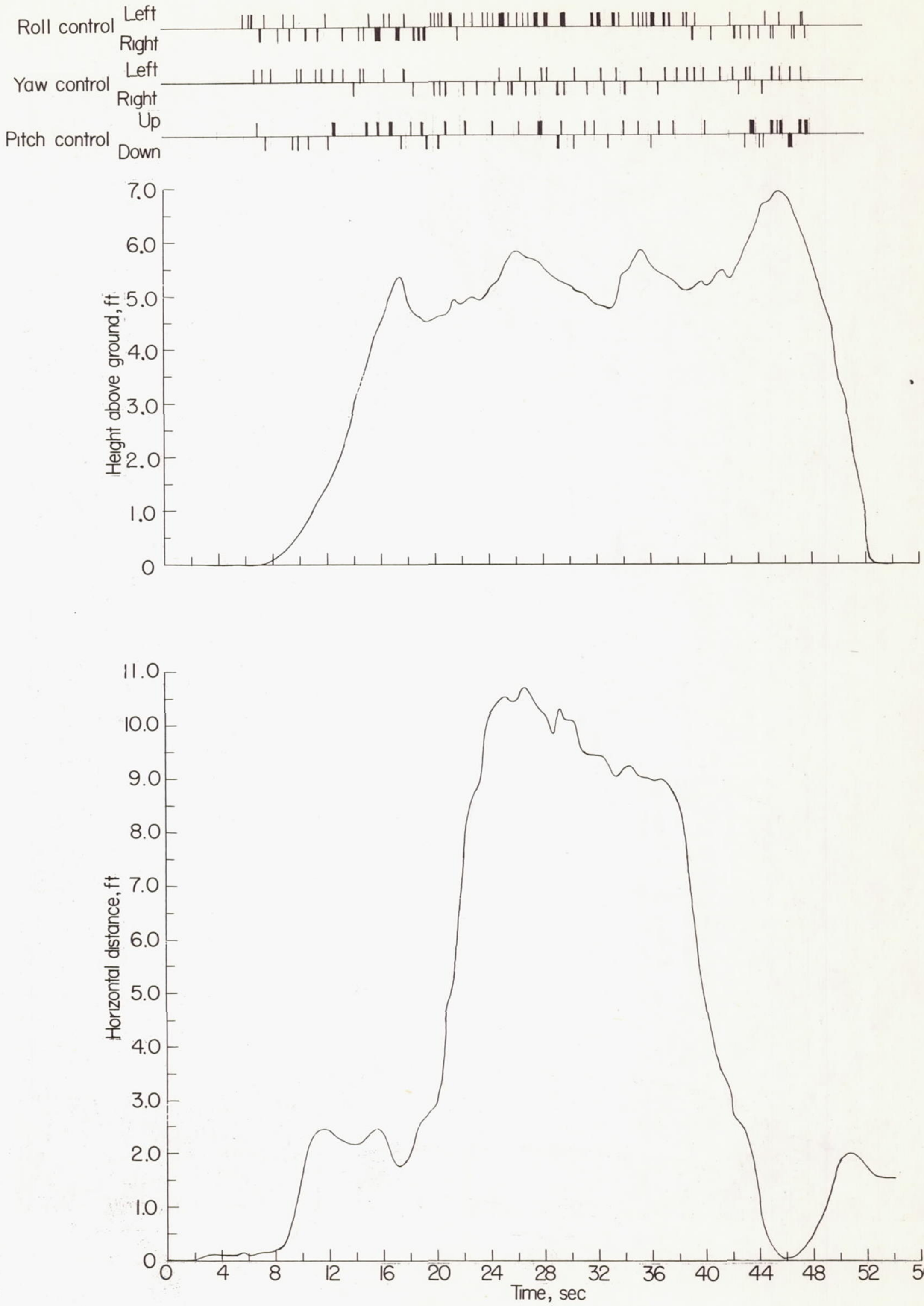

Figure 6.- Time histories of take-offs, hovering flights, and landings in still air.

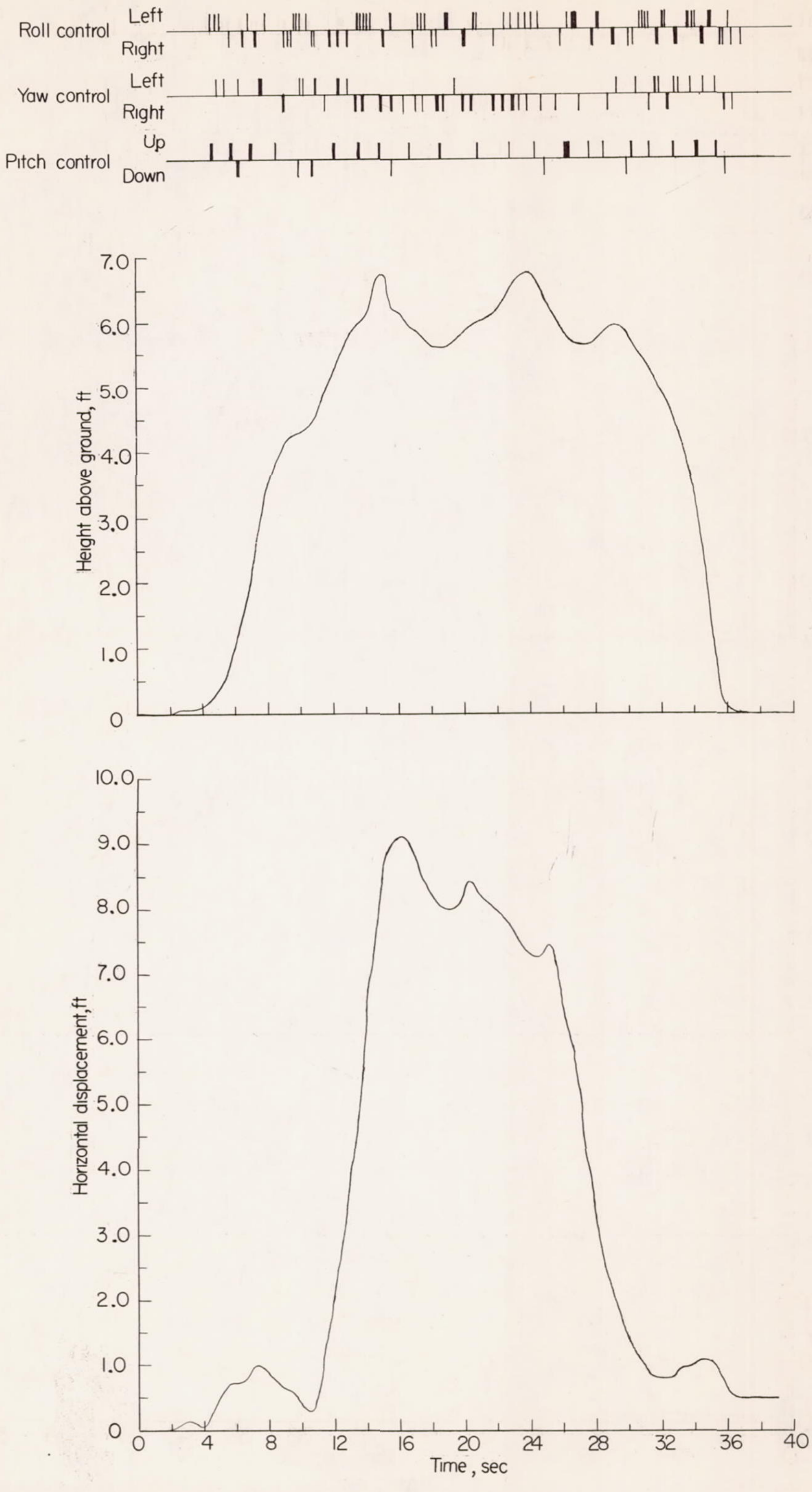

Figure 6.- Continued.

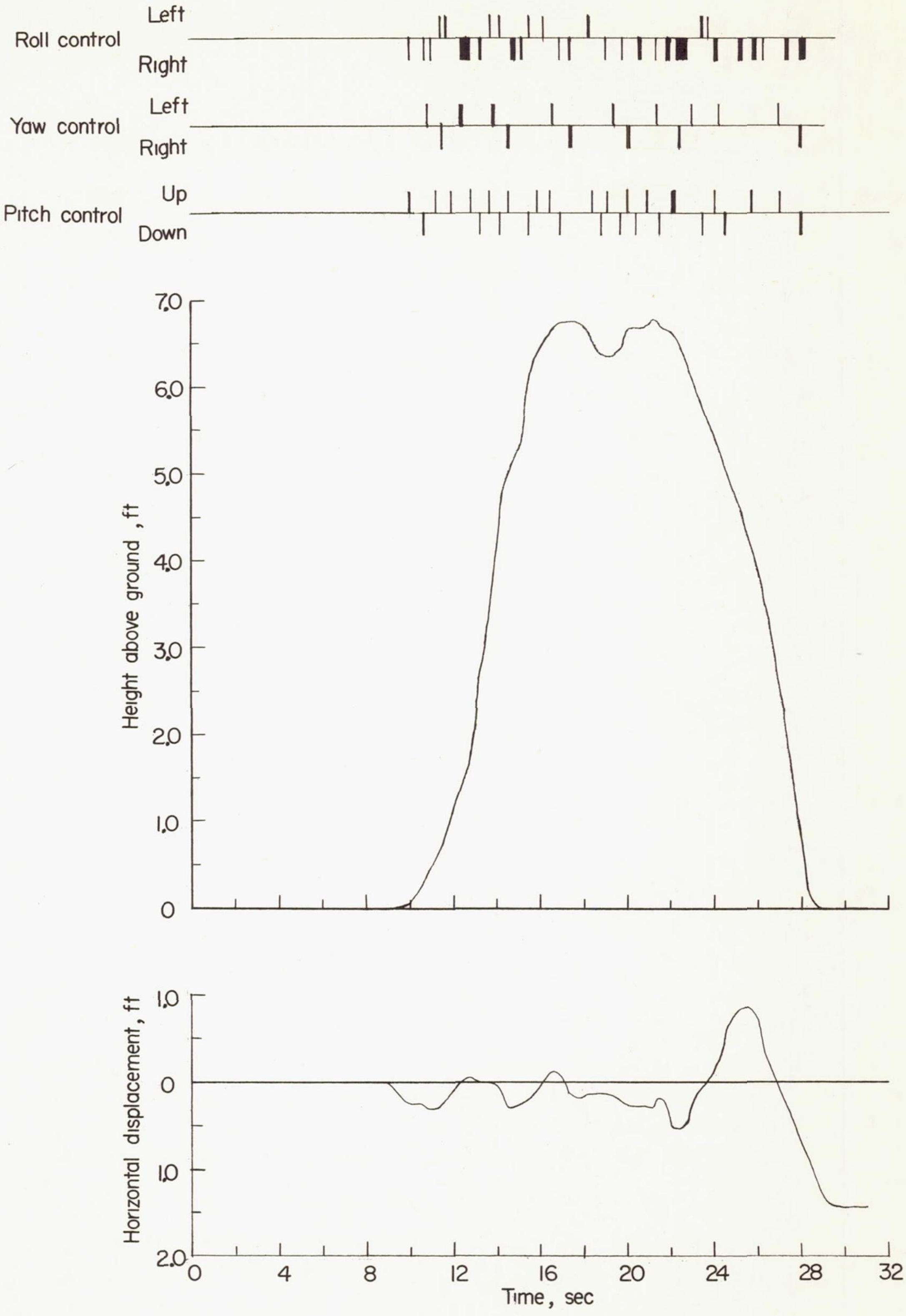

Figure 6.- Concluded.

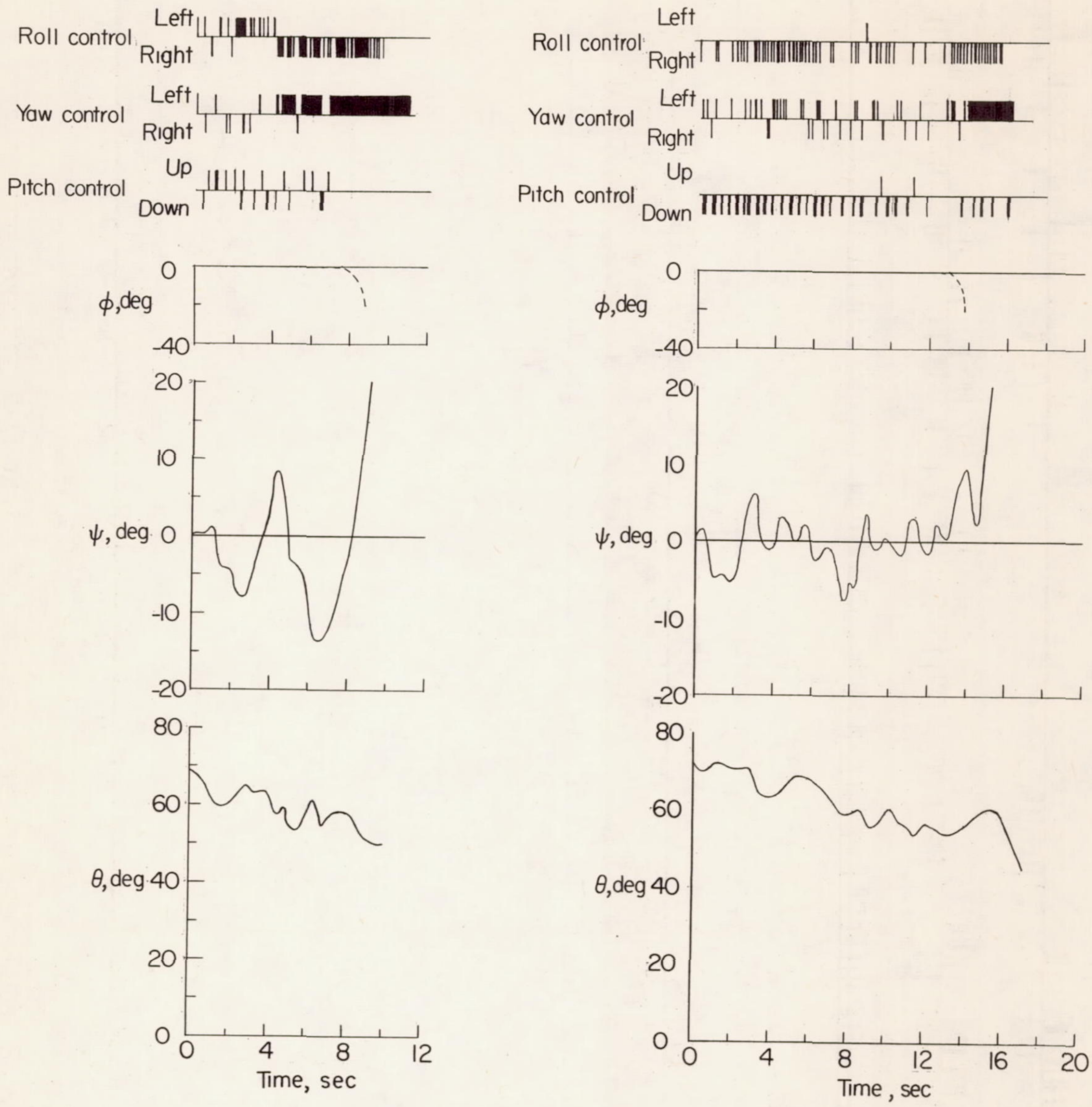

Figure 7.- Time histories of transition flights made without automatic stabilization that ended in lateral divergences. The roll records are only approximate and merely indicate when the rolling divergence started.

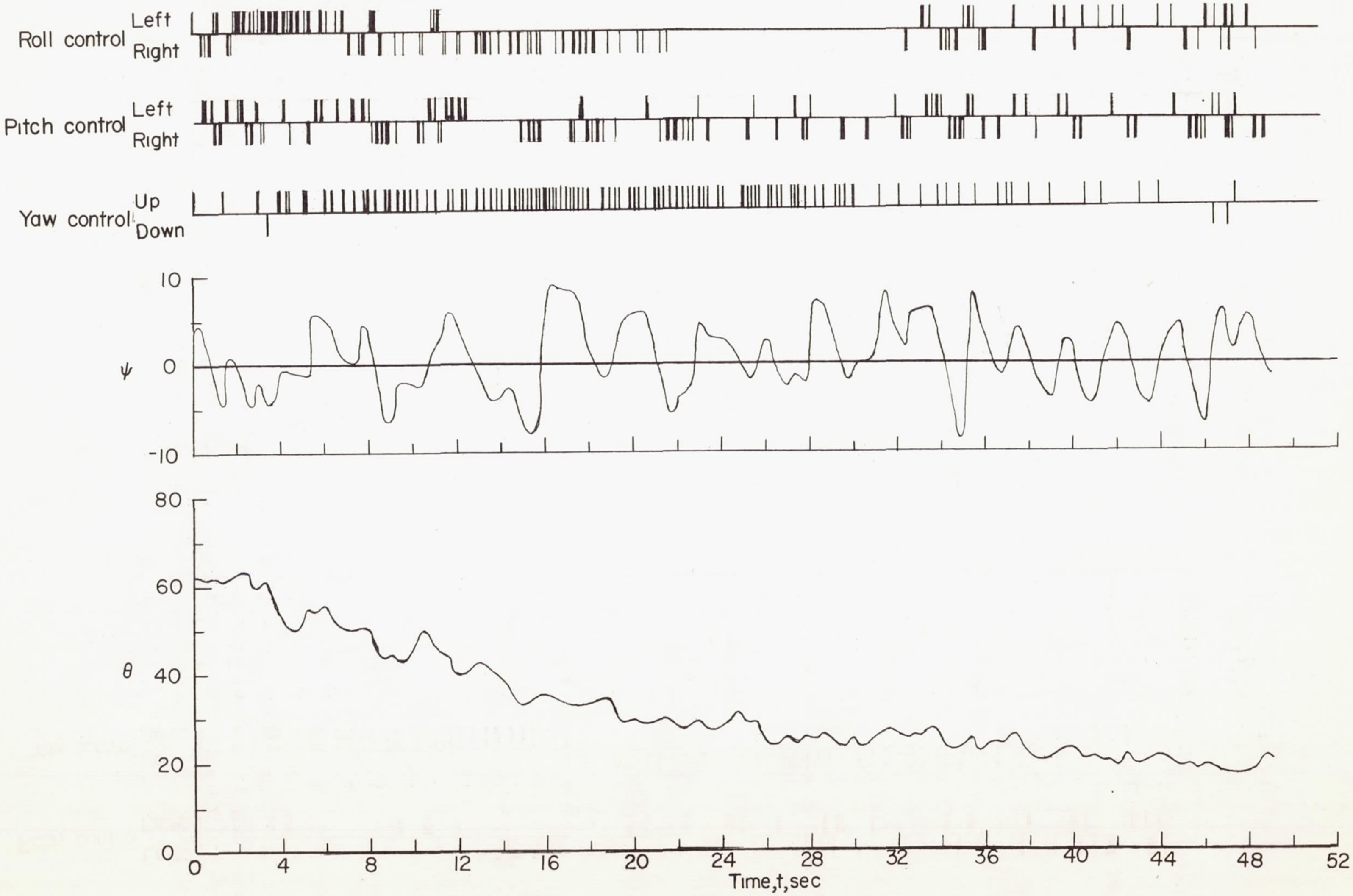

Figure 8.- Time history of a transition flight made without automatic stabilization and in which there was no lateral divergence.

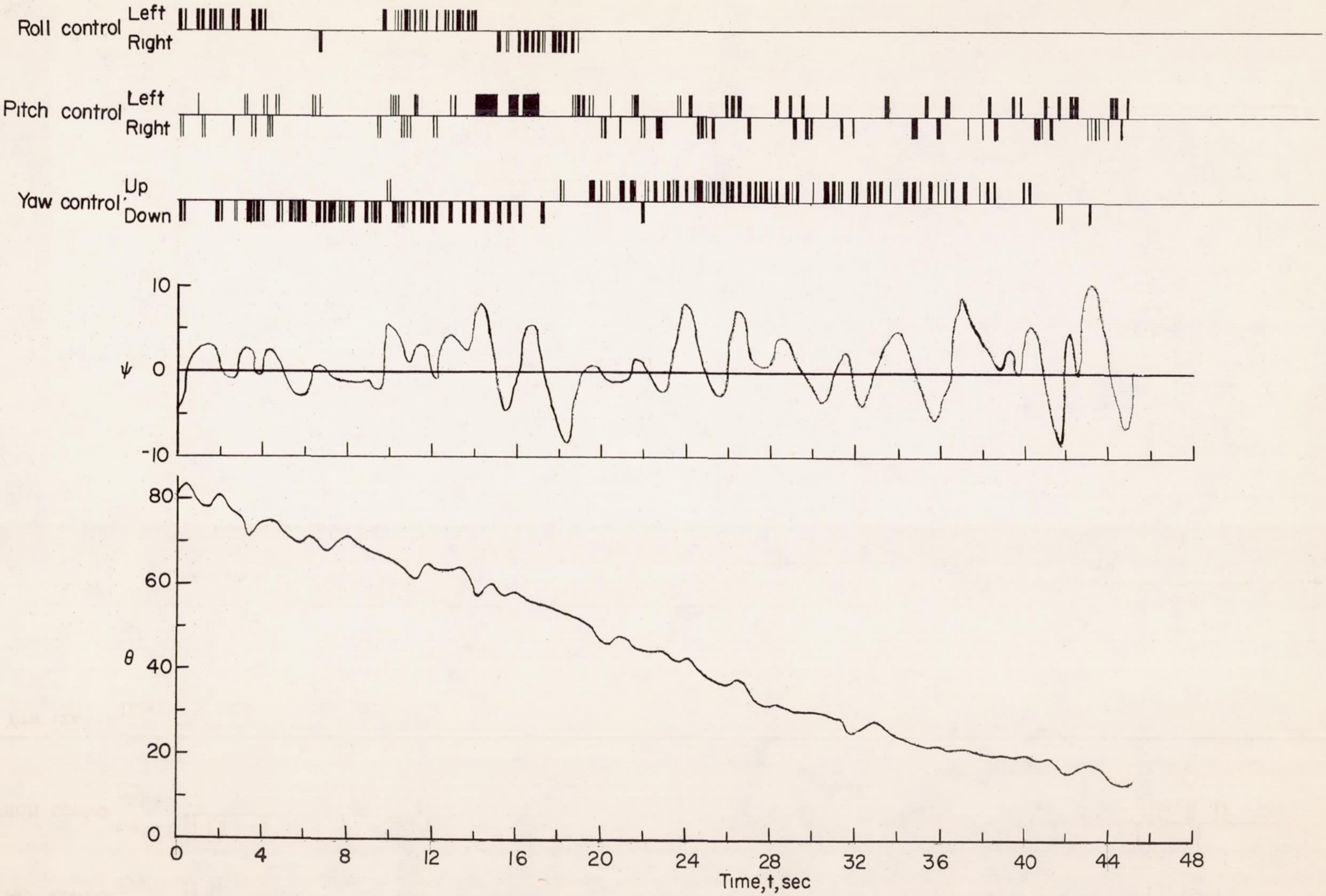

Figure 9.- Time history of a transition flight made with a roll damper installed.

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