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RESEARCH MEMORANDUM

DYNAMIC STABILITY AND CONTROL CHARACTERISTICS OF A DUCTED-FAN MODEL IN HOVERING FLIGHT

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SUMMARY

This paper presents the results of an experimental investigation of the dynamic stability and control of a simple ducted-fan model in hovering flight and is intended to provide some basic information on the stability and control of jet vertically rising airplanes in hovering flight. The model consisted of an 18-inch-diameter dual-rotating propeller in a shroud 4 feet long. Control was provided by all-movable surfaces at the rear of the shroud. The investigation consisted mainly of flight tests with the model hovering at altitude and near the ground.

The model could be flown smoothly and easily in controlled flight without artificial stabilization, although the uncontrolled pitching and yawing motions were unstable oscillations. The period of these oscillations was fairly long and the control surfaces were powerful; thus, the pilot could stop the oscillations quickly, even after they had been allowed to build up to a large amplitude. There was no noticeable reduction in the controllability of the model as it neared the ground.

INTRODUCTION

The interest of the armed services in jet vertically rising airplanes is increasing as turbojet engines with very high thrust ratings (around 20,000 pounds) approach successful development. With such engines the construction of tactical vertically rising fighters appears feasible from thrust and weight considerations. The need is therefore becoming urgent for stability and control research on such airplanes in the unusual phases of flight (vertical take-off and landing, hovering, and transition from hovering to normal unstalled flight). Some related work that might be of general interest is discussed in references 1 to 5 which present the results of flight tests on some propeller-driven vertically rising airplane configurations.

In order to provide some basic information on the stability and control of jet vertically rising airplanes in hovering flight, an experimental investigation has been conducted to study the dynamic stability and control characteristics of a simple ducted-fan model in hovering flight. This work was undertaken as a preliminary step toward studies of the stability and control of jet vertically rising airplanes because the model could be assembled quickly from existing components. It consisted of an 18-inch-diameter dual-rotating propeller in a shroud 4 feet long. Control was provided by all-movable surfaces at the rear of the shroud.

The investigation consisted mainly of flight tests with the model hovering at altitude and near the ground. The results were obtained primarily from the pilots' observations of the stability and controllability and general flight behavior of the model. Some time histories of the motions of the model were obtained from motion-picture records of the flights and some information on the effectiveness of the controls was obtained from force tests.

NOMENCLATURE AND SYMBOLS

The controls and motions are referred to in conventional terms relative to the body system of axes; that is, the rudder at the rear of the shroud produces yaw about the normal (Z) axis, differential deflection of the elevons at the rear of the shroud produces roll about the longitudinal (X) axis, simultaneous up or down deflection of the elevons produces pitch about the spanwise (Y) axis. Figure 1 shows the system of axes and the positive directions of displacements.

The definitions of the symbols used in this paper are as follows:

x	displacement along X-axis, ft
z	displacement along Z-axis, ft
y	displacement along Y-axis, ft
θ	angle of pitch, deg
ϕ	angle of bank, deg
ψ	angle of yaw, deg

MODEL

A photograph of the model is shown in figure 2 and a sketch showing some of the more important dimensions is presented in figure 3. The model had an 18-inch-diameter dual-rotating propeller in a shroud 4 feet long. The five-bladed propeller had three blades in the front element and two blades in the rear element and was powered by a 5-horsepower variable-frequency electric motor, the speed of which was changed to vary the thrust. The shroud was a thin-skin glass-fiber tube with external stiffener rings and a rounded lip which increased the static thrust about 60 percent over that of the shroud with a sharp lip.

The model was controlled by all-movable control surfaces at the rear of the shroud. These control surfaces were remotely operated by the pilots by means of flicker-type (full on, full off) pneumatic servos which were controlled by electric solenoids. The control travel from the trim position provided by the control actuators was approximately:

Total differential deflection of elevons, deg	30 right, 30 left
Simultaneous deflection of elevons, deg	6 up, 6 down
Rudder deflection, deg	8 right, 8 left

The center of gravity was 9.3 inches behind the leading edge of the shroud and on the thrust line. The approximate weight and moments of inertia of the model were:

Weight, lb	31
I_X, slug-ft^2	0.3
I_Y, slug-ft^2	1.5
I_Z, slug-ft^2	1.5

TEST EQUIPMENT AND TECHNIQUE

The flight tests were conducted in the large building used by the Langley free-flight tunnel section for flight testing hovering models where they are protected from the random effects of outside air turbulence. The test setup used in the flight tests is illustrated in figure 4. The power for the motor and electric solenoids and the air for the control actuators were supplied through wires and plastic tubes which were suspended from above for most of the tests and taped to a safety cable from a point about 15 feet above the model down to the model itself. For a few tests, the wires and tubes trailed from the rear of the model and only the safety cable came in from above. The safety cable, which was attached to the nose of the model, was used to prevent crashes in case of control failure. During flight the cable was kept slack so that it would have as little influence as possible on the motions of the model.

Separate pilots operated the pitch, roll, and yaw controls in order that they might give careful attention to studying the motions of the model about each of the axes. No automatic stabilization was used in any of the flights. Two operators in addition to the pilots were used in flying the model: one to control the power to the propellers and one to operate the safety cable to maintain a reasonable amount of slack. The pilots and power operator were the principal observers because they had control of the model and could obtain qualitative indications of the stability, controllability, and general flight behavior.

The test technique is explained by describing a typical hovering flight. The model hangs on a safety cable and the power is increased until the model climbs to the desired altitude. The safety cable becomes slack and the rope operator then recovers any excess slack or releases more cable as required during the flight. During the flight the power is regulated to keep the model at the desired altitude. The pilots keep the model as near the center of the test area as possible during the climb and until the model is in a steady hovering condition. They then perform the maneuvers required for the particular tests and observe the stability and control characteristics.

In order to determine the stability of the model the pilots allow it to fly uncontrolled for as long as possible starting from as near a steady hovering flight condition as can be obtained. Motion-picture records of these uncontrolled motions are made.

TESTS

The investigation consisted mainly of flight tests of the model, although a few force tests were made to provide some indication of the control effectiveness required for hovering flight. Stability, controllability, and general flight behavior were determined in various cases, either qualitatively from the pilots' observations or quantitatively from motion-picture records of the flights. General flight behavior is a term used to describe the overall flight characteristics of a model and indicates the ease with which the model can be flown. In effect, the general flight behavior is much the same as the pilots' opinion of the flying qualities of an airplane and indicates whether stability and controllability are adequate and properly proportioned.

Hovering flight at altitude.- Hovering flight tests were made in still air at a considerable height above the ground to determine the basic stability and control characteristics of the model. For all these flights it was possible to obtain the pilots' opinion of the stability, controllability, and general flight behavior of the model. In some of the flights, quantitative indications of the stability were obtained by taking motion-picture records of the uncontrolled pitching and yawing oscillations. In some other flights, quantitative data on the controllability of the model were obtained by making motion-picture records to show the ability of the pilot to stop the pitching and yawing oscillations after they had been allowed to build up. Hovering flight tests at altitude were made with both the overhead- and trailing-cable techniques to determine whether the cable arrangement had any significant effect on the uncontrolled motions of the model.

Hovering flight near the ground.- Hovering flight tests were also made near the ground to determine the effect of the proximity of the ground on the flight behavior of the model. During these flights, the model was flown with the trailing edges of the control surfaces about 6 to 12 inches above the ground. This height was maintained to the best of the power operator's ability. Actually, the model dropped so low at times that it touched the ground and it rose so high at times that the controls were considerably more than 12 inches above the ground.

RESULTS AND DISCUSSION

The results of the present 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 NACA Headquarters, Washington, D. C.

It was the pilots' opinion that the model was very easy to fly. In fact, it was easier to fly than any of the propeller-driven vertically rising models that have been previously tested in hovering flight by the free-flight section (refs. 1 to 5). Since the model is symmetrical about the longitudinal axis, everything that is said about pitch in the following discussion is also true of yaw.

Time histories of the uncontrolled pitching motions of the model obtained with the overhead- and trailing-cable techniques are presented in figures 5 and 6, respectively. These time histories are not symmetrical about the horizontal axis in all cases, because the model could not be trimmed perfectly. The oscillation is superimposed on the aperiodic motion caused by the out-of-trim moments. The time histories of figures 5 and 6 indicate that the model had an unstable pitching oscillation for both cable configurations and that there was no appreciable difference in the motions of the model for the two different cable arrangements.

The model responded quickly to a control deflection and could be flown smoothly in spite of its lack of stability. It could be maneuvered quickly and easily to various positions in the test area as desired and could be stopped with very little overshoot and no evidence of a tendency to overcontrol. As a further demonstration of the controllability of the model, the pilot at times allowed the pitching oscillations to build up and then applied the controls to stop the oscillation. Data of figure 7, which presents several time histories of these tests, indicate that the pilot could stop the oscillations and return the model to a near vertical attitude in less than one-half cycle. The fact that the model did not return to zero displacement is not significant since the pilot was not making an effort to stop the model over a particular spot or to return it to zero displacement. In stopping these oscillations, the pilot had no tendency to overcontrol and reinforce the oscillation. The ease with which the pilot could stop the oscillations can probably be attributed largely to the fact that the periods of the oscillations were fairly long as well as to the fact that the controls were powerful. Unlike the longitudinal control, the roll control was weak but the pilot was able to maintain control of the model. The random torque fluctuations experienced with previous propeller-driven models were not as pronounced with this model, evidently, because the duct tended to straighten out the inflow to the propellers.

The force tests to determine the control effectiveness showed that the control moments for the deflections used during the flight tests were as follows:

Pitching moments, ($\delta_e = 6^\circ$) ft-lb	3.2
Yawing moments, ($\delta_r = 8^\circ$) ft-lb	4.7
Rolling moment, ($\delta_a = 30^\circ$) ft-lb	0.95

The yaw control, which provided more moment than the pitch control, was the more satisfactory control particularly for rapid maneuvers or for stopping a developed oscillation.

There was no noticeable reduction in the controllability of the model as it neared the ground. It was fairly easy to maneuver the model and to keep it hovering within a foot of the ground over a spot for a considerable length of time. Previous tests of propeller-driven vertically rising airplane models indicated that a reduction in the slipstream velocity over the rear part of the models as they neared the ground caused a reduction in static control effectiveness and in the damping in pitch and yaw. This effect was not experienced with the present model since the slipstream was contained in the shroud and could not spread to reduce the dynamic pressure at the rear of the model.

The model had neutral vertical-position stability but had positive rate-of-climb stability because of the pronounced inverse variation of the thrust of propellers with axial speed. This rate-of-climb stability tended to offset the effect of the time lag in the thrust control so that the model could be maintained at a given height fairly easily.

APPLICATION OF RESULTS

It was originally felt that this model would provide an approximate simulation of the flight characteristics of a jet vertically rising airplane in hovering flight. It was reasoned that both the model and the airplane in hovering flight would be essentially flying thrust vectors - that is, they would have no static stability and no appreciable damping in pitch or yaw. The results of this investigation have shown, however, that the assumptions regarding the model were incorrect. An investigation is therefore being made to determine the static stability derivatives and the damping-in-pitch and damping-in-yaw derivatives in hovering flight. The preliminary results of this investigation have shown the existence of important aerodynamic stability factors other than those normally associated with the exterior of a body. In particular, these tests showed that there is a static restoring moment produced by the forces in the inlet when the model moves sideways. These preliminary results have also indicated the model has stable values of the damping-in-pitch and damping-in-yaw derivatives in hovering flight produced by the transverse acceleration of the air flow within the shroud during a pitching or yawing motion.

The static stability and the damping derivatives of a particular jet vertically rising airplane will be somewhat different from those of the model because, (a) this ducted-fan model had a much greater inflow velocity in proportion to the exit velocity than an airplane with a hot jet would have; (b) the model had no wing or tail surfaces; and (c) the distances from the center of gravity to the inlet and exit for this model are likely to be quite different from those of any particular airplane design. It would seem from these factors that a jet vertically rising airplane will probably have considerably less static restoring moment than the model and that its damping derivatives will be of the same order of magnitude. It is probable, therefore, that the motions of an actual airplane will be less oscillatory than those of the present model and the stability of the oscillation will be about the same as that of the model. Since the model was very easy to fly despite the unstable oscillation, it is believed that an airplane will also be easy to fly in hovering flight.

SUMMARY OF RESULTS

The following results were obtained from hovering flight tests of a ducted-fan model in still air:

1. The model could be flown smoothly and easily in controlled flight without artificial stabilization, although the uncontrolled pitching and yawing motions were unstable oscillations.

2. The period of the oscillations was fairly long and the control surfaces were powerful; thus, the pilot could stop the oscillations quickly, even after they had been allowed to build up to a large amplitude.

3. There was no noticeable reduction in the controllability of the model as it neared the ground.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., February 23, 1954.

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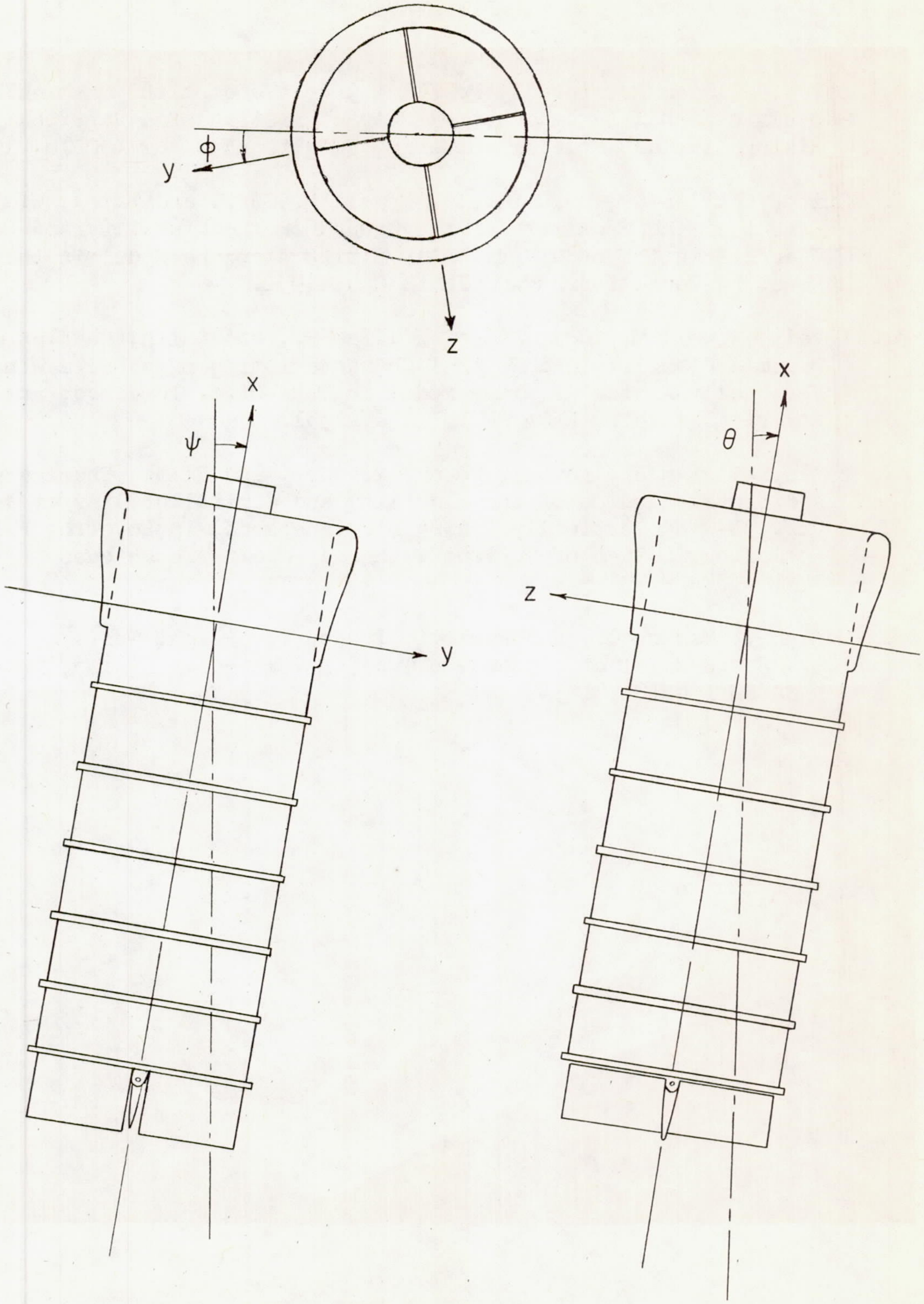
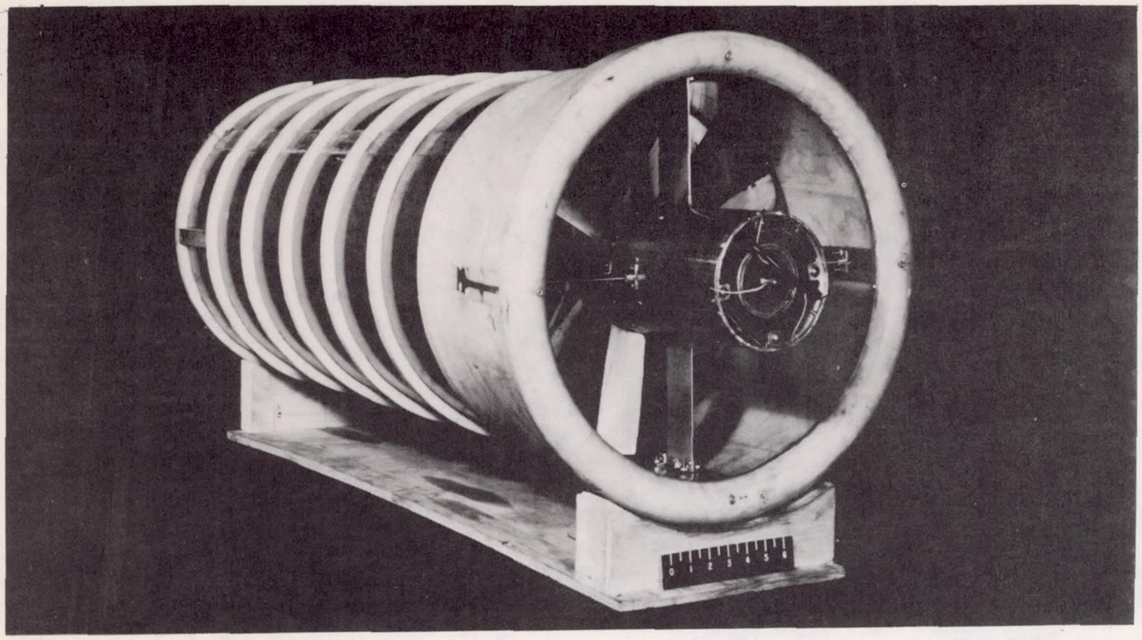
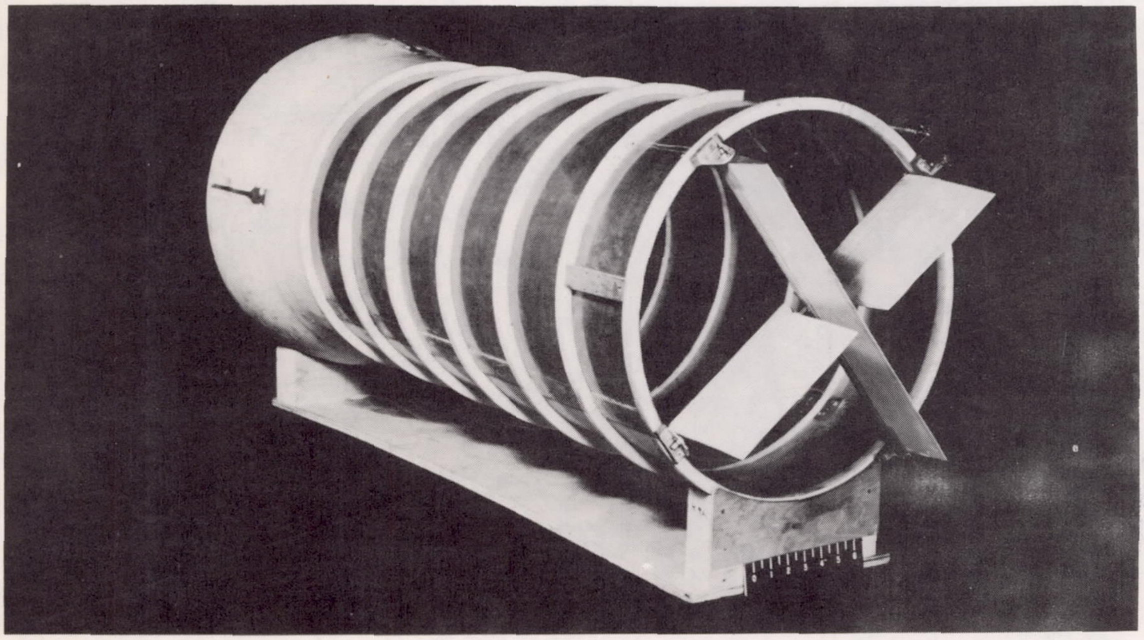


Figure 1.- The body system of axes. Arrows indicate positive directions of displacements.



(a) Three-quarter front view.



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(b) Three-quarter rear view.

Figure 2.- Photographs of ducted-fan model.

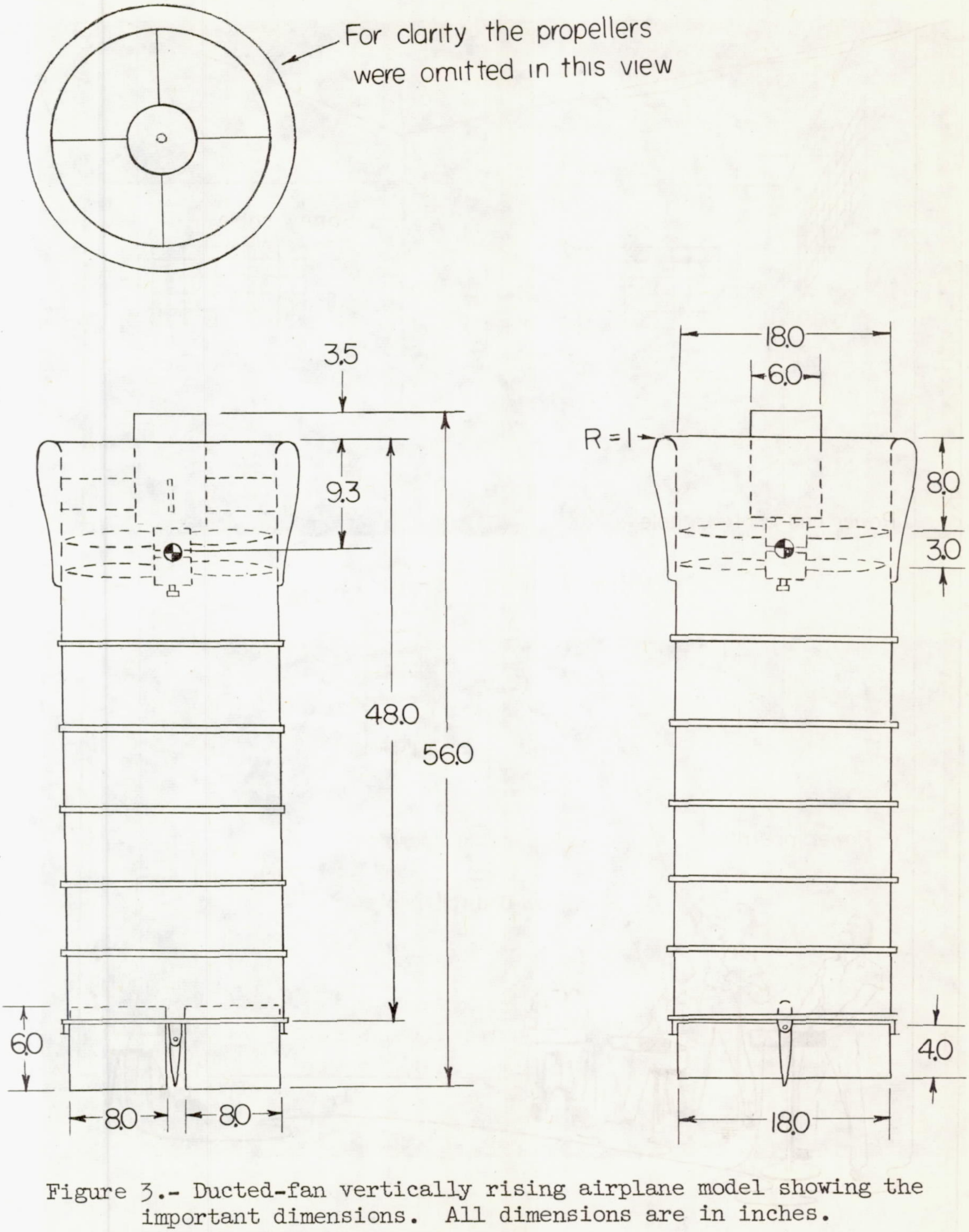

Figure 3.- Ducted-fan vertically rising airplane model showing the important dimensions. All dimensions are in inches.

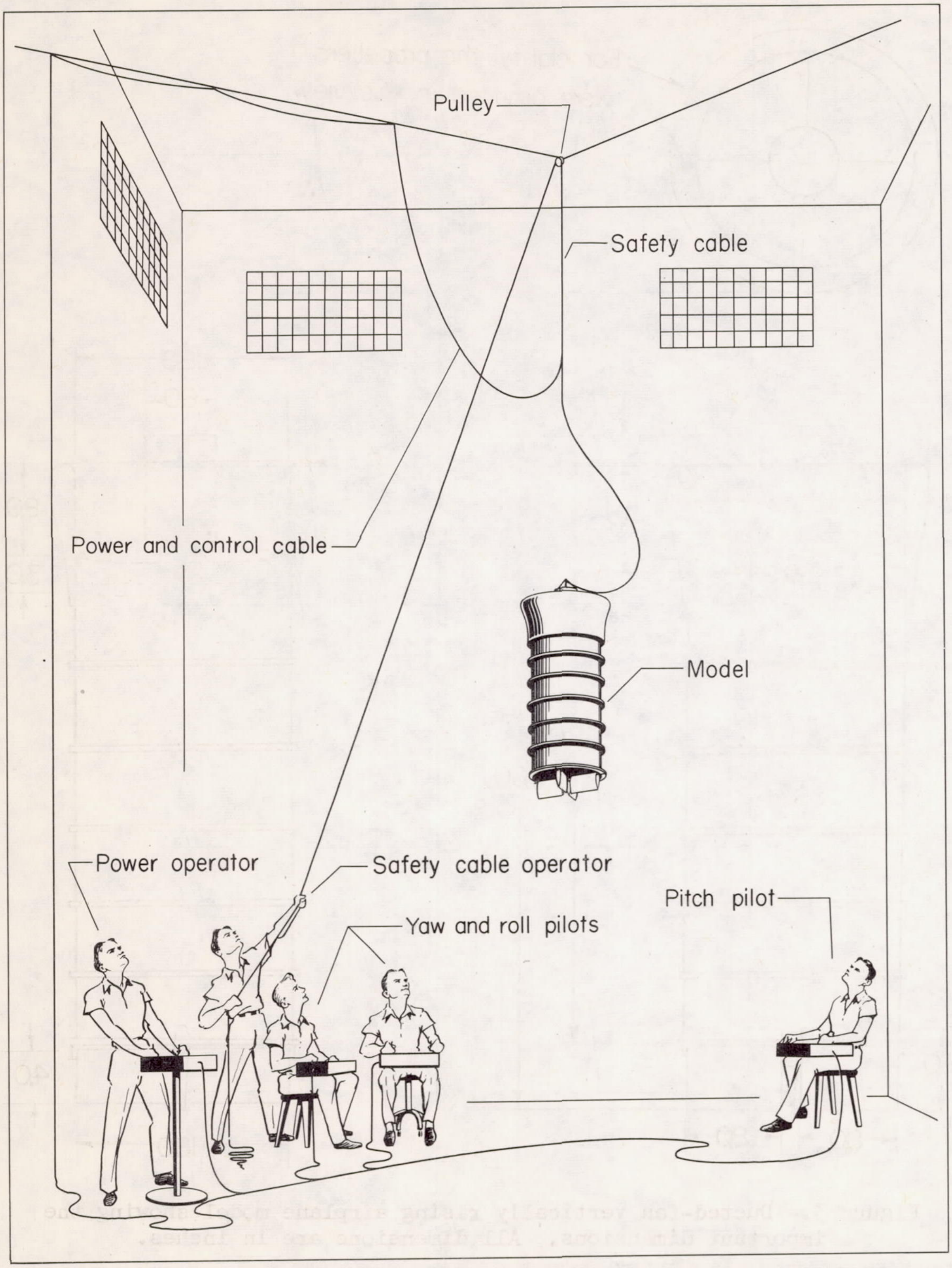

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Figure 4.- Setup used to test hovering models.

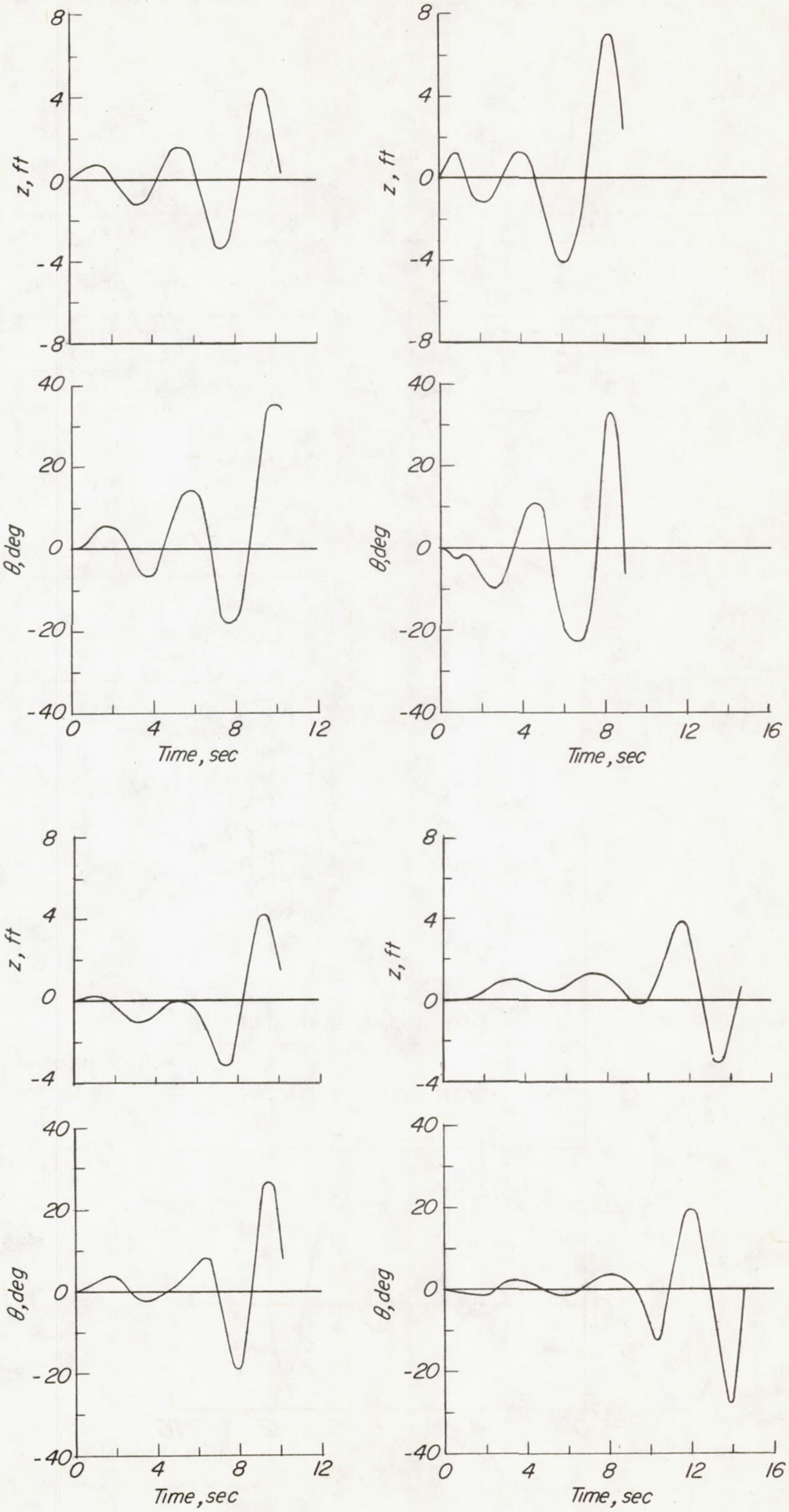

Figure 5.- Uncontrolled pitching motions of the model with the overhead-cable arrangement.

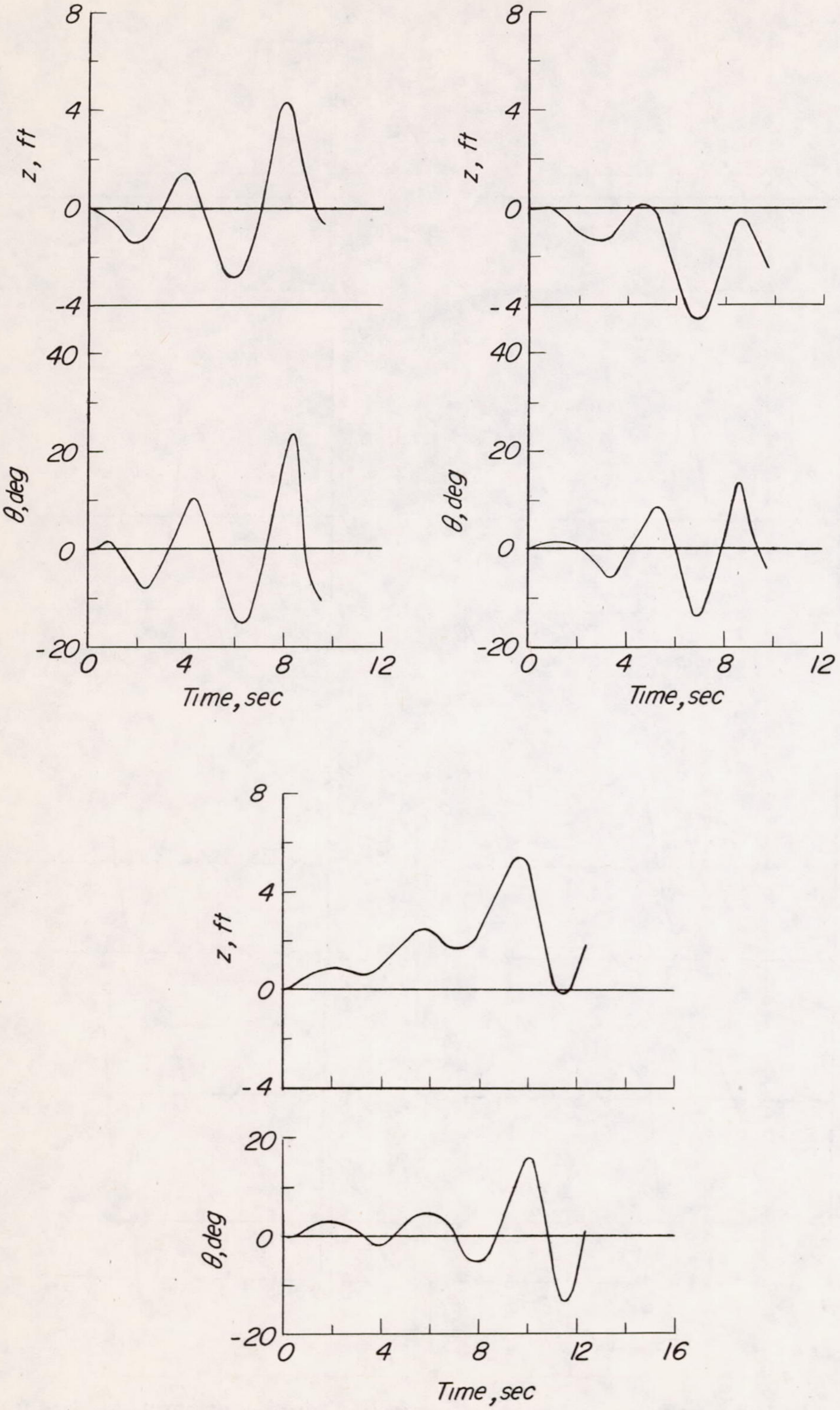

Figure 6.- Uncontrolled pitching motions of the model with the trailing-cable arrangement.

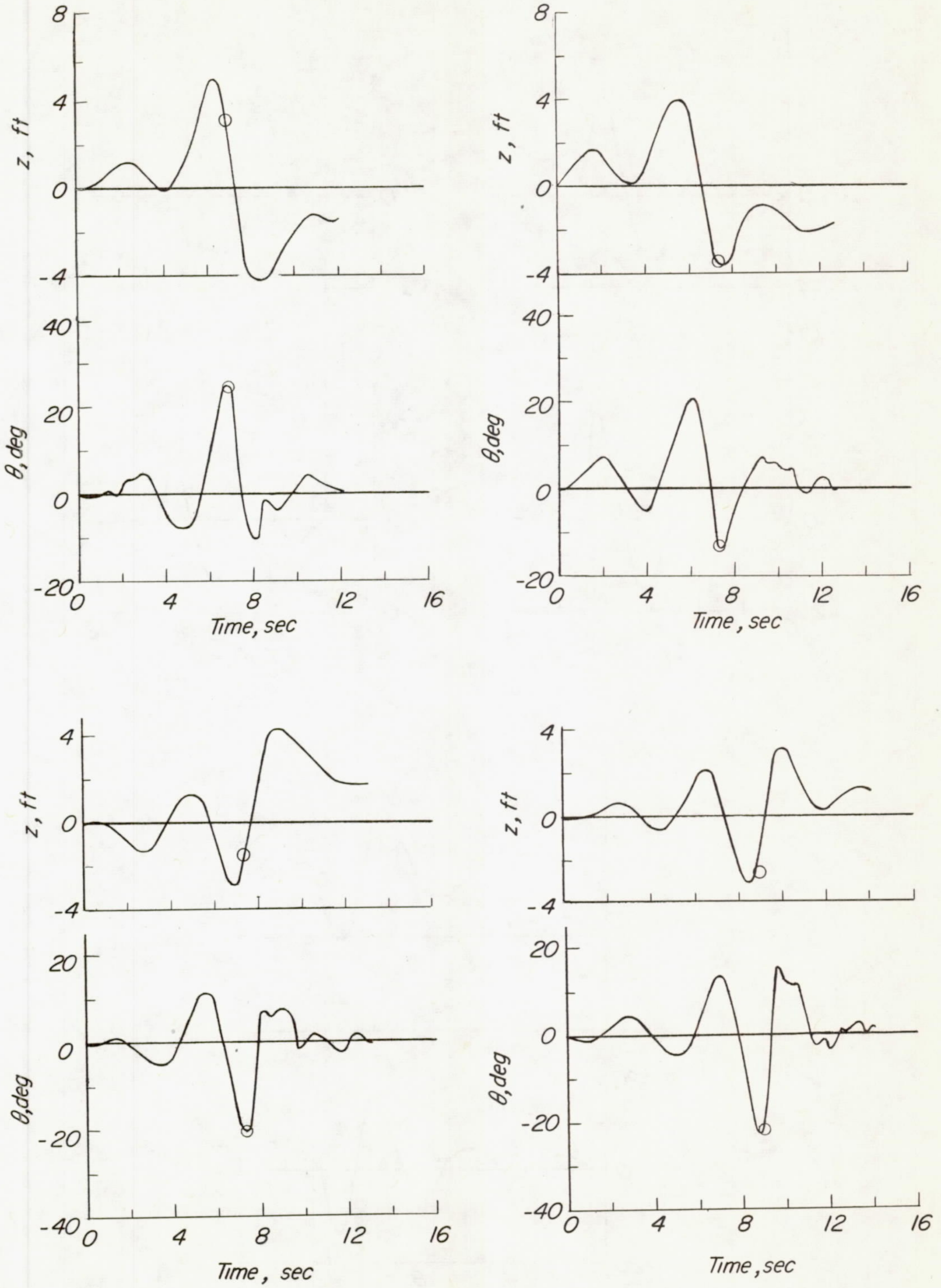

Figure 7.- Flight records with the overhead-cable arrangement showing the ability of the pilot to stop the pitching oscillation. The circular symbols indicate the time at which the pilot began using the controls to stop the oscillations.

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