NASA TECHNICAL NOTE

NASA TN D-2443

NASA TN D-2443

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • SEPTEMBER 1964

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Technical Film Supplement L-835 available on request.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

A flight investigation has been made to study the stability and control characteristics of a 1/9-scale model of a four-propeller tilt-wing V/STOL transport airplane. The tests included hovering flights in and out of ground effect and level flight and descent conditions in the transition speed range. No artificial stabilization was used in any of the tests. Even though the model was statically and dynamically unstable for many of the flight-test conditions, it could generally be controlled and maneuvered easily. The descent tests showed that the configuration had at least a 6° descent capability with no adverse effects, and that an additional 3° or 4° of descent angle was available before completely unacceptable flying qualities were encountered as a result of wing stalling. In all flight regions, the minimum total control powers found to be satisfactory in the model flight tests were less than the control powers planned for the full-scale aircraft.

INTRODUCTION

An investigation to study the low-speed dynamic stability and control characteristics of a four-propeller tilt-wing V/STOL transport airplane has been made at the NASA Langley Research Center using a 1/9-scale model. The wing is provided with a full-span double slotted flap which is programed to deflect as the wing incidence changes.

The investigation included free-flight tests in still air for study of the vertical-take-off-and-landing and hovering-flight conditions and free-flight tests in the Langley full-scale tunnel for study of slow constant-altitude transitions and simulated descending-flight conditions at low transition speeds. The results were mainly qualitative and consisted of pilots' observations and opinions of the behavior of the model.

SYMBOLS

b	wing span, ft
C_n	yawing-moment coefficient, M_Z/qSb

c	local wing chord, ft
$\bar{c}$	wing mean aerodynamic chord, ft
D	model propeller diameter, ft
h	height of model fuselage above ground ($\theta = 0^\circ$)
I_X	moment of inertia about X body axis, slug-ft^2
I_Y	moment of inertia about Y body axis, slug-ft^2
I_Z	moment of inertia about Z body axis, slug-ft^2
i_w	wing incidence, deg
k_X	radius of gyration about X body axis, ft
k_Y	radius of gyration about Y body axis, ft
k_Z	radius of gyration about Z body axis, ft
L	lift, lb
L_∞	lift in hover out of ground effect
$M_{X,\phi}$	rolling moment due to roll angle, ft-lb/deg
$M_{Y,\theta}$	pitching moment due to fuselage pitch angle, ft-lb/deg
M_Z	yawing moment, ft-lb
$M_{Z,\infty}$	yawing moment out of ground effect, ft-lb
p	rate of roll, radians/sec
q	dynamic pressure, lb/ft^2
S	wing area, ft^2
V	velocity, ft/sec
W	weight, lb
x,y,z	coordinate axes
α	angle of attack of fuselage, deg
β	angle of sideslip, deg

γ flight-path angle, deg

δ_a aileron deflection, deg

δ_f total flap angle, measured between wing chord and second element of flap, deg

θ fuselage pitch angle, deg

ϕ roll angle, deg

APPARATUS AND TESTS

Model

General description.- Photographs of the 1/9-scale model used in the investigation are presented as figure 1. Drawings of the model showing some of the more important dimensions are presented in figure 2. The geometric characteristics of the model are listed in table I. The variation of center of gravity with wing incidence for the model and for the airplane is shown in figure 3. The moments of inertia of the configuration were essentially constant throughout the wing incidence range, and the average values for the model (scaled up) are compared with those of the full-scale airplane in table II.

The four main propellers of the model were interconnected by a system of shafts and gear boxes and were driven by a pneumatic motor. The tail rotor was driven by a separate pneumatic motor. The wing was pivoted at the 30-percent mean aerodynamic chord station and could be rotated by an electric motor between angles of incidence of 0° and 90° during flight. The wing was equipped with a slat along that part of the leading edge that was behind the up-going propeller blades. The wing was also equipped with the 47-percent-chord double slotted flap shown in figure 2(b) which was programed with a simple cam and follower to deflect as the wing incidence changed. The programed variation of flap deflection with wing incidence is shown in figure 4.

Control system for hovering flight.- In hovering, roll control was provided by differentially changing the total blade pitch of the four main propellers, and yaw control was provided by differentially deflecting the conventional ailerons at this 90° wing angle. The ailerons were built into the rear element of the flap as shown in figure 2(b) and were located on the two outboard segments of the flap as shown by the shaded area in figure 2(a). Pitch trim was obtained by total blade pitch of the tail rotor and pitch control for maneuvering was provided by a jet mounted at the rear of the model. It should be pointed out that on the airplane both pitch control and trim are obtained from the tail rotor, but on the model, for mechanical reasons, it was not desirable to obtain control from the tail rotor. The controls were deflected by flicker-type (full on or off) pneumatic actuators except for the pitch trim control of the tail rotor which was actuated by an electric motor. The main propeller-blade pitch actuators were equipped with an integrating-type trimmer that trimmed the control a small amount each time the flicker control was given. The aileron actuators were mounted, for trim, on movable platforms driven by a small electric motor. The jet reaction control used for pitch control was not equipped with a trimmer.

Control system for conventional forward flight.- In conventional forward flight where the wing and propellers were at a tilt angle of 0°, the model had conventional ailerons and rudder for roll and yaw control. The rudder, however, did not provide sufficient yawing moment by itself; therefore, the yaw control was augmented in the model tests by the use of differential blade pitch changes on the four main propellers. The jet reaction control used for pitch control in hovering was also used throughout the investigation from hovering to conventional forward flight. The model did have an all-movable horizontal tail that was programed to move as the wing incidence changed but the tail was not controlled by the pilot. The programed variation of the horizontal-tail incidence with wing incidence is shown in figure 4.

Control system for transition flight.- In the transition range the ailerons and the differential propeller pitch control interchange their function as the wing incidence changes. On the full-scale airplane a control mixing device is used to give the desired response to the pilot's control movements. In general, the propeller blade pitch and aileron control are mixed according to the wing incidence so that lateral stick always results in a roll control and pedal displacement gives a yaw control. No such mechanical control mixer was used in this model investigation, however. The model pilots were able to use various combinations and amounts of these controls by electrical switching of the flicker mechanisms and by ground adjustment of the amount of control given by the flicker mechanisms. The control moments used during the different flight conditions are presented subsequently.

Test Techniques

The basic test setup used in the present tests was essentially the same as that used for all flight tests in the Langley full-scale tunnel and is illustrated in figure 5. An additional operator (not shown in fig. 5) was located near the pitch pilot to control the wing incidence in some of the tests. The power for the wing tilt motor, the control trim motors, and the electric-control solenoids was supplied through wires; and the air for the pneumatic motors, the jet-reaction control, and the control actuators was supplied through plastic tubes. These wires and tubes were suspended from the top of the tunnel and were taped to a safety cable (1/16-inch braided aircraft cable) from a point about 15 feet above the model down to the model itself. The safety cable, which was attached to the fuselage near the model center of gravity, was used to prevent crashes in the event of a power or control failure or in the event that the pilots lost control of the model. Separate pilots are used to control the model in pitch, roll, and yaw. The reasons for using this model flight technique in which the piloting duties are divided in preference to the conventional single-pilot technique is explained in detail in reference 1. In forward (and descending) flight two pilots are sometimes used, one pilot controlling both roll and yaw.

Tests to study the level-flight transition characteristics of a model can be made in the Langley full-scale tunnel either by continually increasing or decreasing the tunnel airspeed until the transition is completed or by holding the tunnel airspeed constant at intermediate speeds for more careful study of any stability and control characteristics or problems that may be encountered.

It has been found in previous work with tilt-wing V/STOL aircraft (see ref. 2) that one of the most critical flight conditions is the partially transitioned descent condition which will probably be used for most landing approaches. In order that this condition might be studied in the present investigation, the free-flight testing technique in the Langley full-scale tunnel has been extended to permit tests representing the descent condition to be made in the horizontal airstream of the tunnel. The factors involved in the simulation of a descent condition are illustrated in figure 6. This figure shows the balance of forces involved in actual descent at the left and in the simulated descent at the right. For the actual descent case, the lift, drag, and weight forces are in balance, the drag being balanced by the forward component of the weight acting along the flight path. For the simulated descent condition in the horizontal airstream of the tunnel, the model is flown with effectively the same lift and drag, but the drag cannot be balanced by a component of the weight and must be balanced by some thrust force that is independent of the normal airplane lift and propulsion system. A small high-pressure compressed-air jet exhausting from the rear of the model where the aerodynamic interference effects would be negligible was used. In this way the aerodynamic effects of descending or decelerating flight, which are very important for many V/STOL aircraft types, can be simulated with the model in level flight in the tunnel. This method of simulation, however, does not account for the effects of descent angle on classic dynamic lateral stability, but fortunately these effects are small for the descent angles likely to be encountered in normal operation and are of much less importance than the aerodynamic effects which can be correctly simulated.

For hovering tests, a test setup very similar to that shown in figure 5 is made in a special hovering test area located in a large enclosure where the pilots can be stationed closer to the model than is possible in the test section. It has been found very desirable, particularly during tests in which the model is flown very close to the ground, for the pilots to be near the model so that they can notice more readily and correct for slight changes in model attitude and altitude.

Tests

The free-flight investigation included tests at three different flight conditions: (1) hovering (both in and out of ground effect), (2) steady level forward flight at $\alpha = 0^{\circ}$ (over the whole transition range from hovering to $i_W = 0^{\circ}$), and (3) simulated descent flight (at $i_W = 20^{\circ}$, 30°, 40°, and 50° for descent angles of 0°, 5°, 7°, 10°, 13°, and 15°). The stability, controllability, and the general flight behavior were determined qualitatively from the pilots' observations; and motion-picture records of the flight tests were made as an aid in the pilots' evaluation and to supply some quantitative data on the model motions.

No artificial stabilization was used in any of the tests. The basic stability of the model was studied, in each flight condition, by having two of the pilots controlling the model as steadily as possible (after a trimmed condition had been established) while the third pilot made the tests required to determine the stability of a particular phase of the model motion. In that manner, for example, the stick-fixed pitching or rolling motions of the model were determined. The controllability was determined in the same manner by each pilot in turn varying his control power to determine the amount of control required for steady flying and for performing various maneuvers. The basic stability or control characteristics of a model do not, however, give the complete picture of the model flight characteristics; therefore, the model pilots also assessed its general flight behavior, including the effects of such factors as wing stalling.

A few force tests were made, in addition to the free-flight tests, to help document some of the aerodynamic and stability and control characteristics of the model.

RESULTS AND DISCUSSION

A motion-picture film supplement (L-835) to this report has been prepared and is available on loan. A request card form and a description of the film will be found at the back of this document.

In reviewing the results of the flight tests, it should be remembered that, as shown in table II, the scaled-up weight and inertia characteristics of the test model were high in comparison with the full-scale values. The radii of gyration of the model however were of approximately the right magnitude. These high mass characteristics of the model could have affected the detailed results of this investigation; for example, they could cause slight changes in the period of the hovering oscillations or changes in the damping of the lateral oscillatory motions in forward flight. It is felt, however, that since the periods of the motions experienced with this model were relatively long, the conclusions reached from the flight tests are valid and were not appreciably affected by the high mass characteristics. The results of the forward-flight tests would, however, apply directly to flight at an altitude of about 11,000 feet because of the relationship between correct and actual wing loadings.

All the results are for the case of the aircraft without artificial stabilization since no artificial stabilization was used at any time during the tests.

Hovering Out of Ground Effect

The flight tests in still air out of ground effect to determine the basic stability in hovering flight showed that, as expected with a tilt-wing configuration, the model had unstable control-fixed oscillations in pitch and roll and was neutrally stable in yaw. Examples of the motions encountered in pitch and roll are shown by the time histories presented in figures 7 and 8. These time histories were obtained from motion-picture records of the model flights. The pitching oscillation was a predominantly angular motion without much translation, whereas the rolling oscillation had a substantial translation accompanying the angular motion. The period of the pitching oscillation was about 3.4 seconds and the period of the rolling oscillation was about 6 seconds. These values scale up to about 10 and 18 seconds, respectively, for the full-scale airplane.

In spite of the fact that the model had unstable control-fixed pitching and rolling oscillations in hovering flight out of ground effect, the pilots felt that the general flight behavior of the model was good. The model could be flown smoothly and could be maneuvered readily from one position to another. One reason that the model was easy to control in spite of the unstable oscillations was that the motions were relatively slow in starting and were not easily excited by outside effects such as gust disturbances or movements of the control and power cable. Another reason that the model was easy to control was that the period of the oscillation was very long and thus the pilot was not conscious of its presence in normal flying. This same general type of result was obtained at both model scale and full scale with the VZ-2 research airplane as indicated by references 3 and 4.

In the flight tests to determine how much control power was required for steady flight and for performing various maneuvers, the model pilots found that less control acceleration was required for satisfactory controllability than is provided on the full-scale aircraft. The full-scale aircraft hovering controls should provide accelerations of about 0.80 radian/sec^2 in pitch, 1.08 radians/sec^2 in roll and 0.53 radian/sec^2 in yaw. Actually, the model pilots found that 60 percent of the scaled-down value in pitch, 50 percent of the scaled-down value in roll, and 40 percent of the scaled-down value in yaw were adequate for performing any test maneuver required of the model. It has been found, as pointed out in reference 1, that flying model results generally correlate well with full-scale flight test results on the control power required in pitch and roll, but the yaw-control requirements have not shown correlation with full-scale experience. The yaw-control task in model flying is mainly one of simple alinement under steady flying conditions and does not involve gusts, operation in cross winds, maneuvering in yaw, or other disturbances and requirements found in full-scale tests.

Hovering in Ground Effect

In addition to the hovering flight tests made out of ground effect, a number of flights were made to study the effect of close proximity to the ground on the model characteristics. These flight tests showed that near the ground the model was somewhat easier to fly in roll and pitch than it was out of ground effect. The unstable control-fixed pitching motion that was present at altitude seemed to become stable at very low heights when the wheels were about to touch the ground. This characteristic is indicated by figure 9 which shows a time history of the stick-fixed pitching motions of the model when hovering near the ground. This figure shows the stick-fixed motion to be a somewhat random motion of small amplitude when the wheels were almost touching the ground during the first part of the flight. When the model rose to a slightly greater height above the ground after about 7 seconds, the motion developed into a fixed amplitude oscillation. After about 18 seconds of flight, the motion damped when the wheels touched the ground but built up again to a larger amplitude motion. The effect of ground proximity on roll was less pronounced than that on pitch. The model pilot could not detect any appreciable change in stability but felt that the rolling phase of the model motion became slightly easier to control as the model neared the ground. The variation of static stability with height above the ground, as measured in force tests, is shown in figure 10. These data show that the model had a slight amount of static stability in pitch and roll as the model approached the ground; this condition probably accounts for the improved dynamic stability and controllability.

Unlike the rolling and pitching motions of the model, the yawing motions became somewhat more difficult to control as the model neared the ground. The model experienced erratic yaw disturbances which were apparently caused by the erratic nature of the recirculating slipstream which was aggravated by the other model motions. Although not large in magnitude, these disturbances resulted in greater pilot effort being required to hold a desired heading for hovering near the ground. The yaw pilot also noticed a reduction in the yawing moment produced by the ailerons near the ground, but he did not feel that this loss of effectiveness was the major factor in the increased control effort required. For most of the flights the control used was the same $\pm 20^\circ$ deflection that was used out of ground effect, but a few flight tests were made with a yaw control deflection of $\pm 40^\circ$. The increased control power gave a more positive yaw control and enabled the pilot to correct quickly for the erratic disturbances but did not materially reduce the pilot effort or concentration required to hold a yaw heading. Figure 11 shows the loss of effectiveness of the ailerons in ground proximity for the model as measured in force tests. These data show that the yaw control effectiveness of the ailerons was only about one-half as great when the wheels were almost touching the ground as when the model was out of ground effect.

Take-off and landing flight tests showed no apparent changes in trim with altitude about any of the axes. With the controls perfectly trimmed for hovering out of ground effect, several tests were made which showed no tendency of the model to move either forward or backward at take-off.

A very definite ground effect on the model lift was noted in the landing tests. If the model thrust was reduced slightly so that a slow vertical descent was started from hovering flight, the model would descend down to a certain point and would descend no farther until the thrust was further reduced. If the descent was made at a slightly faster rate, the model would rebound slightly as if it were bouncing on a spring. If the descent rate was too fast, however, the momentum would carry the model on down in spite of the favorable ground effect and it would strike the ground. Figure 12 shows the variation of lift with ground proximity obtained from force tests of this model. These data show a 20-percent increase in model lift with constant propeller speed at a value of h/D of 0.25, which is approximately the height at which the wheels would touch down for the full-scale airplane with the shock struts fully extended. Analysis of the data of reference 5 indicates that practically none of this increase in lift due to ground proximity is caused by increase in the propeller thrust; therefore, it can be presumed that almost the entire 20 percent increase in lift was caused by an upload on the bottom of the fuselage, the source of which is explained in references 5 and 6.

Level Flight in Transition

Longitudinal stability.- The basic stability of the model throughout the transition flight range was determined during constant airspeed flight tests with the model trimmed for flight at $\alpha = 0^{\circ}$. Examples of the type of motions experienced are shown in figure 13 which presents time histories of the control-fixed pitching motions for wing incidence angles representing four different airspeeds. The curves show that, as noted previously, the control-fixed motion in hovering was an unstable oscillation. At a wing incidence of 65°, little difference was noticed in the motion since the model was at a very low forward speed because the programed flap was being deflected during this wing-incidence change. At lower wing incidences, the motions became less unstable and the period of the oscillation became very long. In fact, the unstable motions at lower wing angles were not noticeable at all to the pilot when he was flying the model in the normal manner. For instance, the oscillation at a wing incidence of 25° had a very long period (about 6 seconds model scale) and without looking carefully for the oscillation at constant forward speed, the pilot would not ordinarily distinguish it from the normal gust, or other disturbances that the model experiences in flight tests. At the lowest wing angle ($i_W = 10^{\circ}$) the time history of figure 13 seems to show that the two oscillatory modes normal for conventional forward flight are beginning to appear - the short-period oscillation shows up in the pitch angle record, and the long-period phugoid oscillation seems to be appearing in the longitudinal and vertical displacement traces. This progressive change from a longitudinally unstable to an apparently stable flight condition as the transition progresses from hovering to forward flight is typical of other tilt-wing configurations such as that of reference 7.

Lateral stability.- In the transition range, the model was even easier to fly in roll than it had been in hovering. In fact, as soon as the model started into transition from hovering, the roll control became noticeably easier. This result was evidently caused by the fact that the model was stable in roll in the transition range of flight instead of having an unstable oscillation as it had in hovering, and that the motions resulting from gusts or control disturbances consequently damped out instead of exciting an unstable oscillation. These characteristics were observed in flight tests which were made to study the control-fixed lateral motions in the transition range. In these tests, the model was trimmed as carefully as possible and then the roll and yaw pilots stopped giving control so that the controls remained fixed at this trim setting. At all angles of wing incidence tested below $i_W = 70^{\circ}$, the resulting model motion was a slow sidewise divergence with little yawing and no observable rolling. This type of motion might have been a slight aperiodic divergence or might have been caused by some small remaining out-of-trim setting of the yaw control, but there was clearly no significant degree of oscillatory instability. In order to investigate the oscillatory stability characteristics further, some additional flights were made at angles of wing incidence from 80° to 20° in which, after the trimmed flight condition was established, the model was deliberately disturbed by using the controls to impart a combined rolling and yawing motion. Each time, after the controls became fixed, the rolling and yawing motions damped out quickly but then the model performed the same sidewise translational divergence (with some yawing) noted in the previous control-fixed tests.

The flight tests discussed, as well as normal controlled transition flight tests, indicated that the model had a region of neutral directional stability for small angles of sideslip over the entire transition speed range. This stability problem appeared in controlled flight as a tendency of the model to trim at a small sideslip angle, in either right or left sideslips, which was objectionable to the pilots. Figure 14 presents the results of force tests of the present model which show neutral directional stability for a range of sideslip angles of about 6°, but unpublished results from tests made with a 1/11-scale model in the Langley 7- by 10-foot tunnel indicated a slight amount of directional stability over the entire sideslip range and did not show a flat spot in the directional stability curve. This 1/11-scale model, however, incorporated a number of minor changes in the configuration that were made after the construction of the 1/9-scale flying model had been completed. By temporarily modifying the 1/9-scale model, force tests were made which showed that the flat spot in the directional stability curves could be eliminated with the flying model if the gaps between the fuselage and the wing flap were sealed. (See fig. 14.) The data of figure 14 also show that the other modifications did not significantly change the directional stability of the model. These other modifications consisted mainly of changes to the fillet at the juncture of the vertical tail, pitch fan support boom, and the fuselage.

In order to check the effect of sealing the flap gaps on the dynamic behavior of the model, flight tests were made at various angles of wing incidence with the gaps between the fuselage and the wing flap sealed. The flight characteristics of the model were found in these tests to be essentially unchanged from the unsealed condition and the directional stability was still considered by the pilot to be undesirably low. Because it was very awkward to seal the flaps on the flying model and since very little difference in the flying characteristics resulted from the modification, the flight investigation was continued with the gap unsealed.

During the previously mentioned series of force tests made on the free-flight model, a few tests were made with a larger vertical tail. The area of the vertical tail was increased 59 percent by an addition to the leading edge and top of the fin as shown by the dashed lines in figure 2, and the tests were made with the gaps between the flap and fuselage open. Figure 15 shows the effect of the larger vertical tail on the directional stability at $i_w = 0^\circ$, 10°, and 20°. In addition to eliminating the neutral stability at small sideslip angles, the larger vertical tail gave increased directional stability over the entire range of sideslip angles. In flight tests made by using the large vertical tail, the flight characteristics of the model were much improved by the increase in directional stability and there was no noticeable tendency on the part of the model to sideslip even at wing incidence angles as high as 50° where the airspeed was becoming fairly low.

Descending Flight in Transition

Experience with the VZ-2 tilt-wing research aircraft, reported in reference 4, has shown that in the reduced-power descending-flight conditions in the transition speed range, the wing has a tendency to stall and that this stall leads to buffeting, abrupt wing dropping, and generally erratic, wallowing motions. These results of the stalling were found to become so severe that they effectively limited the rate of descent that the pilot was willing to use. This limitation can be very serious from an operational standpoint since it tends to occur in the speed range corresponding to the landing-approach condition where high rates of descent must be maintained to take advantage of the short-field landing capability of V/STOL aircraft. Free-flight model tests, reported in reference 8, gave reasonably good agreement with the full-scale flight tests in regard to the wing stalling and the limitations imposed on the operation of the aircraft by the wing-dropping and erratic, wallowing motions associated with the stalling. The buffeting, however, was not detected on the model which was not instrumented and was remotely controlled so that the pilot did not feel the buffeting. The free-flight model tests therefore did not give the whole answer but seemed to give the most important results with regard to the seriousness of the wing stalling. The characteristics of the present model were therefore studied very carefully with regard to this important problem.

The characteristics of the present basic model in simulated descending flight were investigated over a wing incidence range of 20° to 50°. The wing flap deflection programed as scheduled on the full-scale airplane (see fig. 4) resulted in a 60° flap deflection over most of the wing incidence range investigated. At each test condition, the model was assigned a flight rating according to the flying-model pilot-rating system shown in table III. This model rating system is shown and compared with the Cooper rating system since the intent of the model rating system is to consider the type of behavior of the model that would represent insofar as possible the behavior required of an airplane to meet all the conditions given under the Cooper rating system. The ratings for the model are limited to the stability and control aspects of flying qualities since the remote-control pilot is unable to sense the buffeting.

The pilot ratings obtained in the tests are shown in figure 16 on a plot of flight path (or descent) angle against wing incidence. Ratings were obtained at angles of wing incidence of 20°, 30°, 40°, and 50° for descent angles of 0°, 5°, 7°, 10°, 13°, and 15°. The ratings shown in figure 16 are overall ratings obtained from the individual ratings on lateral, directional, longitudinal, and power characteristics (and for that reason the longitudinal and lateral stability and control characteristics are not discussed separately as in other sections of the report). At each test point, two ratings were obtained: (1) a rating of the behavior of the model when reasonably smooth and steady flight was maintained and (2) a rating for disturbed flight after the model had been intentionally given a large disturbance or had been allowed to build up its own large-amplitude disturbed motion. At small descent angles, the model was very stable and had to be disturbed intentionally with the controls, after which the disturbed motion damped out quickly; therefore, for these conditions, there was no difference between the two ratings and only one rating is shown in figure 16. At the greatest descent angles, steady flight was not possible so only a disturbed-flight rating was given as indicated in figure 16.

Figure 17 presents a summary of the pilots' opinions of the flying qualities of the model in the form of boundaries obtained from the ratings of figure 16. Above the dotted area in figure 17, the model's characteristics were satisfactory and, in fact, no difference from level flight was detected even when the model was intentionally disturbed. As the descent angle was increased in the dotted area of figure 17, the model required more and more pilot attention to the controls. At the highest descent angles in the dotted area, the lateral oscillations persisted for several cycles after a disturbance. In those conditions intermittent stalling of a part of the wing could be observed from tufts on the wing. In the hatched area of figure 17, the model experienced extensive wing stalling which caused abrupt wing dropping, abrupt losses in height, and the generally erratic, wallowing motions normally associated with wing stall. The model's flying qualities were unacceptable in this region.

Figures 18 and 19 are presented to illustrate for the $i_w = 30^\circ$ condition the types of flight characteristics encountered in the descent tests. Figure 18 shows time histories (from motion-picture records) of the lateral motions performed by the model while the pilots were attempting to make a smooth and steady controlled flight at descent angles of 0° and 13°. In level flight the model was very easy to fly and required only occasional corrective control. The erratic, large-amplitude motions at a descent angle of 13°, however, were extremely difficult to control; and, in fact, control of the model was lost at times during the tests. Figure 19 shows time histories obtained from flights made at $\gamma = -5^\circ$, -7°, and -10° to study the motions performed by the model after it had been intentionally disturbed from a smooth flying condition by the pilot. At $\gamma = -5^\circ$, three long control pulses were used by the pilot to set up the motion, and the ensuing motion was so highly damped that very little pilot effort was needed to reestablish steady flight. At $\gamma = -7^\circ$, only two rapid control pulses were needed to start the motion but the motion was still mild enough so that the pilot was able to reestablish steady flight fairly quickly. At $\gamma = -10^\circ$ only one control pulse resulted in the erratic, wallowing motions shown in the figure. These motions persisted in spite of the pilot's efforts to reestablish steady flying conditions.

Several aspects of the behavior of the model do not show up in the simple ratings. First, it should be noted in figure 16 that a rating of 4 was obtained for level flight at $i_w = 50^\circ$. This rating does not mean that disturbances or wing stalling were noticed in this condition but reflects the fact that at the lower airspeeds the model did not have as much stability as at the higher speeds and more pilot attention was required. A second point is that at times, during flights at high-rate-of-descent conditions at $i_w = 30^\circ$, the model would drop in height abruptly without any appreciable effect on the lateral flight characteristics being noted. This abrupt loss in height was a new type of motion not previously experienced in the VZ-2 model tests. Observation of the tufts on the wing showed that this abrupt dropping was caused by a sudden symmetrical stall over a large part of the wing. The last point that should be brought out in addition to the simple ratings is that at high descent angles, somewhat different model motions were obtained at low angles of wing incidence than at high angles of wing incidence. For example, as shown in figure 16, at $i_w = 20^\circ$, steady flight could be achieved very easily and the tufts showed no apparent stalling with descent angles as great as 10°. However, if a disturbance occurred at this point, the resulting abrupt wing dropping and generally erratic, wallowing motions of the model were very difficult to control and a rating of 7 resulted. At $i_w = 50^\circ$, however, there was not much difference between steady and intentionally disturbed flight at any descent angle. Although the tufts showed disturbed flow on the wing for steady flight at descent angles as low as

7°, the model motions were not appreciably affected until the descent angle exceeded a value of about 11°. This effect might be expected since the high incidence of the thrust line and the high flap deflection at $i_w = 50^{\circ}$ resulted in most of the weight being supported by power rather than by wing lift so that wing stall affected only a very small part of the total lift.

A few tests were made with the larger vertical tail installed on the model. These tests did not cover all the descent test conditions that were covered with the basic model but did cover enough conditions to indicate that the larger tail did not appreciably improve the behavior of the model at the descent conditions in which wing stalling was causing the behavior to be unsatisfactory.

In summary, the model had at least a 6° descent capability with no adverse effects. Another 3° or 4° of descent was available as a safety margin before completely unacceptable flying qualities were encountered. It should be pointed out again that buffet effects could not be evaluated in these tests. It might be inferred, however, that since no disturbed flow could be detected on the wing at descent angles of 6° or less, buffeting would not be expected to cause any trouble in this flight region.

Evaluation of Control Power Required

Longitudinal control.- As mentioned previously, the pitch jet was used throughout the flight range to provide the longitudinal control required for maneuvering while the longitudinal trim required was provided by the tail rotor. Figure 20 shows the longitudinal control power, in excess of that required for trim, planned for the airplane compared with the pitch jet longitudinal control power (scaled up to full-scale values) required on the model. The longitudinal control used on the model, which was less than that available for the full-scale airplane in all cases, was found to be adequate for any of the test conditions including some rather abrupt maneuvering in both level and descending flight.

Lateral control.- In the transition-flight mode, the full-scale aircraft has a control mixing device which provides, at each angle of wing incidence, a predetermined combination of propeller pitch and aileron deflection in response to a roll or yaw control from the pilot. The controls were not mechanically phased on the model but the roll and yaw pilots could command preselected amounts and combinations of control moment during the transition in order to study the control requirements. Figure 21 shows the planned control powers for full lateral stick control and full rudder pedal control on the full-scale aircraft, in terms of angular accelerations, along with the control powers found to be required during the present model tests (including descending flight) scaled up to full-scale values. In all cases the maximum control powers found desirable by the model pilots were less than the planned aircraft values. Also shown in figure 21 are the helicopter control power requirements as set forth in the military specification of reference 9 and a point indicating the lateral control power required for roll at the higher forward speed.

The roll-control requirements determined with the model are in good agreement with the helicopter requirements at the low-speed end of the transition range and with the normal airplane requirements at the high-speed end of the transition range. The yaw-control power required in the model tests, however, was much less than the helicopter specification. It should be noted again that yaw-control power required in model testing has not shown correlation with full-scale experience for the hovering condition, evidently because the task is simpler in the model tests. The model flight tests did indicate, however, that even though force tests had shown that the rudder was providing as much yawing-control moment as might be expected, the model could not be flown by using only the aileron and rudder as a coordinated control even at the highest speeds in these tests ($i_w = 0^\circ$ with $\delta_f = 30^\circ$). Analysis of the force-test data and the film records of the flight tests indicated that two factors were involved in the apparent lack of rudder effectiveness. First, the adverse yawing moment caused by aileron deflection was apparently so large that the yawing-control moment provided by the rudder was completely ineffective for opposing the adverse aileron yawing moment. Second, the film records showed that when, for example, a right rudder control was given while the ailerons remained fixed, the large side force and adverse rolling moment due to rudder deflection caused the model to first roll and slide to the left before it would finally yaw and roll to the right and start into the intended right turn. Since the rudder was ineffective in flight for these reasons, it was necessary to obtain yaw-control moment on the model from the differential propeller pitch.

SUMMARY OF RESULTS

The results of the flight tests of the 1/9-scale model of a four-propeller tilt-wing transport airplane without artificial stabilization may be summarized as follows:

1. Hovering-flight tests out of ground effect showed that basic controls-fixed motions of the model consisted of unstable oscillations in pitch and roll and that the model was neutrally stable in yaw. The unstable oscillations were of relatively long period, however, and were very easy for the pilot to control.

2. Hovering-flight tests in ground effect showed that the model had a positive ground effect on lift. The pitching oscillation became less unstable as the model neared the ground and was about neutrally stable when the wheels were just off the ground. The effect of the ground on the rolling oscillation was less pronounced, but the rolling motions became slightly easier to control as the model neared the ground. The model experienced significant random yaw disturbances when hovering near the ground, and there was a noticeable reduction in yaw-control power available, but the yawing motions could be kept under control by the pilot with suitable attention to the controls.

3. In the transition range no trouble was experienced with either longitudinal or lateral stability or control in level forward flight, except that the model had about neutral directional stability for very small angles of sideslip. In general, the model had at least 6° descent capability with no adverse effects and no noticeable wing stalling. Another 3° or 4° of descent was available before stalling caused the flying qualities to become completely unacceptable.

4. In all flight regions, the minimum total control powers found to be satisfactory in the model flight tests were less than the control power planned for the full-scale aircraft.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., August 5, 1964.

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3. Tosti, Louis P.: Flight Investigation of the Stability and Control Characteristics of a 1/4-Scale Model of a Tilt-Wing Vertical-Take-Off-and-Landing Aircraft. NASA MEMO 11-4-58L, 1959.

4. Pegg, Robert J.: Summary of Flight-Test Results of the VZ-2 Tilt-Wing Aircraft. NASA TN D-989, 1962.

5. Newsom, William A., Jr.: Effect of Ground Proximity on the Aerodynamic Characteristics of a Four-Engine Vertical-Take-Off-and-Landing Transport-Airplane Model With Tilting Wing and Propellers. NACA TN 4124, 1957.

6. Schade, Robert O.: Ground Interference Effects. NASA TN D-727, 1961.

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8. Schade, Robert O.; and Kirby, Robert H.: Effect of Wing Stalling in Transition on a 1/4-Scale Model of the VZ-2 Aircraft. NASA TN D-2381, 1964.

9. Anon.: Helicopter Flying and Ground Handling Qualities; General Requirements for. Military Specification MIL-H-8501A, Sept. 7, 1961.

TABLE I.- GEOMETRIC CHARACTERISTICS OF THE MODEL

Fuselage:	
Length, ft	5.56
Cross-sectional area, maximum, sq ft	1.01
Height, maximum, ft	1.36
Width, maximum, ft	1.01
Wing:	
Area, sq ft	6.60
Span, ft	7.50
Aspect ratio	8.53
Mean aerodynamic chord, ft	0.90
Airfoil section	NACA 63_3-318
Tip chord, ft	0.67
Root chord, ft	1.09
Taper ratio	0.61
Sweepback of quarter chord, deg	4.13
Dihedral angle, deg	-2.12
Pivot station, percent root chord	42.5
Aileron, each:	
Chord, percent wing chord	25
Area, sq ft	0.38
Flap, each:	
Type	Double slotted
Chord, percent wing chord	47
Span	Full
Slat, each:	
Inboard, 0.45 wing semispan to 0.69 wing semispan	Chord, 0.20 wing chord inboard to 0.10 wing chord outboard
Outboard, 0.85 wing semispan to 1.00 wing semispan	Chord, 0.10 wing chord full length
Vertical tail:	
Basic:	
Area, sq ft	1.61
Span, ft	1.73
Aspect ratio	1.87
Airfoil section:	
Root	NACA 0018
Tip	NACA 0012
Tip chord, ft	0.37
Root chord, ft	1.48
Taper ratio	0.25
Sweepback of quarter chord, deg	26
Rudder:	
Tip chord, ft	0.15
Root chord, ft	0.42
Span, measured from tip chord, ft	1.06
Tail length, center of gravity to 0.25 mean aerodynamic chord, ft	2.38
Large:	
Area, sq ft	2.60
Span, ft	2.11
Aspect ratio	1.71
Tip chord, ft	0.57
Root chord, ft	1.89
Taper ratio	0.30
Horizontal tail:	
Area, sq ft	2.11
Aspect ratio	5.68
Airfoil section:	
Root	NACA 0015
Tip	NACA 0012
Tip chord, ft	0.39
Root chord, ft	0.78
Span, ft	3.46
Taper ratio	0.50
Sweepback of quarter chord, deg	9.50
Mean aerodynamic chord, ft	0.61
Tail length, center of gravity to 0.25 mean aerodynamic chord, ft	2.76
Propellers:	
Main:	
Number of blades	4
Diameter, ft	1.72
Tail:	
Number of blades	3
Diameter, ft	0.89
Moment arm, wing pivot to rotor center, ft	3.56

TABLE II.- COMPARISON OF AVERAGE MASS CHARACTERISTICS OF

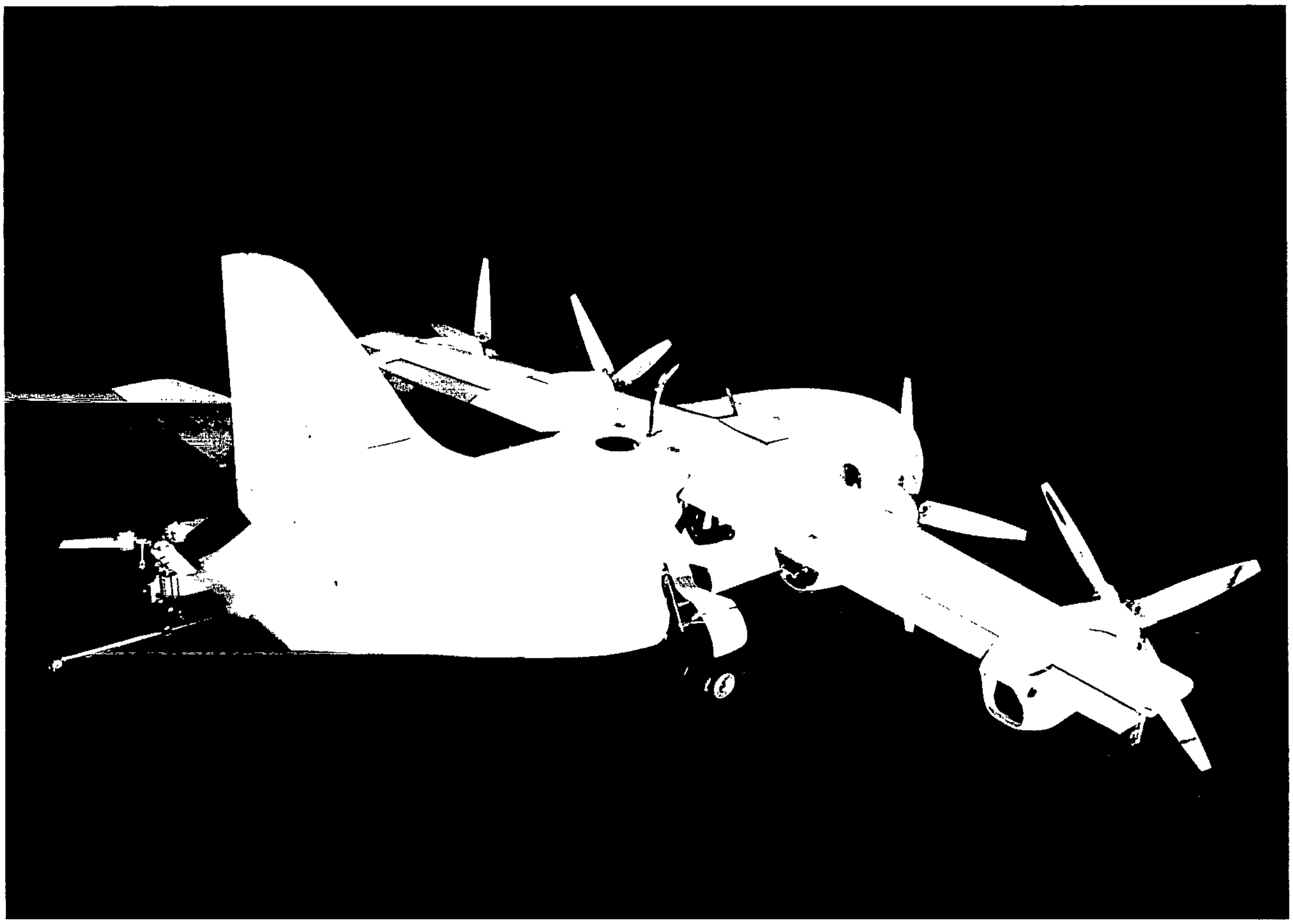
MODEL (SCALED UP) AND FULL-SCALE AIRPLANE

Characteristic	Model (scaled up)	Airplane
Gross weight, lb	52,000	37,424
I_X, slug-ft^2	307,000	176,430
I_Y, slug-ft^2	205,000	125,000
I_Z, slug-ft^2	418,000	270,631
k_X, ft	13.8	12.2
k_Y, ft	11.3	10.4
k_Z, ft	16.1	15.4
W/S, lb/ft^2	97.2	70

TABLE III.- COMPARISON OF MODEL RATING SYSTEM WITH COOPER RATING SYSTEM

Numerical rating	Flying-model pilot-rating system	Cooper pilot opinion rating system				
	Description	Description	Primary mission accomplished	Can be landed	Adjective rating	Operating conditions
1	Extremely easy to fly - requires no attention to control	Excellent, includes optimum	Yes	Yes		
2	Very easy to fly - requires practically no attention to control	Good, pleasant to fly	Yes	Yes	Satisfactory	Normal operation
3	Easy to fly - requires very little attention to control	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes		
4	Not difficult to fly - requires attention to control	Acceptable, but with unpleasant characteristics	Yes	Yes		
5	Not too difficult to fly - requires considerable attention to control	Unacceptable for normal operation	Doubtful	Yes	Unsatisfactory	Emergency operation
6	Difficult to fly - requires almost constant attention to maintain flight	Acceptable for emergency condition only[1]	Doubtful	Yes		
7	Very difficult to fly - requires constant attention to maintain flight	Unacceptable even for emergency condition[1]	No	Doubtful		
8	Extremely difficult to fly - flyable only with maximum attention given to maintain flight	Unacceptable - dangerous	No	No	Unacceptable	No operation
9	Unflyable - cannot be flown even with maximum attention given to maintaining flight	Unacceptable - uncontrollable	No	No		
10	Catastrophic - model destruction	Motions possibly violent enough to prevent pilot escape	No	No	Catastrophic	

[1]Failure of stability augmenter.

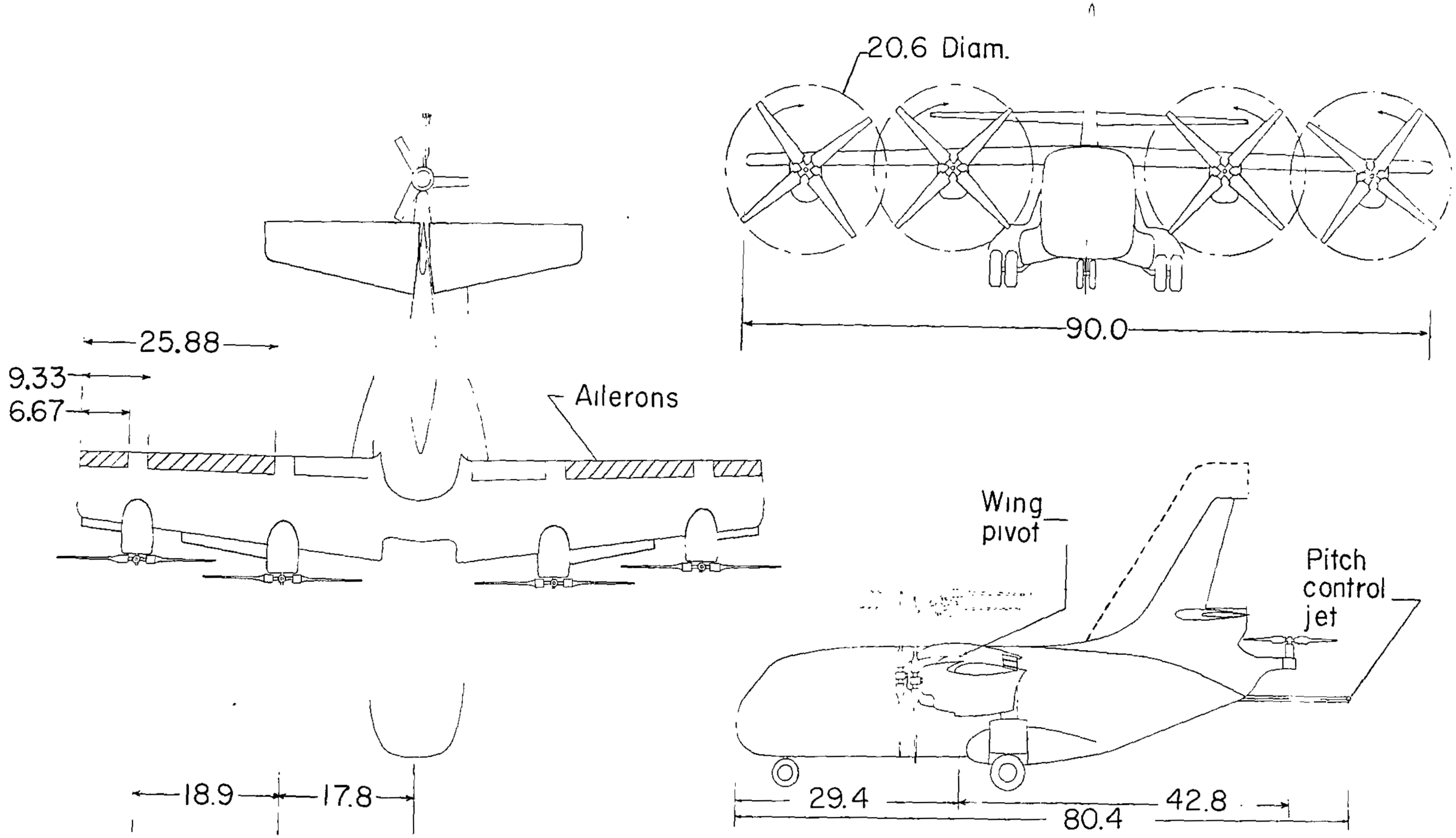


(a) Model with $i_w = 0^{\circ}$ and $\delta_f = 0^{\circ}$. L-62-9665

Figure 1.- Photograph of model used in investigation.

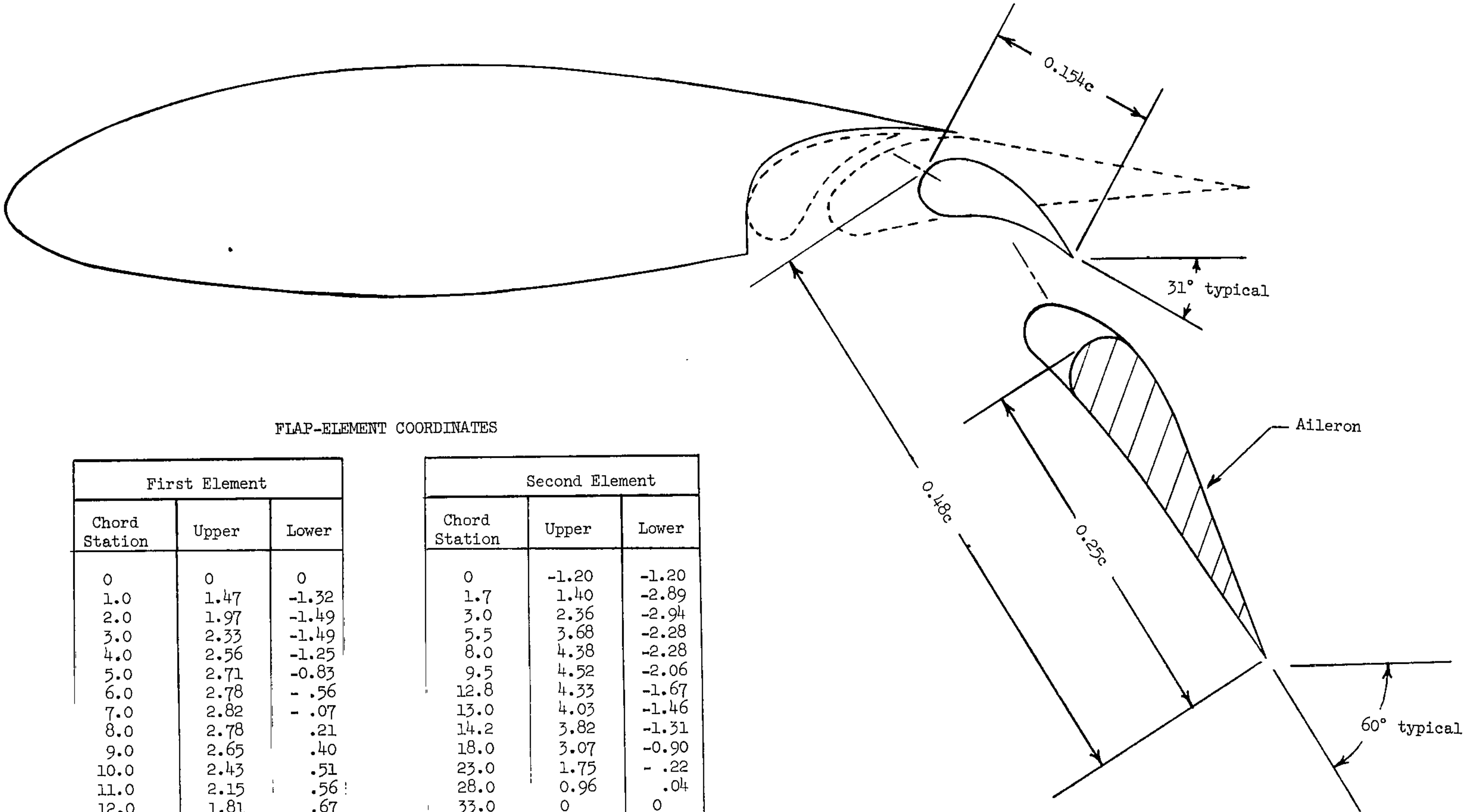
(b) Transition flight in Langley full-scale tunnel. L-63-8475

Figure 1.- Concluded.



(a) Three-view sketch of model. All dimensions are in inches.

Figure 2.- Model sketch.



FLAP-ELEMENT COORDINATES

First Element		
Chord Station	Upper	Lower
0	0	0
1.0	1.47	-1.32
2.0	1.97	-1.49
3.0	2.33	-1.49
4.0	2.56	-1.25
5.0	2.71	-0.83
6.0	2.78	- .56
7.0	2.82	- .07
8.0	2.78	.21
9.0	2.65	.40
10.0	2.43	.51
11.0	2.15	.56
12.0	1.81	.67
13.0	1.35	.42
14.0	.76	.25
15.4	0	0

Second Element		
Chord Station	Upper	Lower
0	-1.20	-1.20
1.7	1.40	-2.89
3.0	2.36	-2.94
5.5	3.68	-2.28
8.0	4.38	-2.28
9.5	4.52	-2.06
12.8	4.33	-1.67
13.0	4.03	-1.46
14.2	3.82	-1.31
18.0	3.07	-0.90
23.0	1.75	- .22
28.0	0.96	.04
33.0	0	0

(b) Typical cross section of wing with double slotted flap showing maximum flap deflection and 0.25c aileron on second flap element. All coordinates in percent wing chord.

Figure 2.- Concluded.

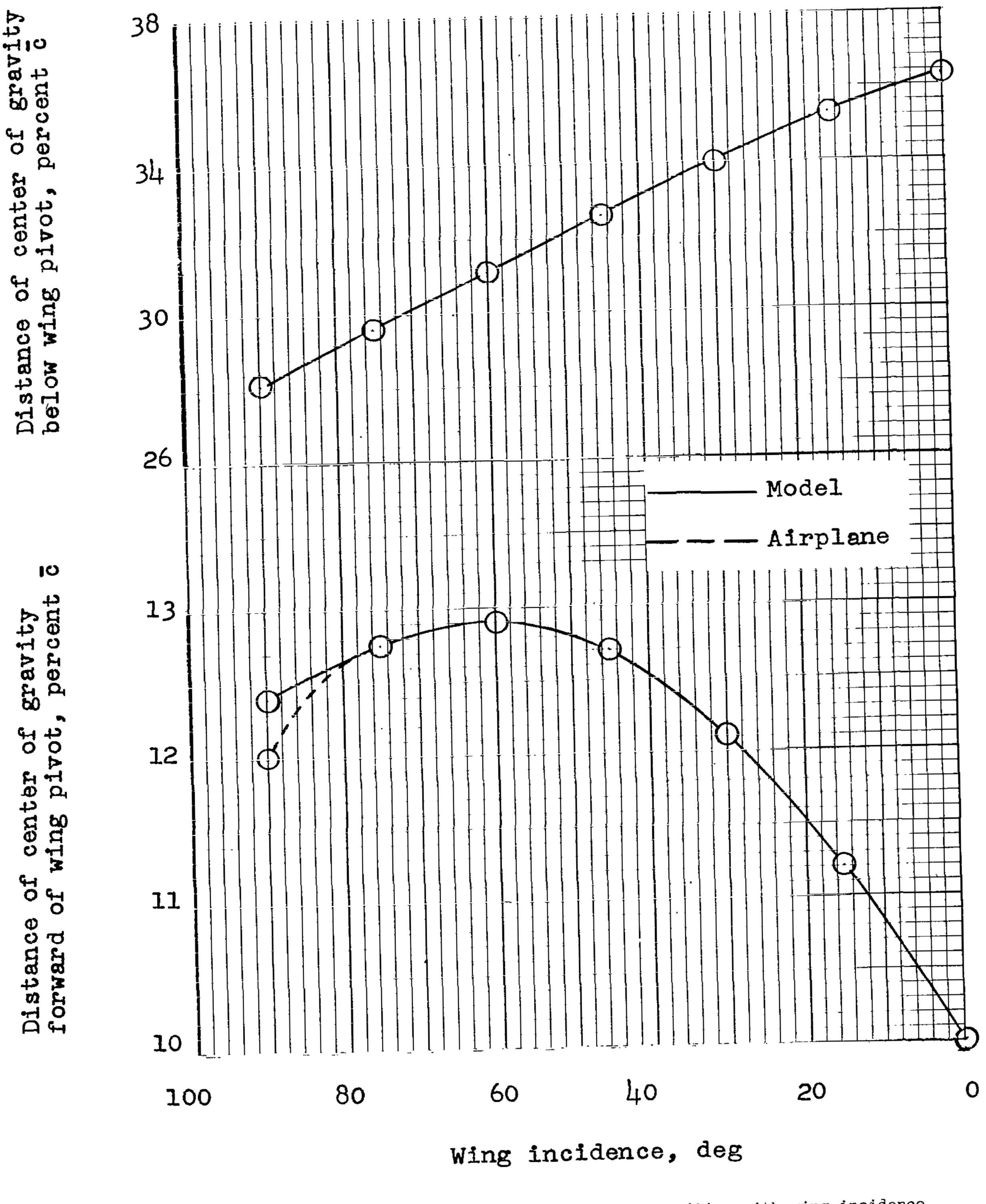


Figure 3.- Variation of model and airplane center-of-gravity position with wing incidence.

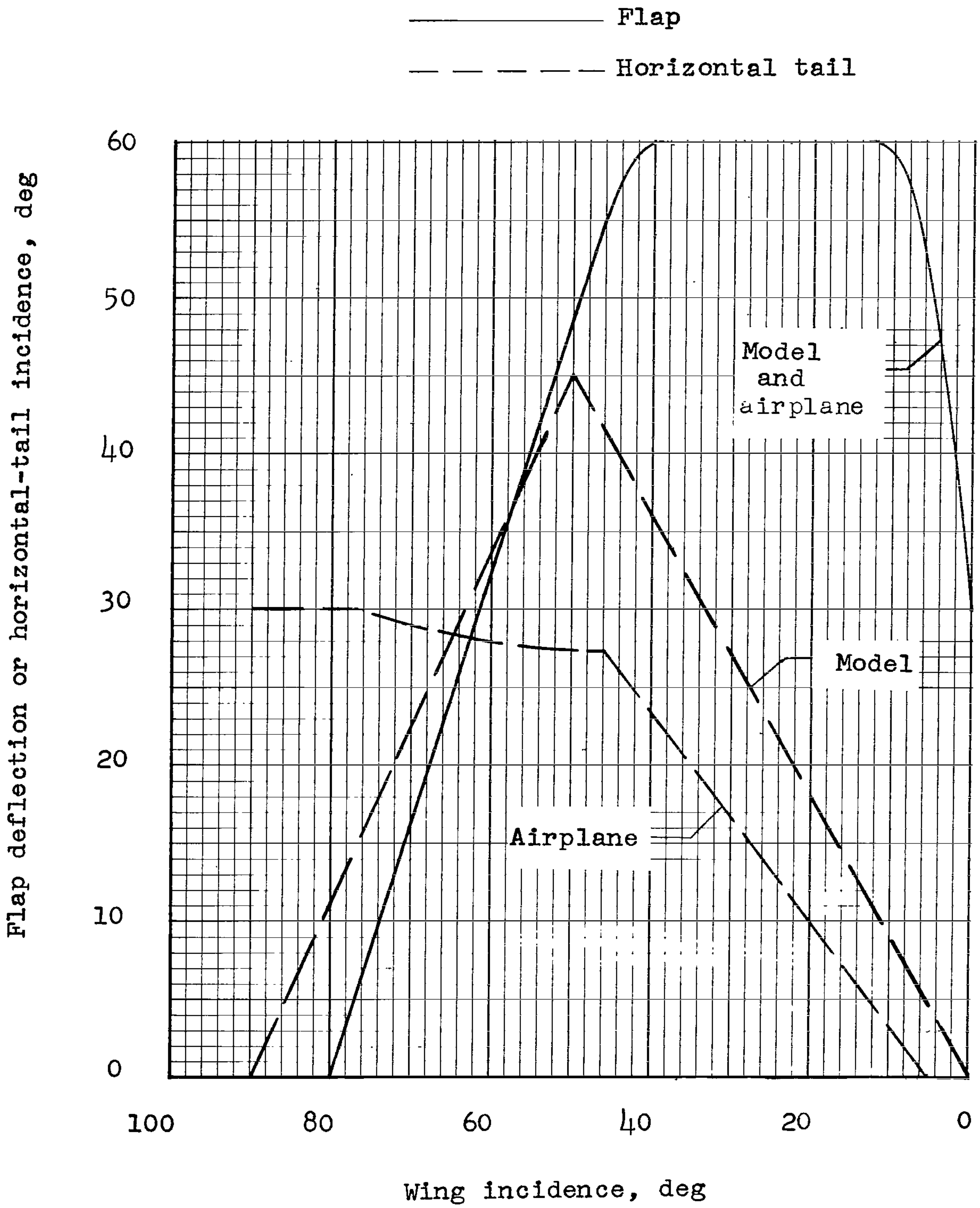
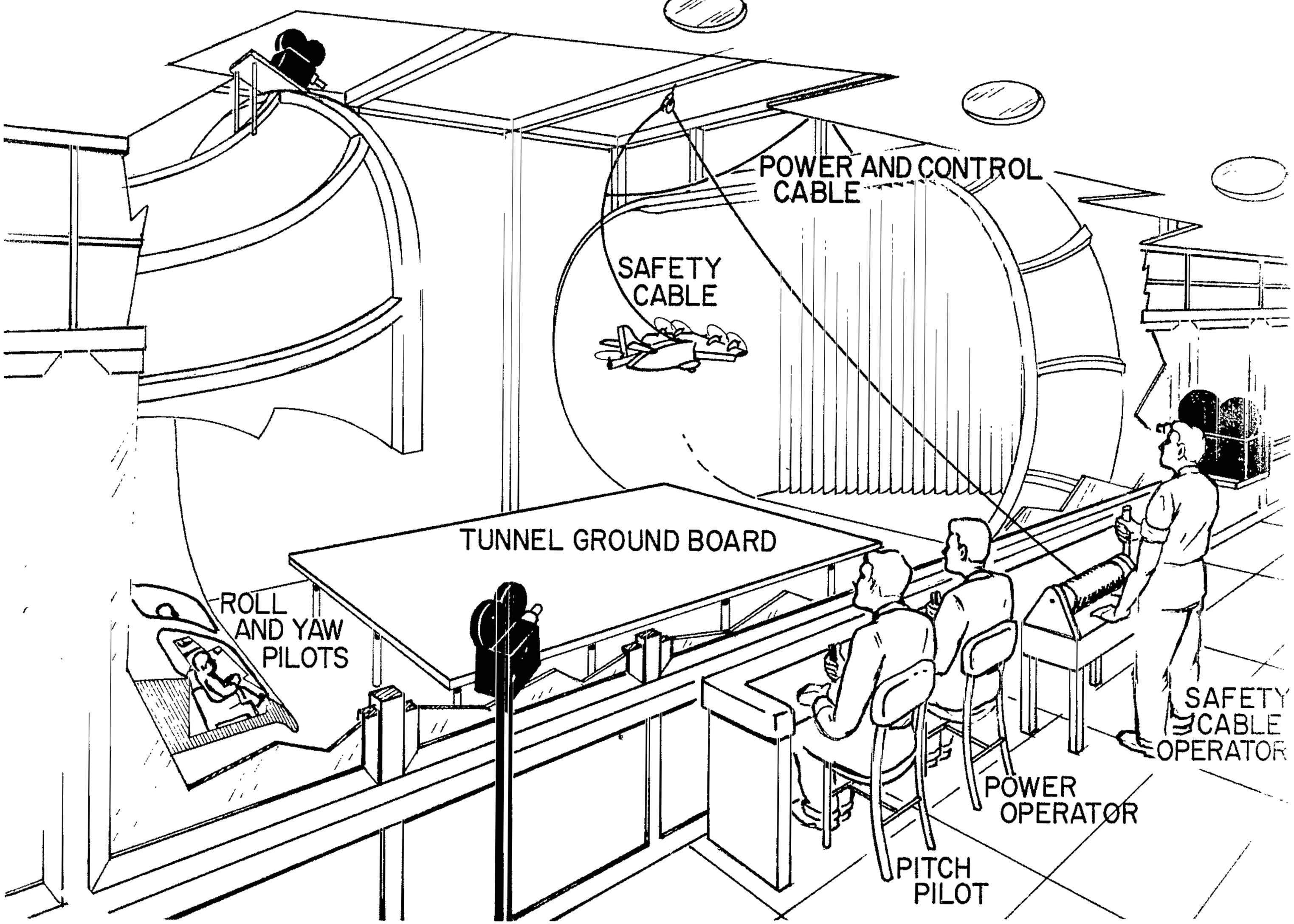


Figure 4.- Variation of flap deflection and horizontal-tail incidence with wing incidence.



L-64-3008
Figure 5.- Sketch of the setup used for flight tests in the Langley full-scale tunnel.

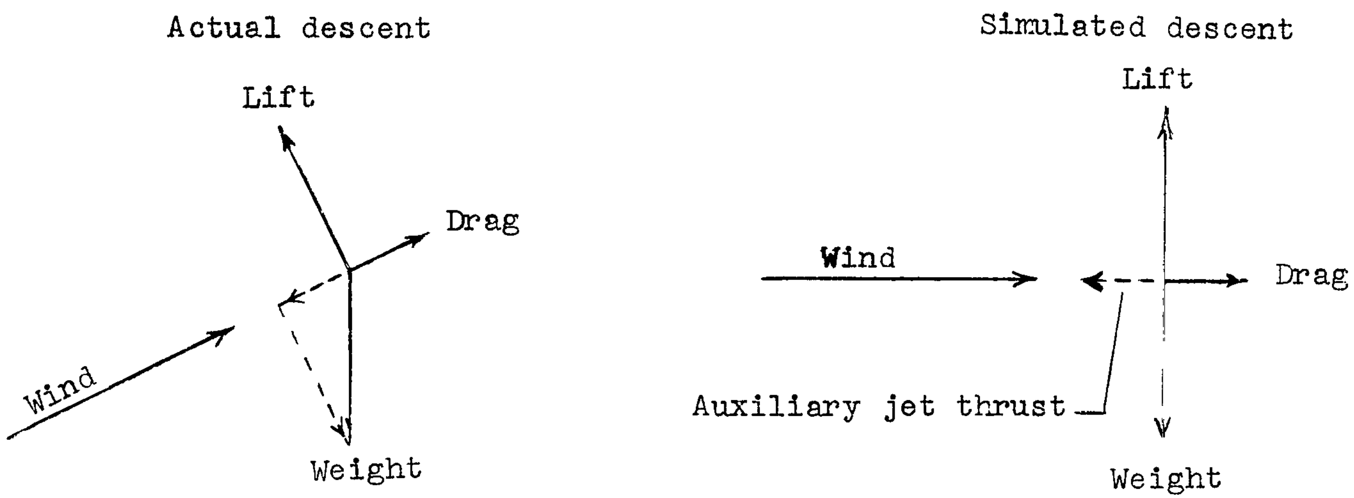


Figure 6.- Balance of forces in descent and simulated descent conditions.

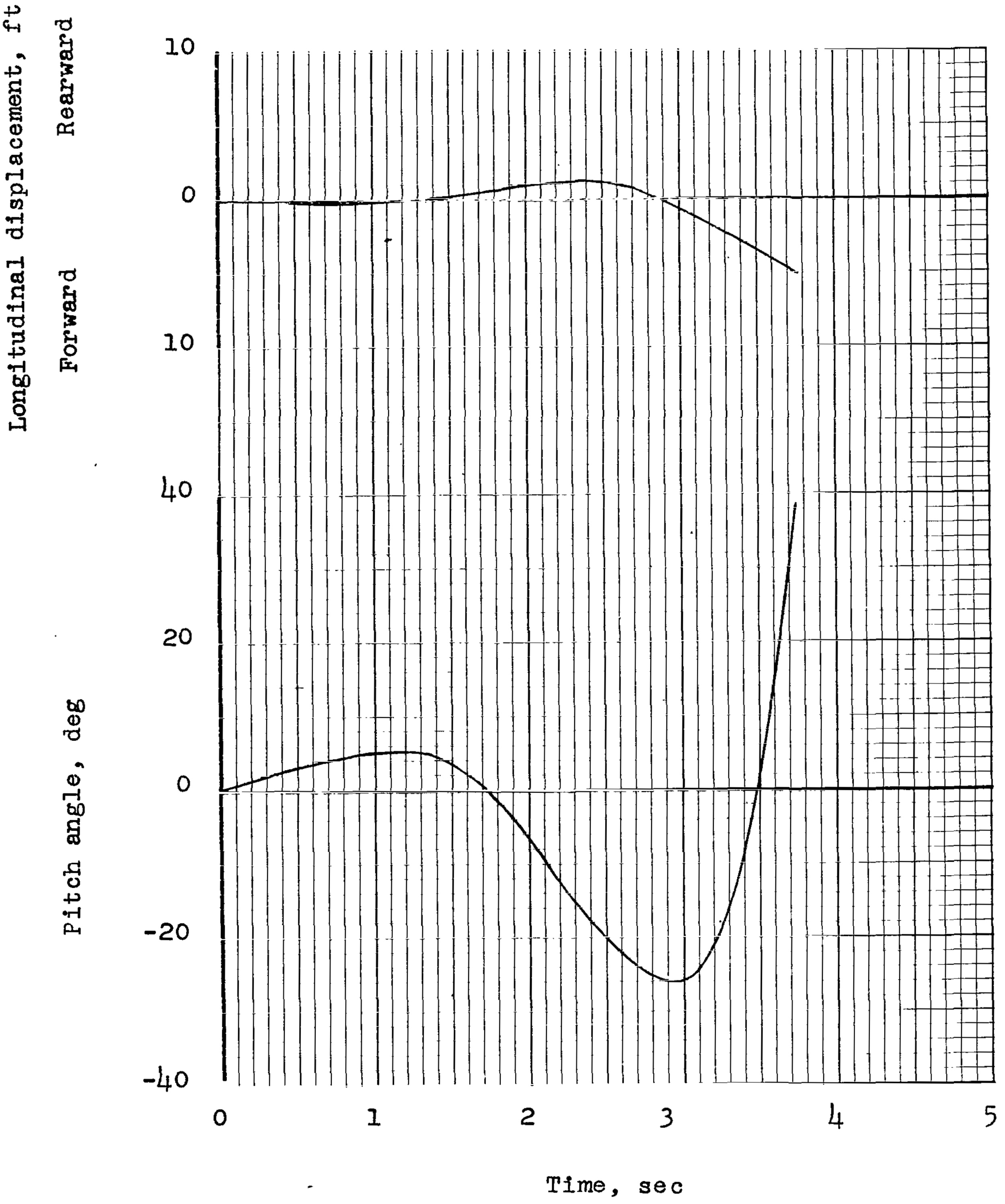


Figure 7.- Control-fixed pitching oscillation of model in hovering flight out of ground effect.

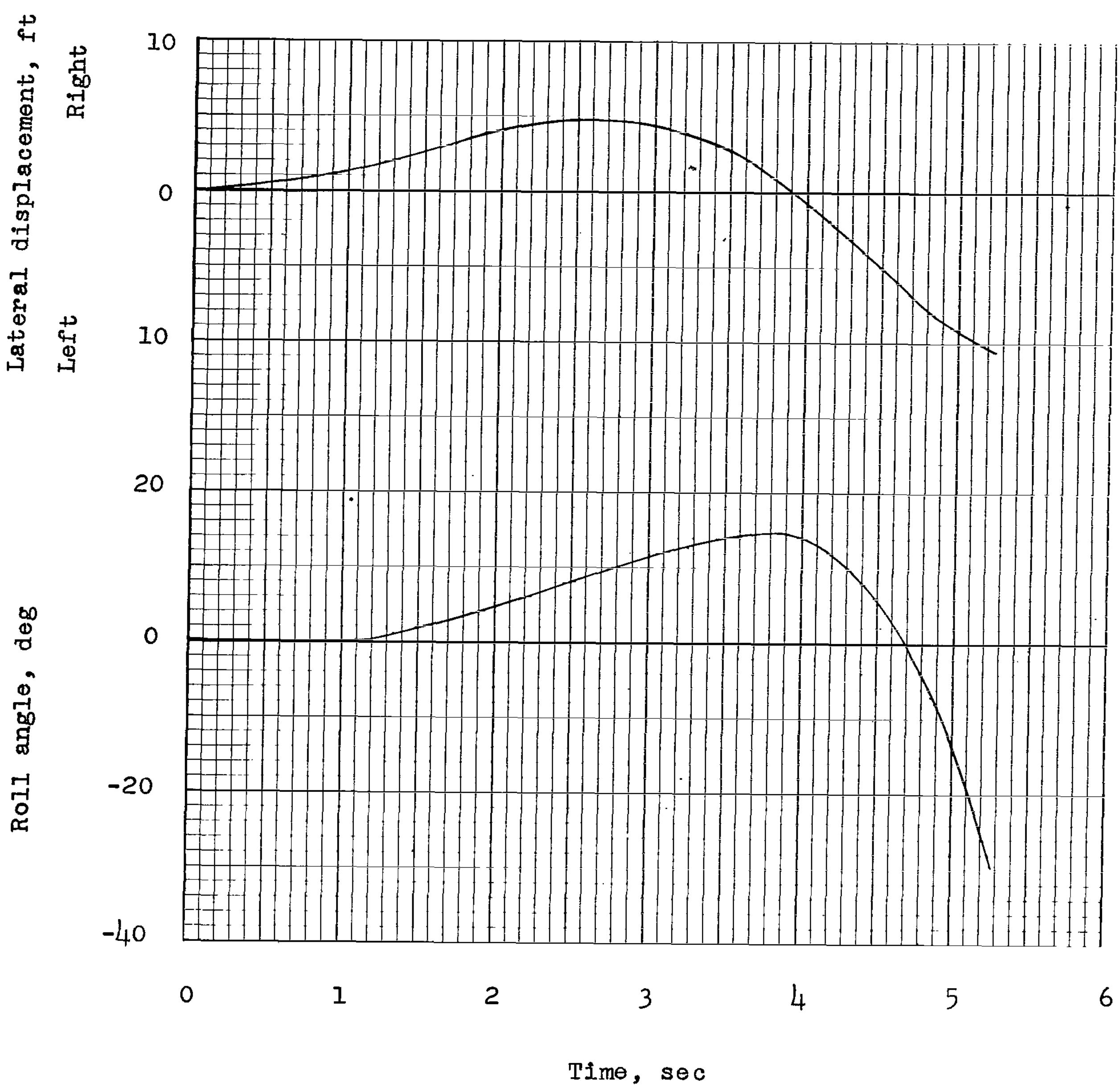


Figure 8.- Control-fixed rolling oscillation of model in hovering flight out of ground effect.

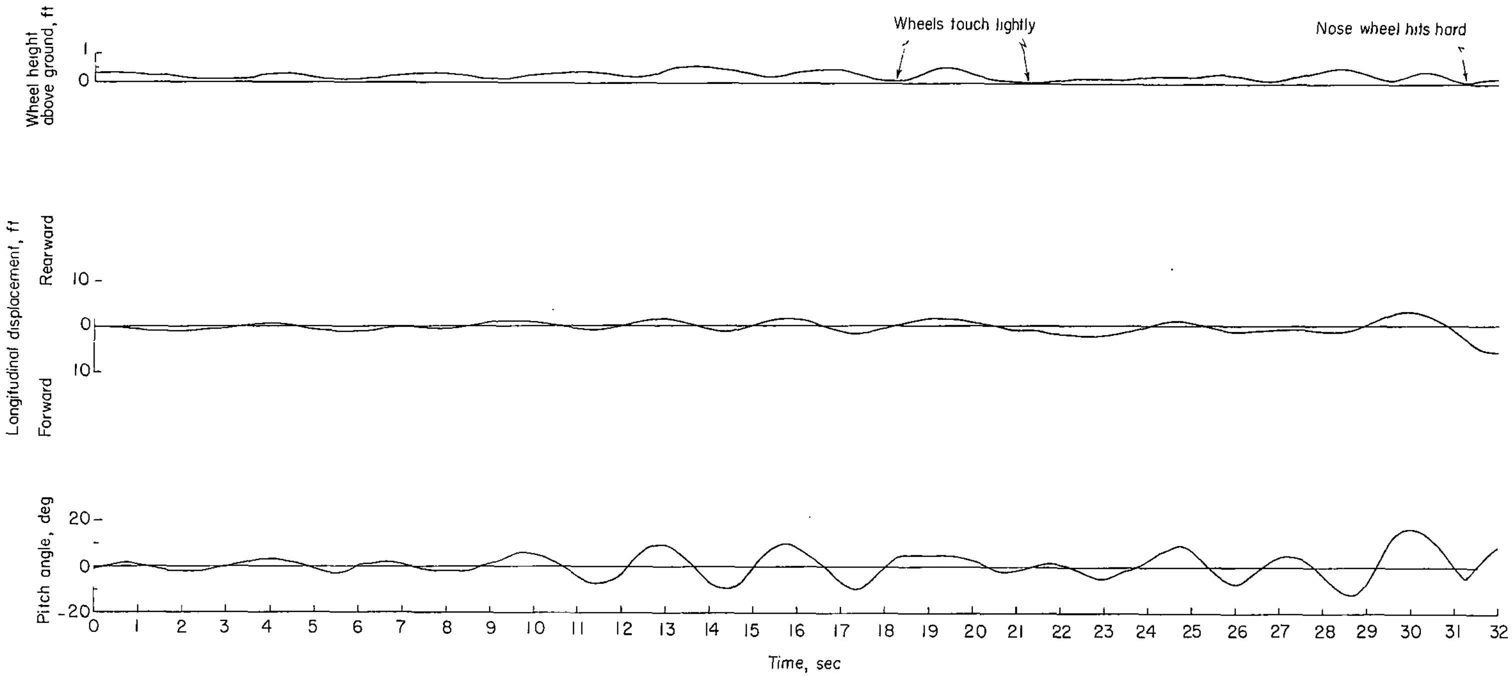


Figure 9.- Control-fixed pitching motion of model during hovering flight in ground effect.

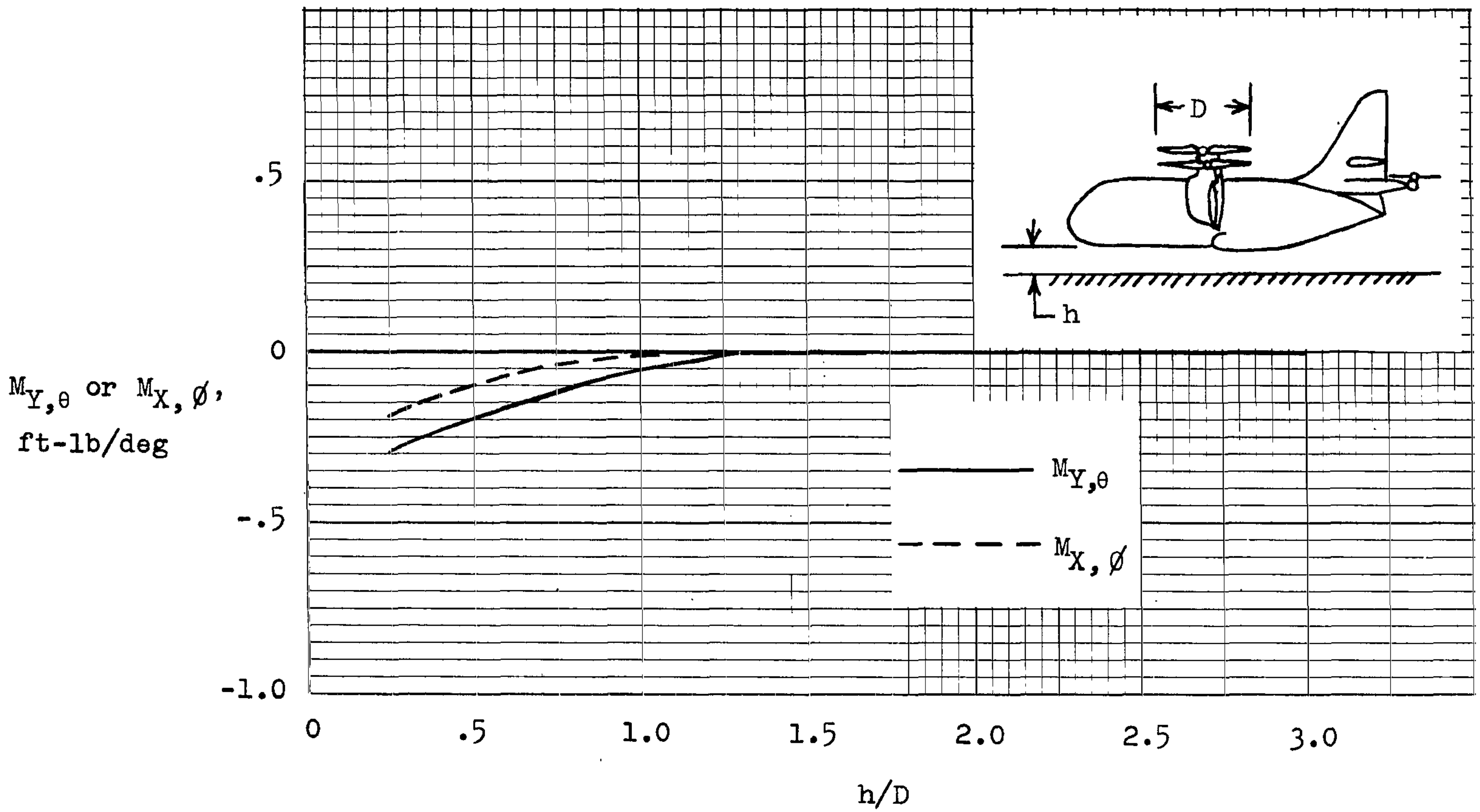


Figure 10.- Effect of ground proximity on static stability. Wheels touch at $h/D \approx 0.24$.

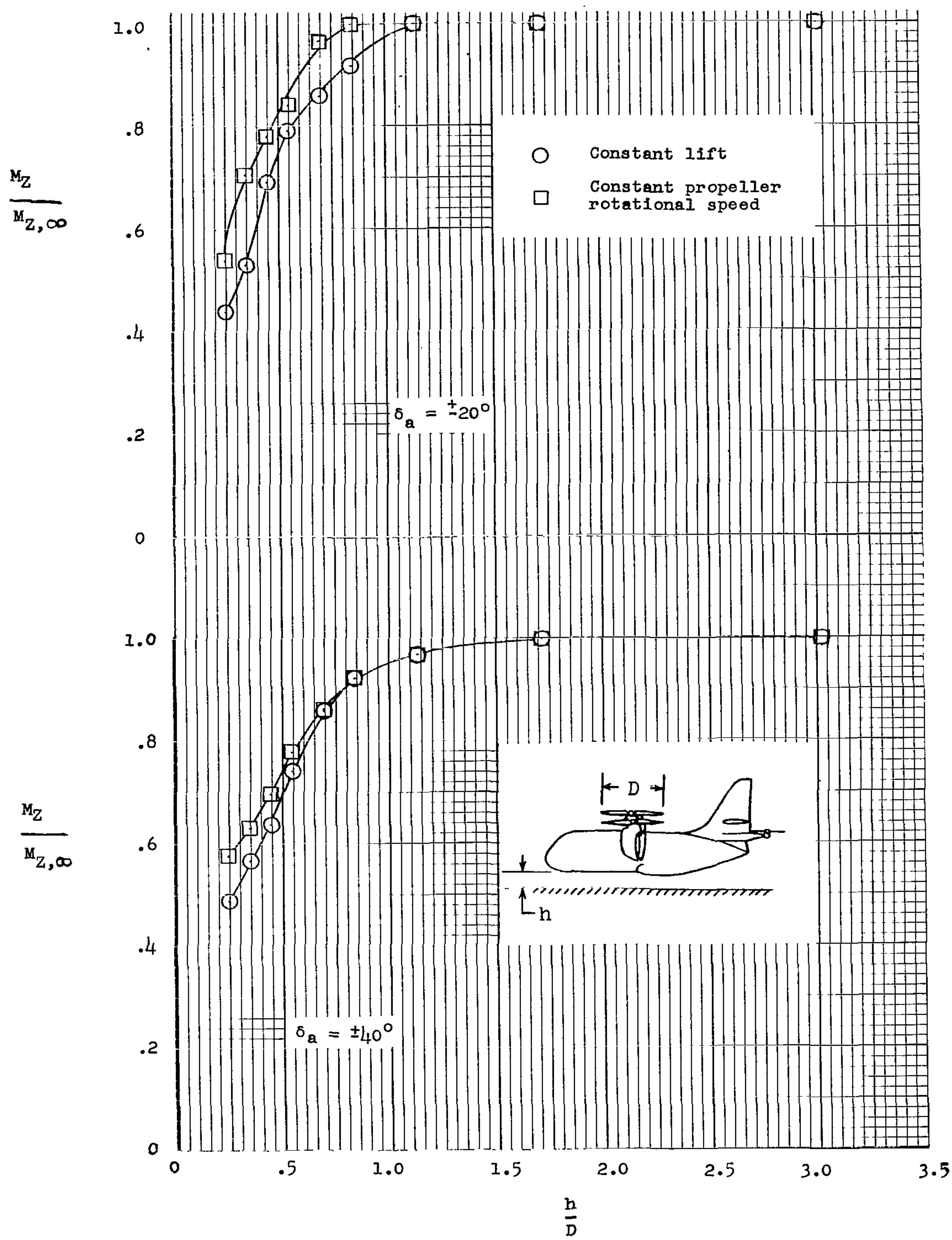


Figure 11.- Effect of ground proximity on aileron yaw control effectiveness. Wheels touch at $h/D \approx 0.24$.

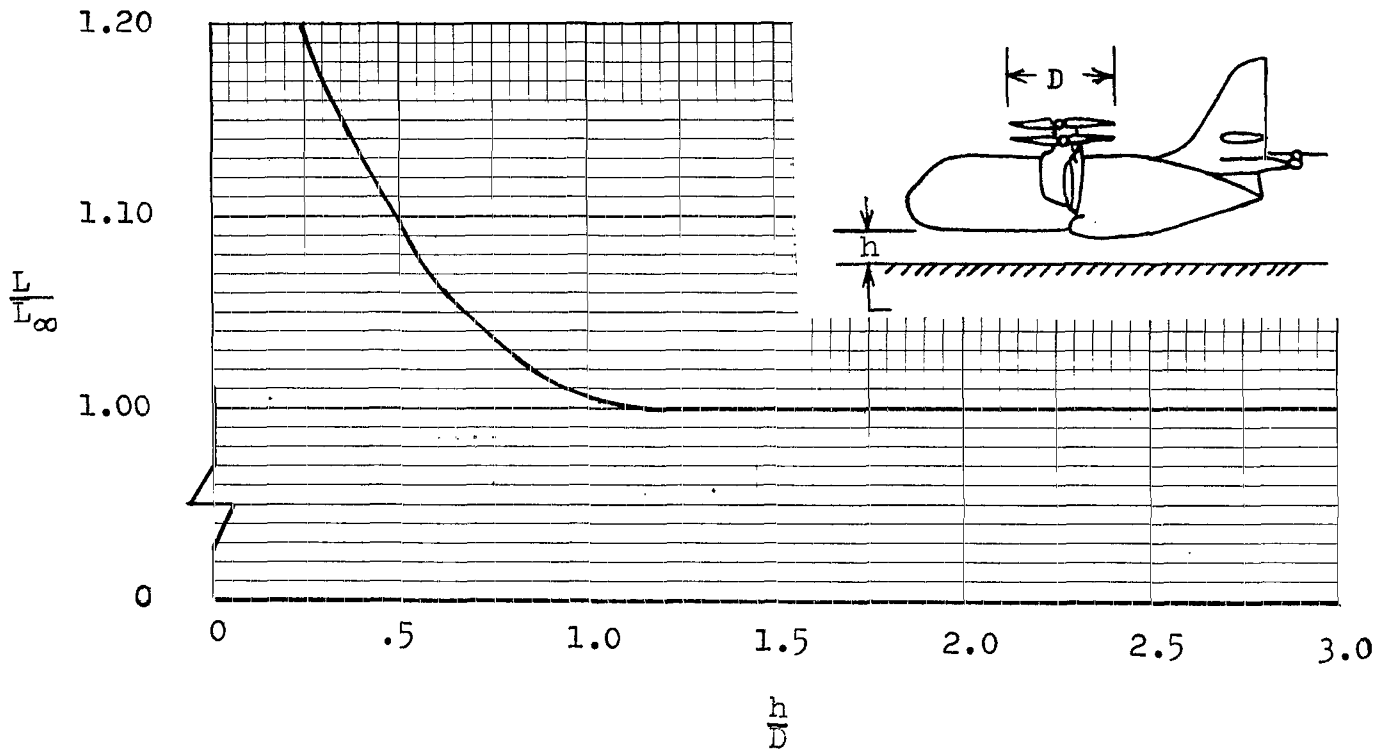


Figure 12.- Effect of ground proximity on lift at constant propeller rotational speed and blade pitch angle. Wheels touch at $h/D \approx 0.24$.

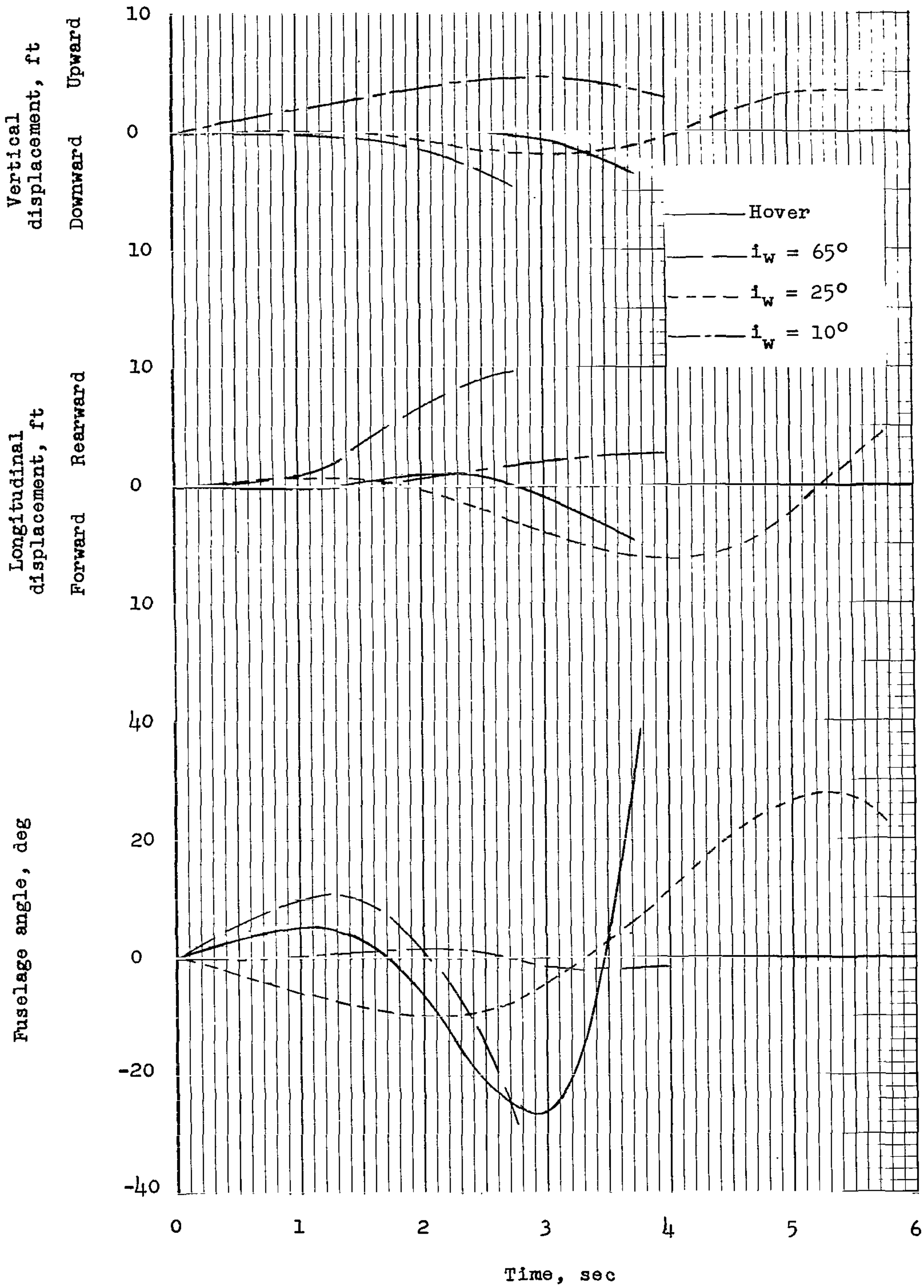


Figure 13.- Control-fixed longitudinal motions of model in transition flight range.

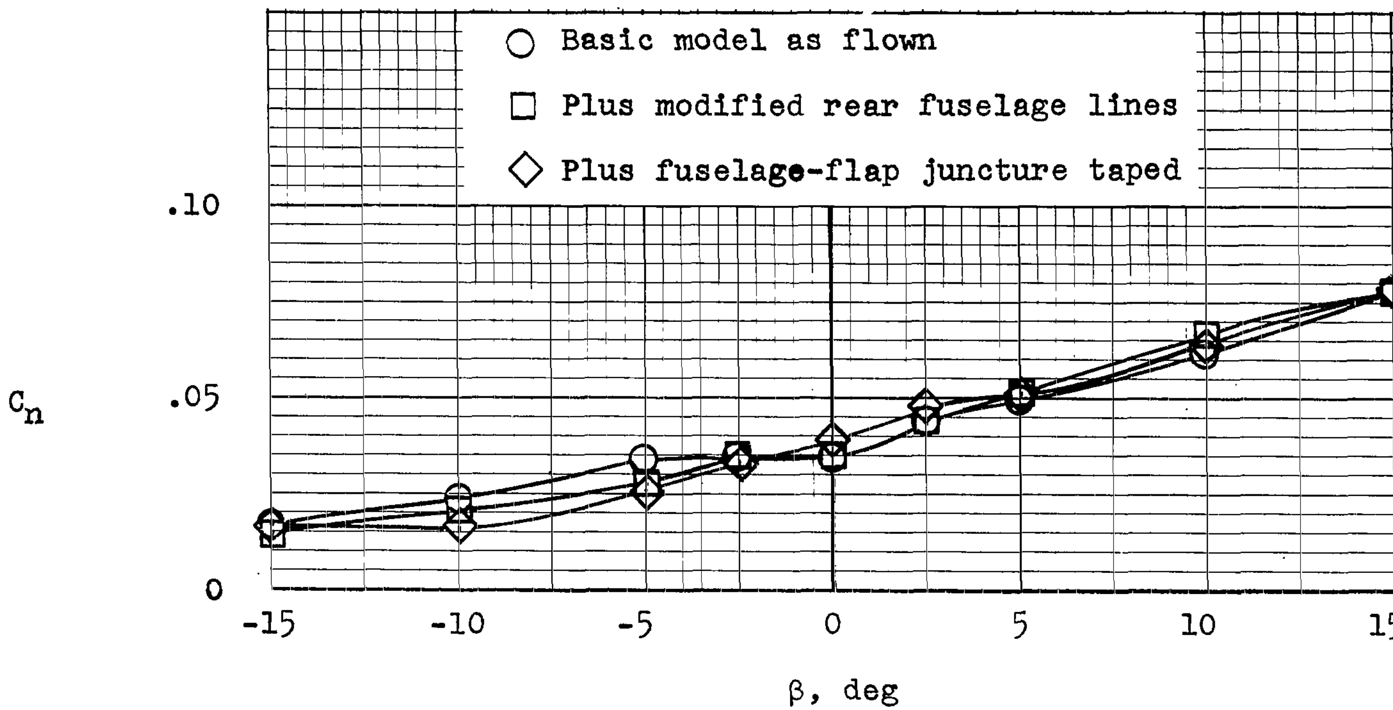


Figure 14.- Effect of some model modifications on variation of yawing-moment coefficient with sideslip. $i_w = 0^{\circ}$ and $\alpha = 0^{\circ}$.

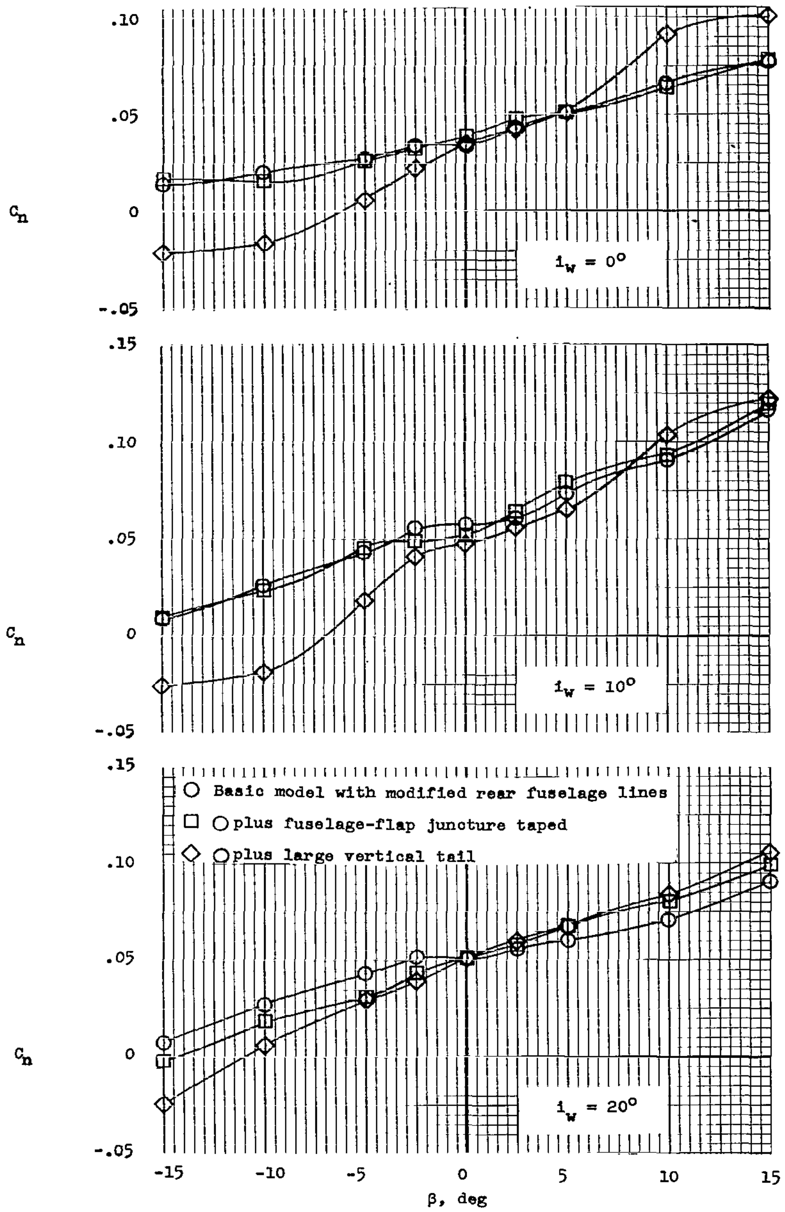


Figure 15.- Effect of a larger vertical tail on variation of yawing-moment coefficient with sideslip.

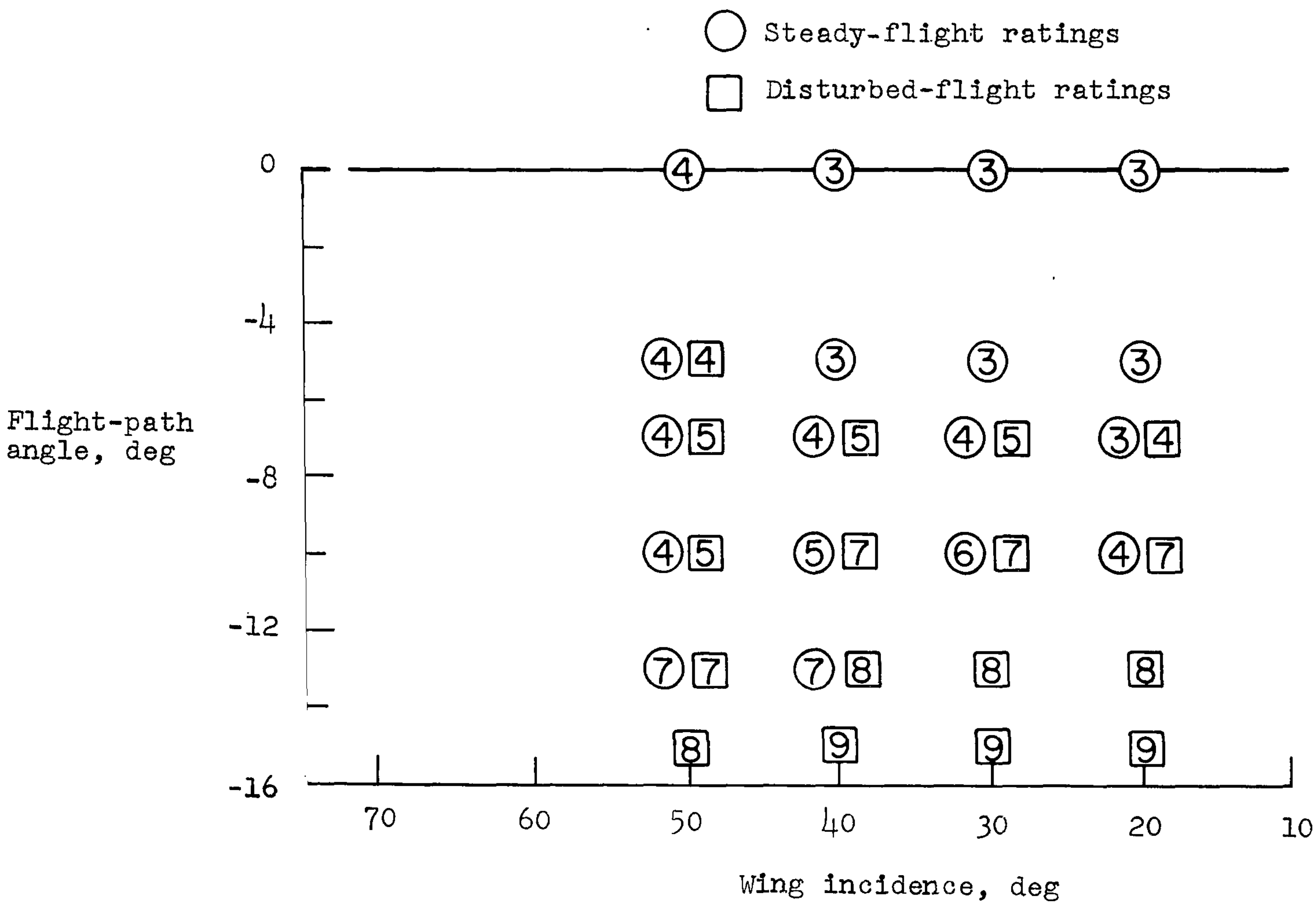


Figure 16.- Pilot ratings obtained in descent tests of a 1/9-scale model of a four-propeller tilt-wing transport.

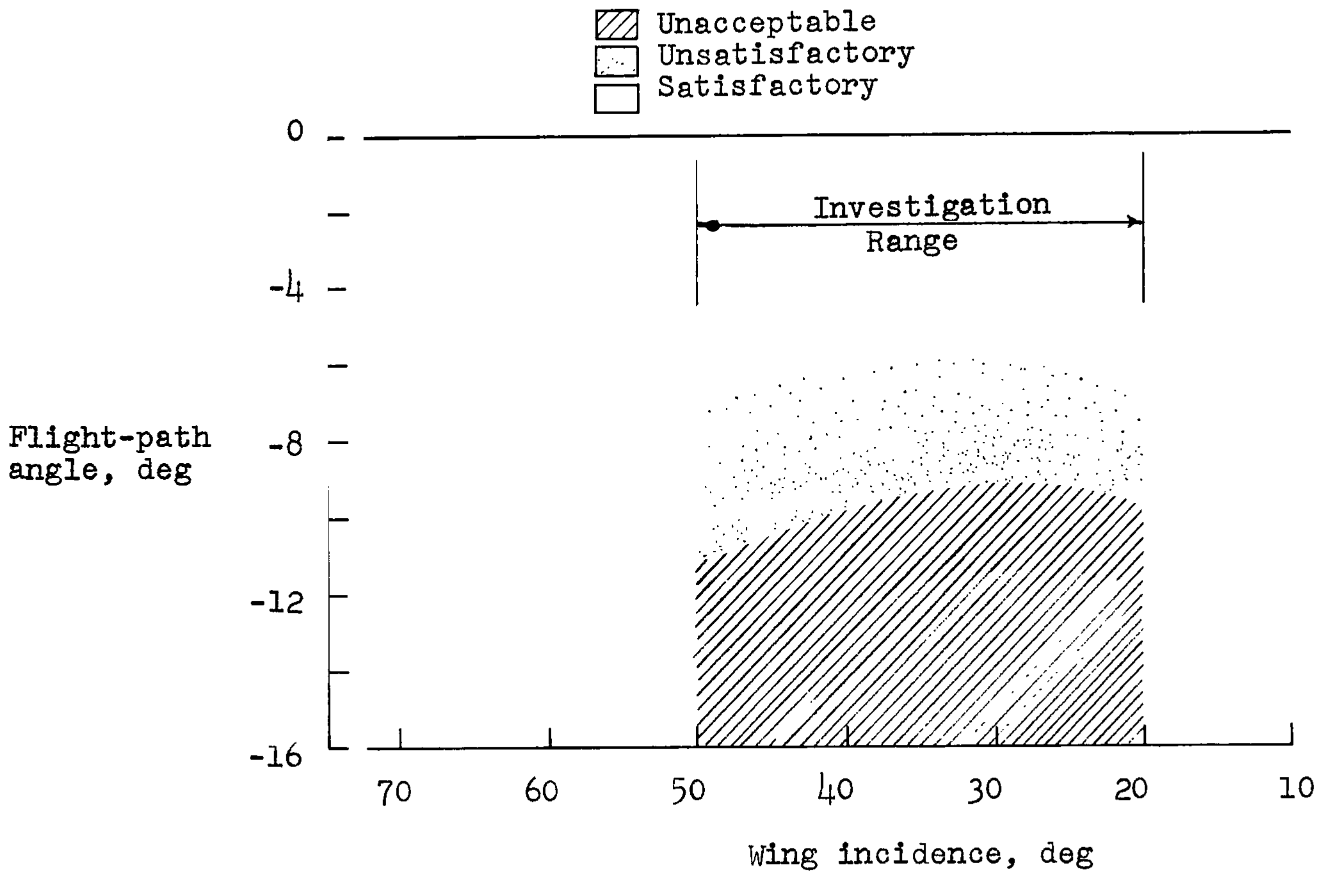


Figure 17.- Descent capability in transition from flight tests of a 1/9-scale model of a four-propeller tilt-wing transport.

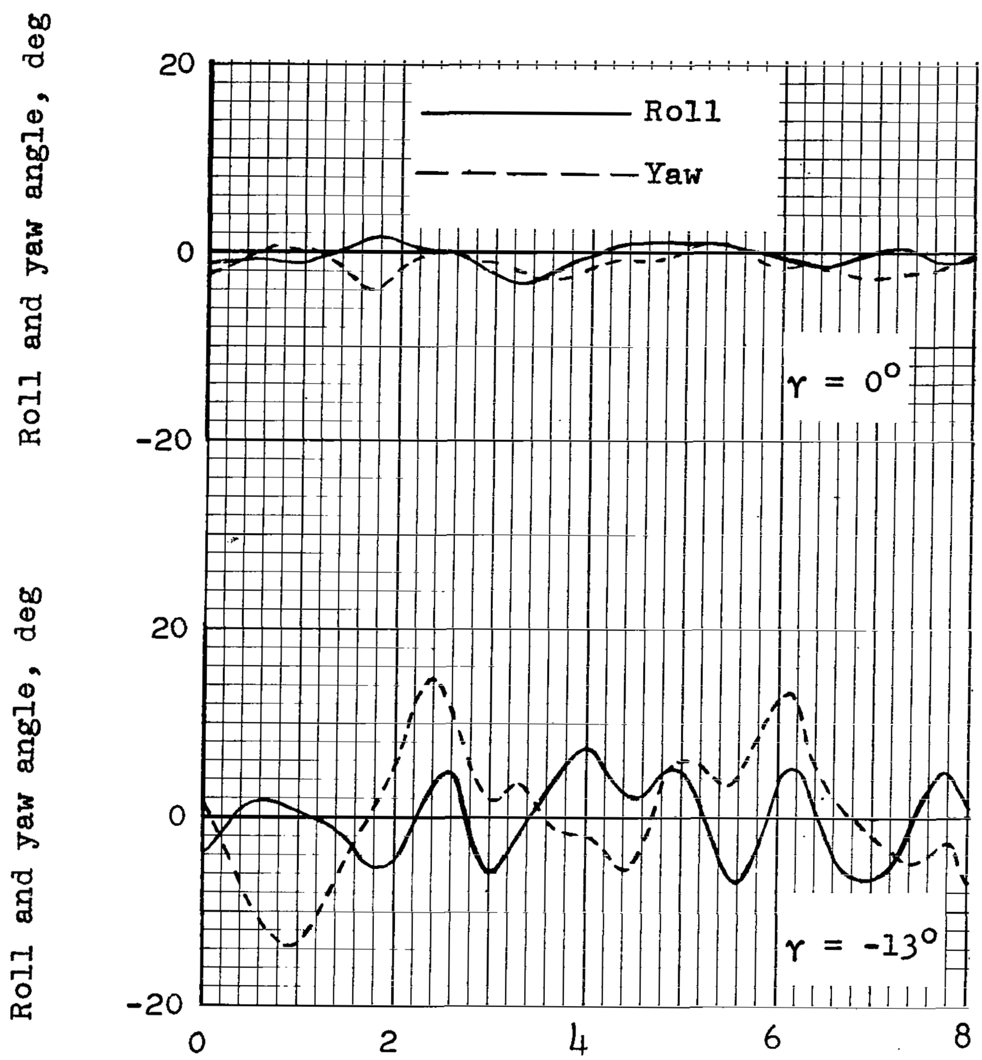


Figure 18.- Lateral motions of model while attempting smooth flight. $i_w = 30^{\circ}$.

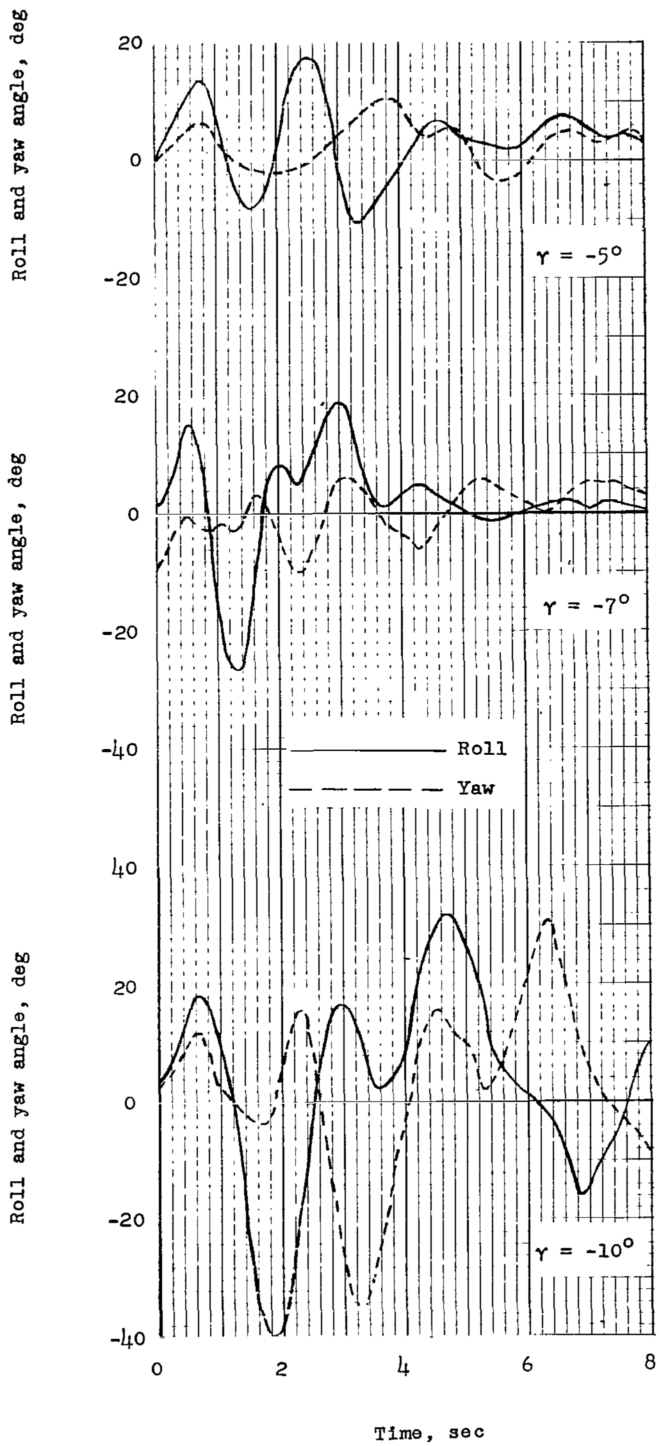


Figure 19.- Lateral motions of model after a deliberate disturbance. $i_w = 30^{\circ}$.

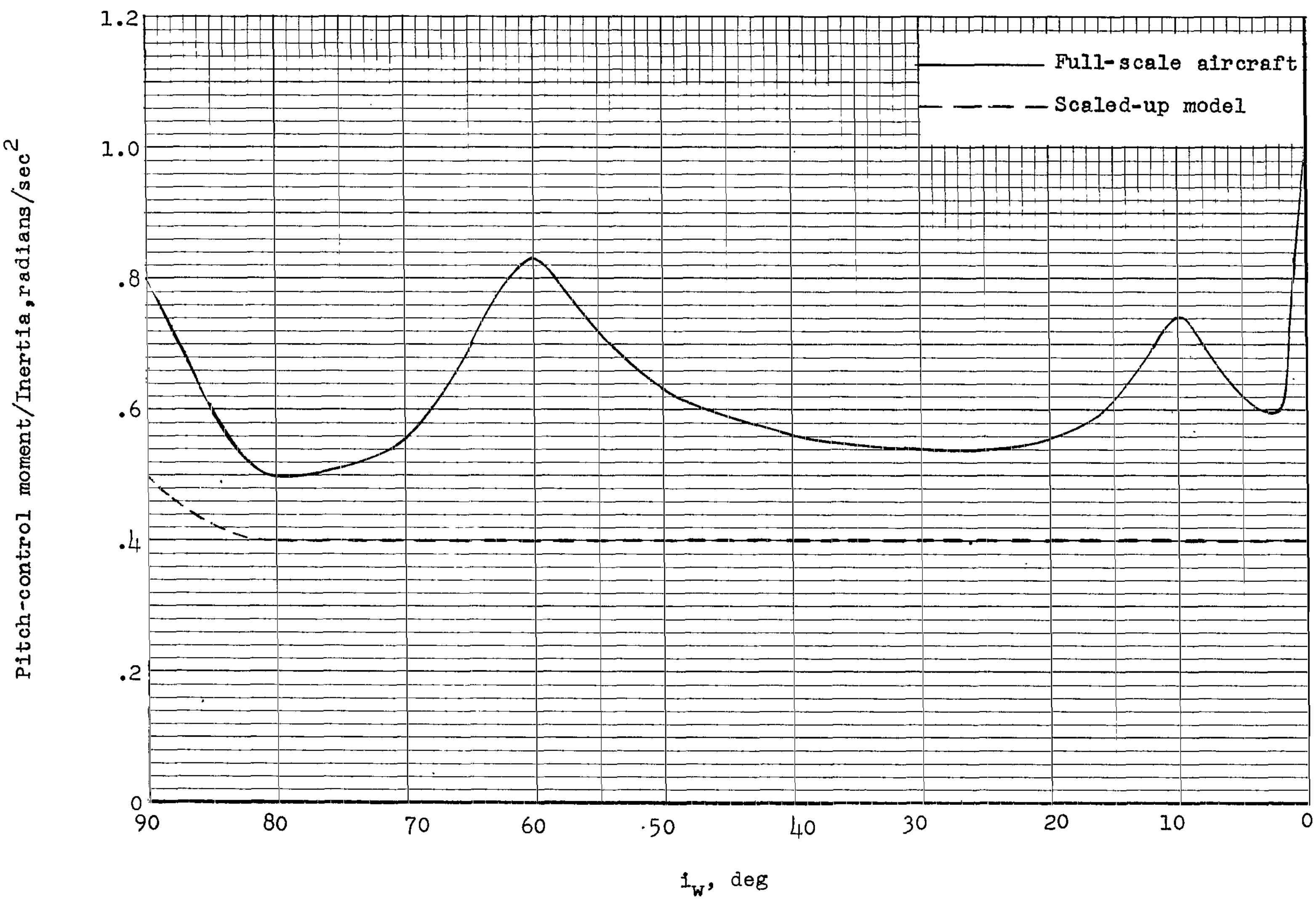


Figure 20.- Longitudinal control power available in excess of that required for trim on the full airplane compared with scaled-up model control power required in tests.

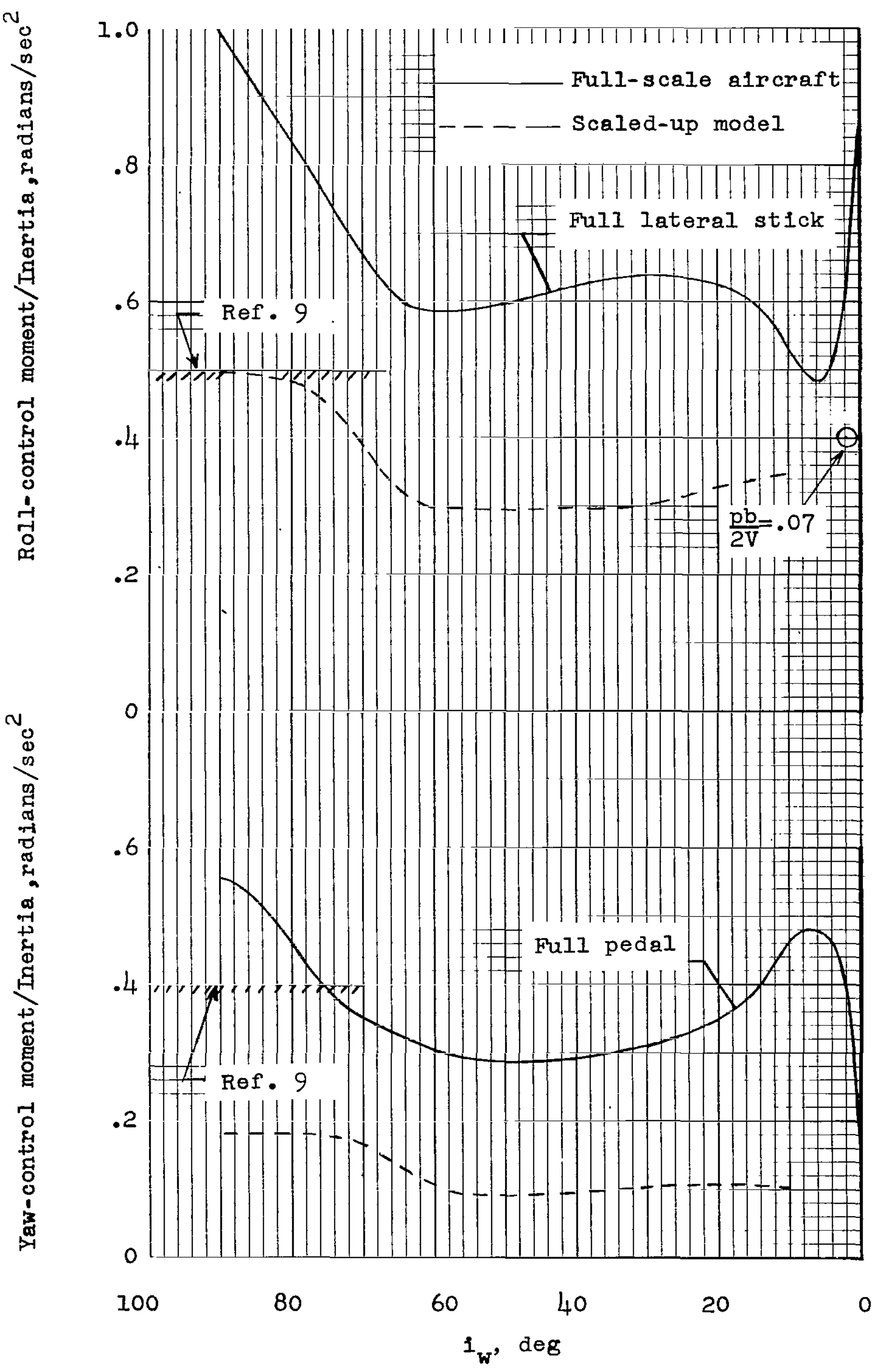


Figure 21.- Lateral control power available on airplane compared with scaled-up model control power required in tests.

NASA TN D-2443
National Aeronautics and Space Administration.
FLIGHT INVESTIGATION OF STABILITY AND CONTROL CHARACTERISTICS OF A 1/9-SCALE MODEL OF A FOUR-PROPELLER TILT-WING V/STOL TRANSPORT. William A. Newsom, Jr., and Robert H. Kirby. September 1964. 41p. OTS price, $1.25. (Film Supplement L-835 available on request.)
(NASA TECHNICAL NOTE D-2443)

The tests included hovering flights in and out of ground effect and level flight and descent tests in the transition speed range. In each flight condition, the stability, controllability, and general flight behavior of the model were investigated. Even though the model was statically and dynamically unstable for many of the flight-test conditions, it could generally be controlled and maneuvered easily. The descent tests showed that the configuration had at least a 6° descent capability with no

(over)

I. Newsom, William A., Jr.
II. Kirby, Robert H.
III. NASA TN D-2443

NASA

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