NACA

RESEARCH MEMORANDUM

EFFECT OF THE PROXIMITY OF THE GROUND ON THE STABILITY AND CONTROL CHARACTERISTICS OF A VERTICALLY RISING AIRPLANE MODEL IN THE HOVERING CONDITION

By Charles C. Smith, Jr., Powell M. Lovell, Jr., and William R. Bates

Langley Aeronautical Laboratory
Langley Field, Va.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON
September 19, 1951

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

EFFECT OF THE PROXIMITY OF THE GROUND ON THE STABILITY AND CONTROL CHARACTERISTICS OF A VERTICALLY RISING AIRPLANE MODEL IN THE HOVERING CONDITION

By Charles C. Smith, Jr., Powell M. Lovell, Jr.,
and William R. Bates

SUMMARY

An investigation has been made to determine the effect of the proximity of the ground on the stability and control characteristics of a vertically rising airplane model in the hovering condition. The investigation included flight tests to determine the dynamic behavior of the model in take-offs and landings and when it was hovering near the ground. Force tests were also included to determine the change in the vertical-tail yawing moments with control deflection and with angle of yaw for various heights above the ground. Dynamic-pressure surveys were also made for various longitudinal and radial stations behind the propeller. The model was essentially a conventional airplane model having an eight-blade dual-rotating propeller in a tractor arrangement, a rectangular wing and a cruciform tail with rectangular surfaces, and was controlled by conventional airplane-type control surfaces operating in the slipstream.

Flight tests showed that the model became somewhat more difficult to fly as the tail surfaces neared the ground. Take-offs and landings with the model in a tail-down attitude were not particularly difficult to perform, however, because the model passed quickly through the range of heights for which this ground effect occurred. The results of the force tests indicated that the reason for the adverse effect of the ground on the flight behavior of the model was a decrease in the effectiveness of the tail controls with a decrease in height above the ground. This reduction in control effectiveness resulted from the reduction in dynamic pressure of the slipstream at the tail as the model approached the ground. The force-test results indicated that the model would have neutral stability of attitude when hovering near the ground just as it would have at a considerable height above the ground. For the static thrust condition, large random variations in rolling, yawing, and pitching moments were caused by fluctuations of the direct propeller moments and by fluctuations of the fuselage and tail moments caused by the slipstream.

[redacted]

INTRODUCTION

An investigation is being conducted to determine the stability and control characteristics in hovering flight of the vertically rising airplane model shown in the sketch of figure 1. This model is essentially a conventional airplane model with a large dual-rotating propeller and sufficient power to take-off and land vertically. It has a rectangular wing and a cruciform tail with rectangular tail surfaces and is controlled by conventional airplane-type control surfaces operating in the propeller slipstream.

The results of the first part of this investigation which consisted of hovering flight tests of the model in still air at a considerable height above the ground were reported in reference 1. The investigation has been extended to include a determination of the effect of the proximity of the ground on both the dynamic and static stability and control characteristics. This study did not include consideration of the effects of flying near a vertical obstruction or of irregularities in the surface of the ground. Flight tests were made to determine the dynamic behavior of the model in take-offs and landings and when it was hovering near the ground. Force tests were also made to determine the change in the vertical-tail yawing moments with control deflection and angle of yaw for various heights above the ground. The investigation also included dynamic-pressure surveys of the slipstream in the vicinity of the vertical tail and at various radial and longitudinal stations behind the propeller.

SYMBOLS

ρ density of air, slugs per cubic foot

V slipstream velocity, feet per second

q dynamic pressure, pounds per square foot $\left(\rho V^2/2\right)$

δ rudder deflection, degrees

N yawing moment, foot-pounds

h distance of ground board from trailing edge of tail surface, feet

N_δ variation of yawing moment with control deflection with the ground board in place $(\partial N/\partial \delta)$

N_{δ_∞} variation of yawing moment with control deflection with ground board removed $\left(\frac{\partial N}{\partial \delta}\right)_{D=\infty}$

ψ angle of yaw about an axis normal to the plane of the wing, degrees

c.g. center of gravity

D propeller diameter, feet

MODEL

The model used in the present investigation was previously used in the investigation described in reference 1. It was essentially a conventional airplane model having an eight-blade dual-rotating propeller in a tractor arrangement, a rectangular wing, and a cruciform tail with rectangular surfaces. A landing gear that supported the model in a tail-down position was added to the model for the flight tests. A sketch of the model with this landing gear installed is shown in figure 1. The geometric characteristics of the model are presented in table I. It may be noted that some of the model dimensions presented in figure 1 and table I are different from those presented in reference 1. The values in the present paper are the correct values. The model was powered by a 5-horsepower variable-frequency electric motor, the speed of which was changed to vary the thrust.

The model was controlled by conventional control surfaces operating in the propeller slipstream. The ailerons were controlled automatically by a displacement-type autopilot which kept the model oriented in roll with respect to the pilot's position. The model was maneuvered by the elevator and rudder controls which were remotely controlled by the pilot. The control surfaces were actuated by flicker-type (full-on, full-off) pneumatic servos which were controlled by electric solenoids.

The power for the motor and electric solenoids and the air for the servomechanisms were supplied through wires and plastic tubes which trailed from the tail of the model.

APPARATUS AND TESTS

Force Tests

Moment fluctuations caused by propeller.- Preliminary force tests of the vertically rising airplane model in the static-thrust condition on the six-component strain-gage balance of the Langley free-flight tunnel showed there were large random fluctuations in the rolling, pitching, and yawing moments. The variations in the moments were so great that they tended to obscure the magnitude of the control moments and thereby made direct determination of the control effectiveness impossible. An investigation was therefore made to determine the cause of the moment fluctuations. A run with only one of the propellers revealed that these fluctuations were not peculiar to dual-rotating propellers but also occurred for single propellers; so for convenience in testing, all subsequent tests made to study the moment fluctuations were made with a single propeller. In order to determine whether the slipstream or direct propeller forces were the cause of these fluctuations the blades and direction of rotation were reversed so that negative thrust was produced and the slipstream did not flow over the fuselage. With the propeller operating in this manner, only a slight reduction in the fluctuations was noted. This reduction indicated that the fluctuations were caused mainly by the propeller moments and only to a minor extent by the slipstream over the fuselage, tails, and wings. The results of several runs with the original propeller, which had twisted blades, indicated that the fluctuations in propeller moment were approximately proportional to the thrust but that there was some fluctuation even when the thrust was zero. Since there is a radial thrust distribution on a twisted blade when producing zero net thrust, a propeller with untwisted blades was tested in order to eliminate any possible fluctuations in the induced drag. With the untwisted blades set to give zero thrust, no fluctuations in propeller moments were noted. For forward and lateral speed conditions there were no fluctuations for either the propeller with the twisted or the untwisted blades. Forward speeds as low as 2 miles per hour or lateral speeds as low as 4 miles per hour were sufficient to eliminate the fluctuations.

The fact that fences installed on the blades to eliminate radial drift of the boundary layer failed to help gave an indication that the fluctuations were not related to the profile characteristics of the blades but to the induced flow. Smoke flow tests showed that there were fluctuations in the induced flow particularly near the periphery of the propeller disk. Increasing the Reynolds number of the propeller-blade elements about 7 times by using a larger propeller (tip Reynold number $\approx$ 1,400,000) did not eliminate the propeller moment fluctuations. These tests do not necessarily prove, however, that these moment fluctuations will occur on full-scale propellers.

Test setup.- The results of the preliminary study of moment fluctuations caused by the propeller showed the necessity for a test setup that would prevent fluctuations of the direct propeller moments and the tail and fuselage moments caused by the slipstream from obscuring the magnitude of the control moments. A sketch of the test setup used to minimize the effects of the propeller moment and slipstream fluctuations is shown in figure 2. The propeller of the original model was reversed so that the slipstream went over the dummy fuselage and vertical tail. A boom supporting a vertical-tail surface was mounted on a strain-gage moment balance. A dummy fuselage surrounding the boom was mounted directly to the balance support so that the fuselage moment did not register on the balance. In order to eliminate any possibility of interference of the wake of the strut on the vertical tail, only the top vertical tail was used. This tail projected through a slot in the fuselage so that the fuselage and tail did not touch. This test setup prevented fluctuations of the direct propeller moments and the fuselage moments caused by the slipstream from obscuring the control moments but some fluctuations in the yawing moments were present because of the effects of the slipstream fluctuations on the tail. The ground board used in the tests was an 8- by 6-foot plywood board mounted behind the model as indicated in figure 2.

Test conditions.- All force tests were made at a propeller speed of 2000 revolutions per minute which gave a static thrust of about 10.7 pounds. Force tests to determine the effectiveness of the rudder were made for rudder deflections from 20° to -20° with the ground board perpendicular to the body axis and at distances ranging from 0.25- to 3-propeller diameters behind the trailing edge of the tail and with the ground board removed. Force tests to determine the variation of vertical-tail yawing moment with angle of yaw were made with the ground board 0.5-propeller diameter behind the trailing edge of the tail for angles of yaw from 20° to -20° for rudder deflections from 20° to -20°. Because of the symmetry of the tail surfaces, separate tests were not made to determine the elevator effectiveness and stability in pitch of the model.

Dynamic-Pressure Survey

For the dynamic-pressure survey the model with the vertical tails removed was mounted on a stand in front of the ground board. A pitot rake having sixteen tubes (eight total-head and eight static-head tubes) spaced alternately 1/2 inch apart was used in conjunction with eight U-tube alcohol manometers to measure the dynamic pressure. A preliminary test showed that static pressure was essentially constant across the slipstream. For simplicity, therefore, the dynamic pressure was measured directly by connecting adjacent static- and total-head tubes to a single manometer. The pitot rake was suspended perpendicular to the body axis with the first tube (a total-head tube) 3/16 inch above the fuselage.

Dynamic-pressure measurements were made at the 0.25- and 0.75-chord stations of the vertical tail with the ground board 0.5 propeller diameter behind the trailing edge of the tail and with the ground board removed. The power condition used in the flow survey was the same as that used in the force tests. In order to obtain a general survey of the slipstream for the static-thrust condition, additional dynamic-pressure measurements were also made in the plane of the vertical tail with the rake at four longitudinal stations (0, 19, 35, and 51 in. behind the plane of the propeller) with the ground board removed.

Flight Tests

The flight tests were made by the trailing-flight-cable technique inside a large building where the air was free from outside disturbances. A description of the test apparatus and of the test technique for hovering flight is given in reference 1.

Flight tests consisted of vertical take-offs and landings in a tail-down attitude, and of hovering flights with the tail near the ground. Vertical take-offs were accomplished by rapidly increasing the speed of the propellers until the model took off. These take-offs were rather abrupt and the model generally climbed to a height of about 10 feet before the power operator adjusted the power for steady hovering flight. Tail-down landings were made by decreasing the speed of the propellers so that the model descended slowly until the landing gear was about 0.5-propeller diameter above the ground. At this point the power was cut and the model dropped to the ground. In the hovering flights with the tail near the ground, the model was flown with the trailing edge of the tail surfaces 0.5- to 0.75-propeller diameter 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 the landing gear touched the ground and it rose so high at times that the tail surfaces were several feet above the ground. The flight behavior of the model was judged, however, only when the tail surfaces were about 0.5- to 0.75-propeller diameter above the ground. All flight tests were made with the center of gravity located at the leading edge of the mean-aerodynamic-chord line of the wing. The data of reference 1 show that moving the center of gravity from the 0-percent to the 45-percent mean-aerodynamic-chord line of the wing had little effect on the flight behavior of the model.

RESULTS AND DISCUSSION

Force Tests

The force-test results presented in figure 3 show clearly a reduction in control effectiveness as the tail approached the ground. Since these tests were made with only one unit of the four-unit tail surfaces, they did not give a quantitative measure of the control effectiveness of the flight model. They did, however, give a quantitative indication of the degree to which the control effectiveness was reduced by the ground. The data are therefore presented in terms of the ratio of the effectiveness of the controls in the presence of the ground to the effectiveness of the controls with the ground board removed. These data show that there is a pronounced reduction in the static effectiveness of the tail controls as the model neared the ground. For example, with the tail surfaces 0.5-propeller diameter above the ground the control effectiveness was about 60 percent of the effectiveness with the ground board removed.

Figure 4 presents the results of tests made to determine whether the ground introduced any instability of attitude as the tail of the model neared the ground. It was thought that, if the model were yawed when its tail was near the ground, the turning of the slipstream as it approaches the ground might produce an appreciable side load on the tail which would cause a yawing moment tending to increase the angle of yaw of the model. The data of figure 4, however, show that no such instability of attitude existed when the tail of the model was 0.5-propeller diameter above the ground. The model had neutral stability of attitude with its tail near the ground just as it would have at considerable heights above the ground.

Dynamic-Pressure Survey

The results of a dynamic-pressure survey made in the vicinity of the 0.25- and 0.75-chord lines of the vertical tail with the ground board 0.5-propeller diameter behind the trailing edge of the vertical tail and with the ground board removed are presented in figure 5. These data indicate that the reduction in the effectiveness of the controls of the model as the tail approaches the ground is caused by a reduction in the dynamic pressure over the tail surfaces. A comparison of the data of figures 3 and 5 indicates that the ratio of the average dynamic pressure with the ground board in place to that with the ground board removed is approximately equal to the ratio $N_{\delta}/N_{\delta_{\infty}}$ when the tail was 0.5-propeller diameter above the ground. The results of a tuft survey made in the vicinity of the vertical tail for various ground board distances indicated that the change in dynamic pressure over the tail is caused by a spreading of the slipstream as the tail approaches the ground.

The results of additional dynamic-pressure surveys at various radial and longitudinal stations behind the propeller with the ground board removed are presented in figure 6. These results are presented for use by designers of convertaplanes in the estimation of control moments since there is a lack of information on the dynamic-pressure distribution at various radial and longitudinal stations behind a dual-rotating propeller in the static-thrust condition.

Flight Tests

The model became more difficult to fly as it neared the ground. The pilot found that it was considerably more difficult to keep the model in an erect attitude and to keep it over a spot when hovering near the ground than when hovering well above the ground. It was possible to keep the model hovering low over a spot on the ground (representing a landing deck, perhaps) for a short time, but eventually the behavior would become somewhat erratic and the model would move off despite the pilot's efforts to keep it over the spot. This adverse effect of the ground on the flight behavior of the model resulted from a reduction in controllability and probably from an increase in sensitivity of the model to disturbances such as the propeller force fluctuations. Analysis indicates that the reduction in slipstream velocity at the tail causes a reduction in the damping in pitch and yaw in addition to the reduction in static-control effectiveness previously discussed. This reduction in damping causes the model to be more sensitive to disturbances but does not cause an increase in the response of the model to the controls because the static-control effectiveness is reduced more rapidly than the damping as the model approaches the ground. In fact the response of the model to the controls is actually reduced considerably.

A full-scale airplane should be easier to fly than the model because the pilot could sense the movements of the airplane and apply the proper amount of corrective control more exactly than was possible with the model.

Take-offs and landings with the model in a tail-down attitude were not difficult to perform. In fact, take-offs were easy because the model quickly went through the range of heights for which the ground could affect the flight behavior. Landings were somewhat more difficult, however, because the model was required to fly near the ground for longer periods of time. This difficulty was particularly noticeable when attempts were being made to land the model on a spot because it was brought down more slowly and was required to fly longer at heights for which the ground effect on controllability was pronounced.

CONCLUDING REMARKS

The results of an experimental investigation of the effect of the proximity of the ground on the stability and control characteristics of a vertically rising airplane model in the hovering condition with the normal airplane-type controls operating in the slipstream may be summarized as follows:

1. The model became more difficult to fly as the tail neared the ground but, take-offs and landings were not difficult to perform because the model passed quickly through the range of heights for which the ground could affect the flight behavior.

2. Force tests indicated that the reason for the adverse effect of the ground on the flight behavior of the model was a decrease in the effectiveness of the tail controls with decrease in height above the ground. This reduction in control effectiveness resulted from the reduction in dynamic pressure of the slipstream at the tail as the model approached the ground.

3. The model had neutral stability of attitude when hovering near the ground; that is, there was no variation of yawing moment with angle of yaw or of pitching moment with angle of pitch. This is the same result that would be obtained at considerable heights above the ground.

4. For the static-thrust condition, large random variations in rolling, yawing, and pitching moments were caused by fluctuations of the direct propeller moments and by fluctuations of the fuselage and tail moments caused by the slipstream.

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

REFERENCE

1. Bates, William R., Lovell, Powell M., Jr., and Smith, Charles C., Jr.: Dynamic Stability and Control Characteristics of a Vertically Rising Airplane Model in Hovering Flight. NACA RM L50J16, 1951.

TABLE I

GEOMETRIC CHARACTERISTICS OF THE MODEL

Weight, lb	27.5
Wing:	
Rectangular plan form	
Flat-plate section (0.5 thick)	
Aspect ratio	5.00
Area, sq in.	376.71
Span, in.	43.40
Chord, in.	8.68
Span of aileron, in.	15.67
Chord of aileron, in.	2.17
Over-all length of model, in.	56.68
Fuselage:	
Length, in.	44.00
Diameter, in.	6.00
Horizontal and vertical tails:	
Rectangular plan form	
Flat-plate section (0.25 thick)	
Aspect ratio	3.36
Area (horizontal or vertical total), sq in.	169.34
Span, in.	23.85
Chord, in.	7.10
Moment arm, distance from leading edge of wing to hinge line of controls, in.	30.06
Propellers:	
Eight-blade dual-rotating	
Diameter, in.	23.85
Hamilton Standard design, drawing number	3155-6-1.5
Solidity, one blade	0.0475
Gap, in.	3.00
Moment arm, distance from leading edge of wing to center of gap between propellers, in.	14.81

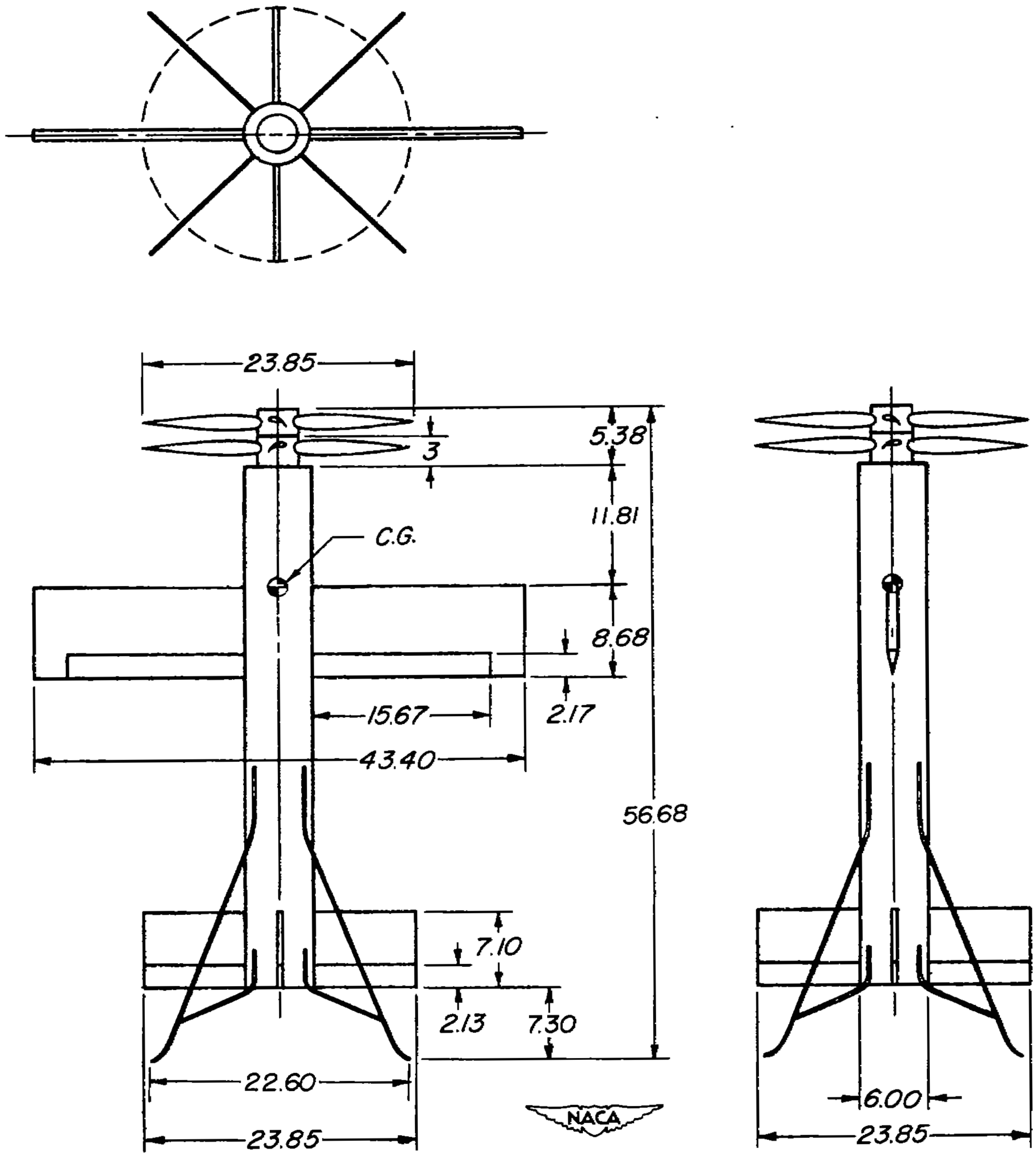

Figure 1.- Vertically rising airplane model showing the important dimensions.
All dimensions are in inches.

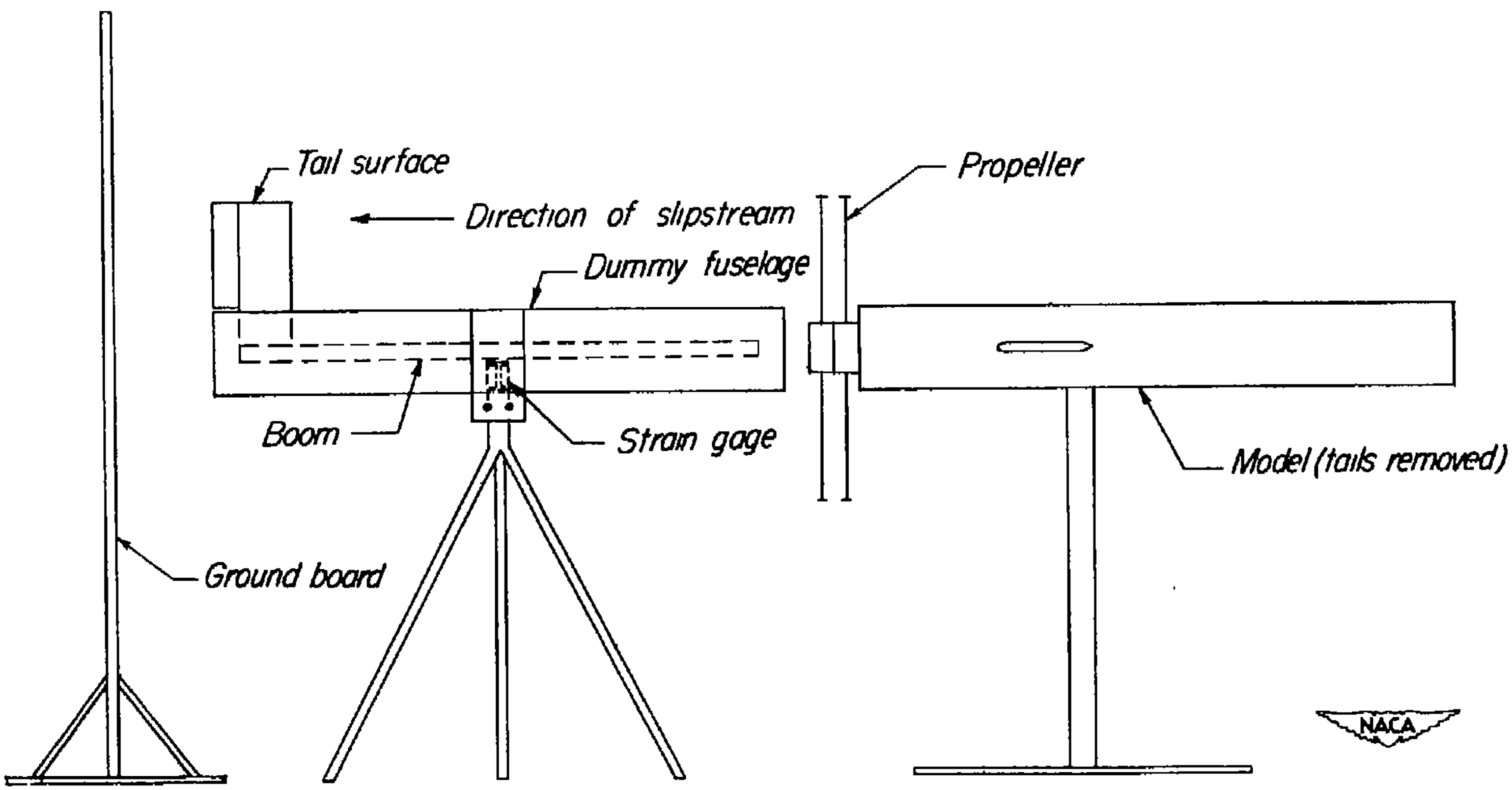

Figure 2.- Sketch of the test setup used in the force test investigation.

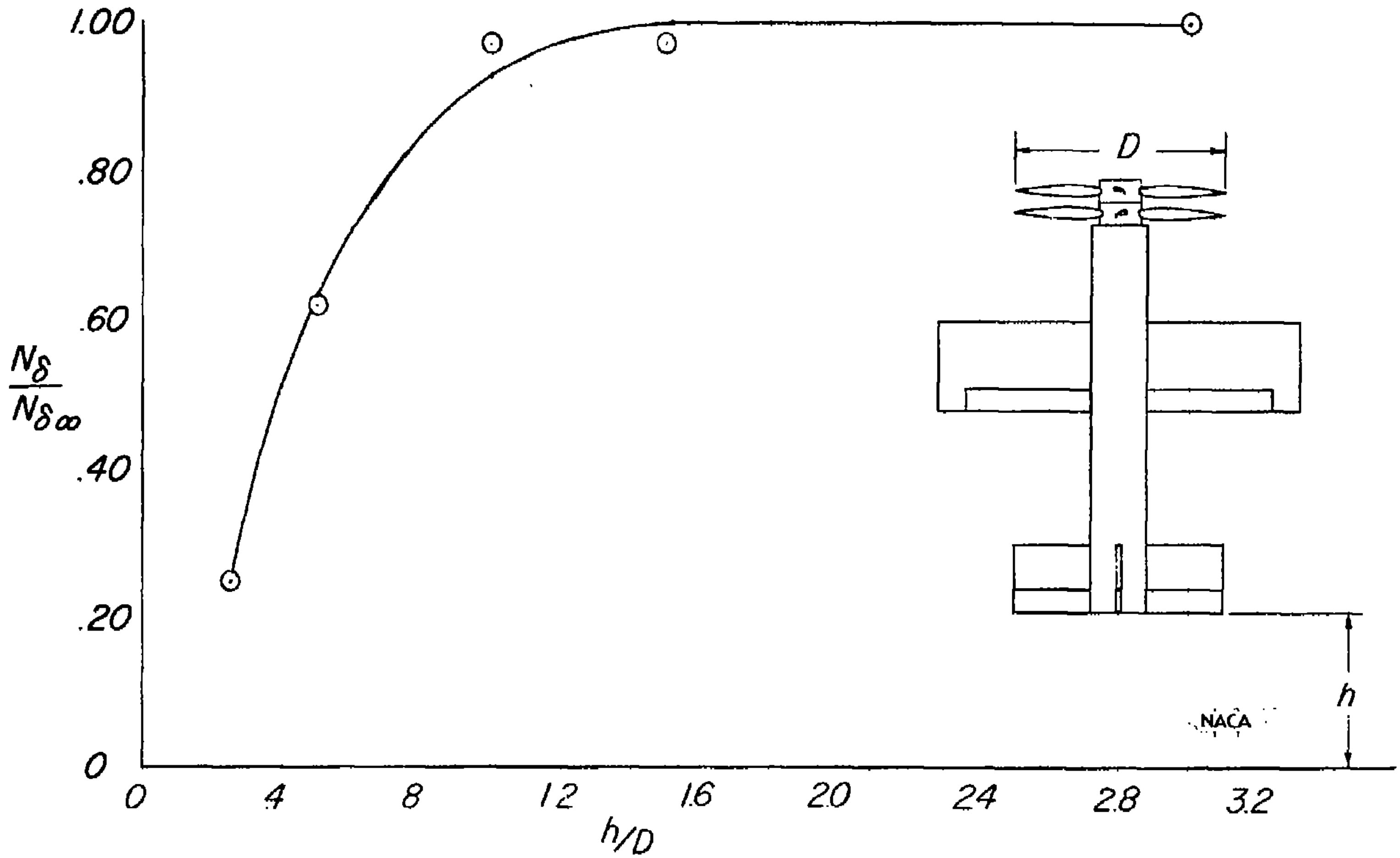

Figure 3.- Change in control effectiveness caused by the proximity of the ground board.

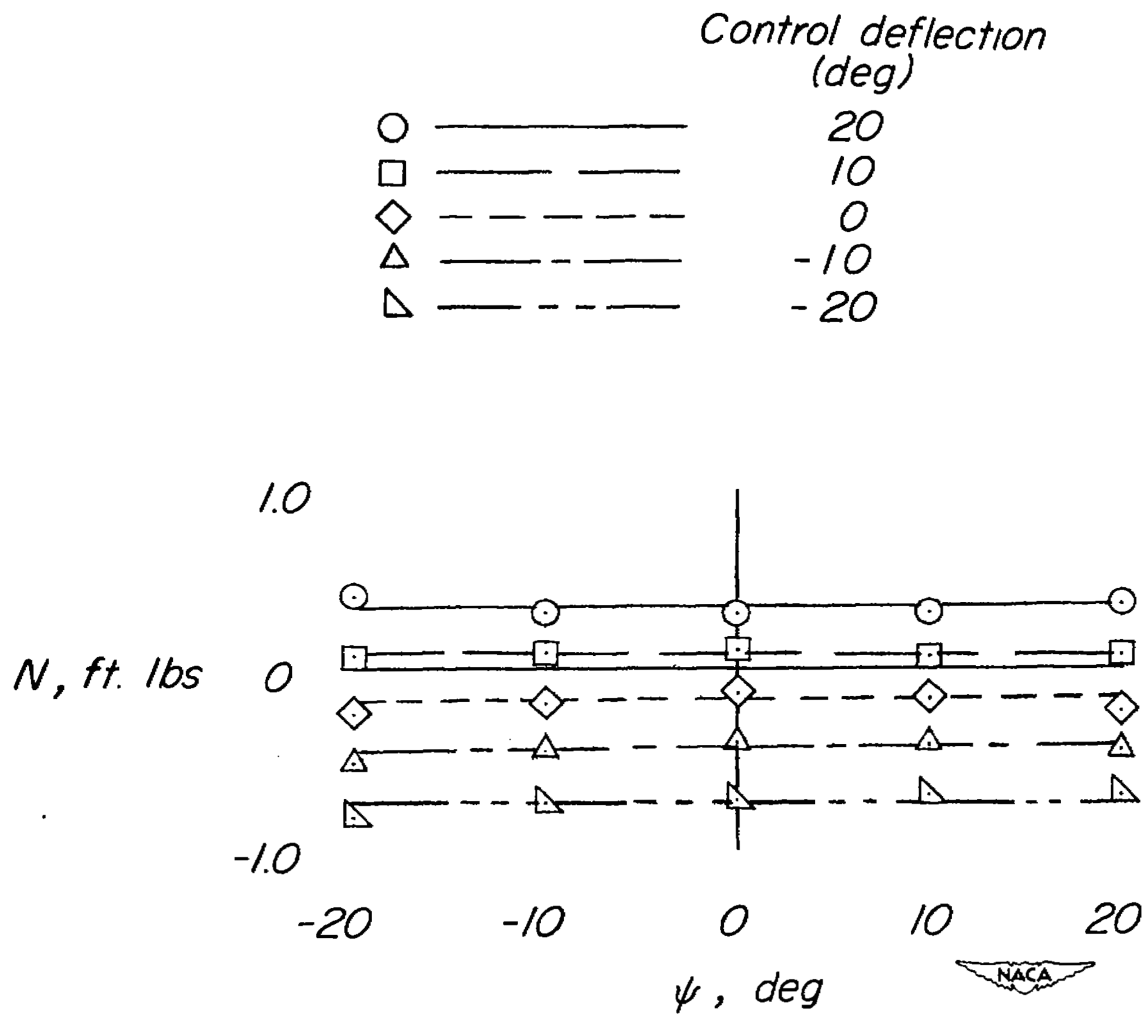

Figure 4.- Stability of attitude of the model with the trailing edge of the tail 0.5-propeller diameter above the ground.

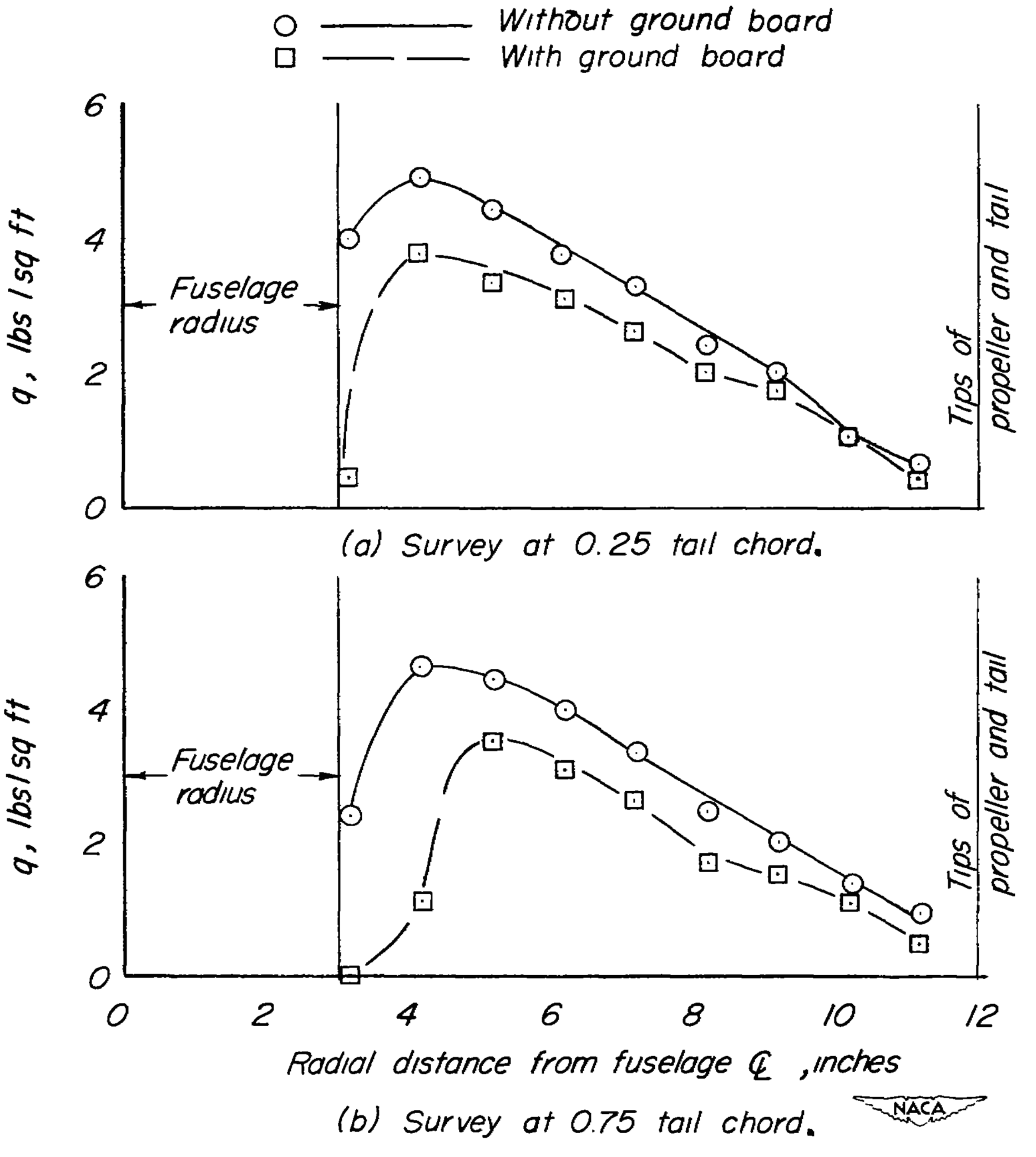

Figure 5.- Effect of the ground on the dynamic pressure over the vertical tail with the trailing edge of the tail 0.5-propeller diameter above the ground.

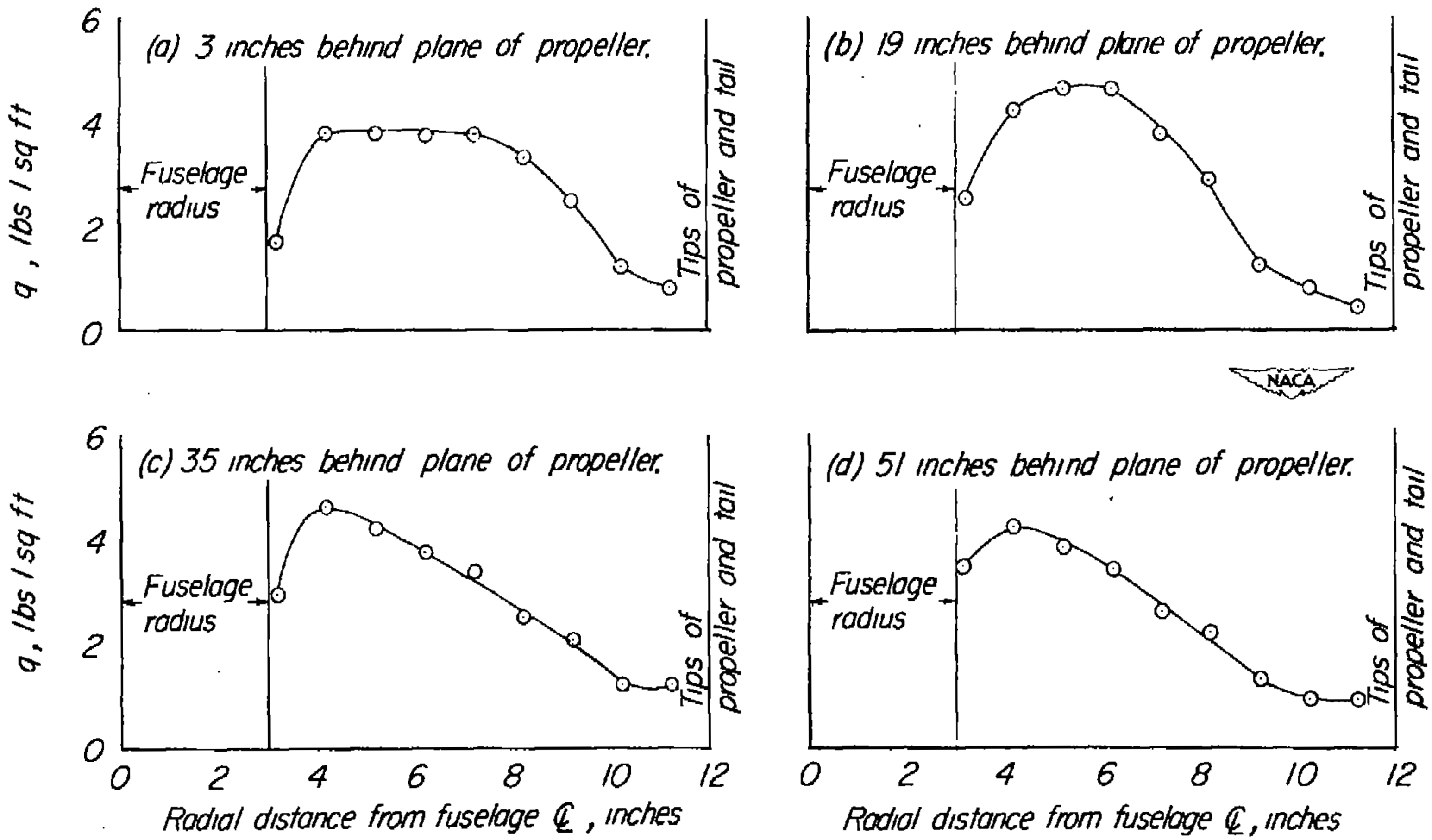

Figure 6.- Dynamic-pressure distribution at four longitudinal stations behind a dual rotating propeller in a static-thrust condition.

[redacted]