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THE EFFECTS OF STATIC MARGIN AND ROTATIONAL DAMPING IN PITCH ON THE LONGITUDINAL STABILITY CHARACTERISTICS OF AN AIRPLANE AS DETERMINED BY TESTS OF A MODEL IN THE NACA FREE-FLIGHT TUNNEL

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ADVANCE RESTRICTED REPORT

THE EFFECTS OF STATIC MARGIN AND ROTATIONAL DAMPING IN PITCH ON THE LONGITUDINAL STABILITY CHARACTERISTICS OF AN AIRPLANE AS DETERMINED BY TESTS OF A MODEL IN THE NACA FREE-FLIGHT TUNNEL

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SUMMARY

The effects of static margin and rotational damping in pitch on the longitudinal stability characteristics of an airplane have been determined by flight tests of a model in the NACA free-flight tunnel. In the investigation, the rotational damping in pitch was varied over a wide range by using horizontal tails that varied in area from 0 to 24 percent of the wing area. A range of static margins from 2 to 16 percent of the mean aerodynamic chord was covered in the tests. For each test condition the model was flown and the longitudinal steadiness characteristics were noted.

It was found in the investigation that longitudinal steadiness was affected to a much greater extent by changes in static margin than by changes in rotational damping. The best longitudinal steadiness was noted at large values of static margin. For all values of rotational damping, the steadiness of the model decreased as the static margin was reduced. The model was especially unsteady at low values of static margin (0.03 or less). Reduction in rotational damping had little effect on longitudinal steadiness, except that with low values of static margin (0.03 or less) the longitudinal divergences were sometimes more violent with the tailless (low rotational damping) condition.

In the applications of the model test results to full-scale airplanes the small scale of the model and the method of control make the model tests conservative; that is, the steadiness of the airplane is expected to be somewhat greater than that of the model for given values of

static margin and rotational damping in pitch. The model test results indicate that the tailless airplane, in spite of its low rotational damping in pitch, should have longitudinal steadiness characteristics similar to those of a conventional airplane with the same amount of static margin, provided the static margin is greater than 0.03.

INTRODUCTION

Full-scale flight investigations have indicated that static longitudinal stability and rotational damping in pitch are two important factors affecting the longitudinal handling characteristics of airplanes. No flight investigations have been made, however, in which both of these factors were systematically varied. Such an investigation was considered desirable especially because of the recent trend toward tailless airplanes, which have inherently low damping in pitch. An investigation has therefore been carried out in the NACA free-flight tunnel to determine the effects of large changes in static margin and rotational damping in pitch on the longitudinal stability characteristics of airplanes. Static margin is a measure of static longitudinal stability and is defined as the distance between the center of gravity and the neutral point of an airplane expressed in terms of the mean aerodynamic chord.

The investigation was made with a free-flying, dynamic model. The longitudinal steadiness of the model was observed in flights made with variations in horizontal tail area and center-of-gravity location that gave a wide range of values of rotational damping and static margin. In the investigation an attempt was made to determine the relation between the observed longitudinal stability characteristics in flight and the calculated characteristics of both the phugoid and the short-period longitudinal oscillations.

SYMBOLS

C_L lift coefficient $\left(\dfrac{\text{Lift}}{\frac{1}{2}\rho V^2 S}\right)$

C_m	pitching-moment coefficient $\left(\frac{\text{Pitching moment}}{\frac{1}{2}\rho V^2 \bar{c} S}\right)$
$\frac{dC_m}{di_t}$	rate of change of pitching-moment coefficient per degree stabilizer incidence
i_t	angle of incidence of horizontal tail, positive when trailing edge is down, degrees
C_{m_q}	rate of change of pitching-moment coefficient with pitching angular velocity $\left(\frac{dC_m}{d\frac{q\bar{c}}{2V}}\right)$
ρ	mass density of air, slugs per cubic foot
q	pitching angular velocity, radians per second
V	airspeed, feet per second
$\bar{c}$	mean aerodynamic chord, feet
$-\frac{dC_m}{dC_L}$	static margin, chords ($x/\bar{c}$, for propeller off)
x	distance from center of gravity to neutral point, feet
S	wing area, square feet
k_Y	radius of gyration about Y-axis, feet
b	wing span, feet
$T_{1/2}$	time to damp to one-half amplitude, seconds
P	period of longitudinal oscillation, seconds
θ	angle of pitch, degrees

APPARATUS

The investigation was carried out in the NACA free-flight tunnel, which is fully described in reference 1.

A photograph of the test section of the tunnel showing a model in flight is presented as figure 1. Force tests made to determine the static stability characteristics of the model were run on the free-flight-tunnel six-component balance. (See reference 2.) A free-oscillation apparatus similar to that described in reference 3 was used to obtain values of C_{m_q}.

A three-view drawing of the model used in the investigation is given in figure 2. The model was constructed principally of balsa and was fitted with control surfaces similar to those described in references 1 and 2. In addition, a movable elevator was installed on the inboard portion of the wing (fig. 2) to provide longitudinal trim and control during flights with the horizontal tail removed. Three geometrically similar horizontal tails were used on the model. (See fig. 2 and table I.) For the tailless condition, the horizontal tail was removed while the vertical tail and the fuselage were retained on the model. The center-of-gravity location of the model was varied by shifting lead weights located in the nose and the tail.

METHODS

Calculations

The period and the time to damp to one-half amplitude for both the short-period longitudinal oscillation and the phugoid, or long-period longitudinal oscillation, were computed for each tail condition for a range of values of static margin from 0.02 to 0.16 mean aerodynamic chord. Values of the static longitudinal stability derivatives used in making the calculations were obtained from force tests of the model, and values of the rotational damping derivative C_{m_q} were obtained by a free-oscillation-test method similar to that described in reference 3. All the calculations were made for a lift coefficient of 0.5.

Flight-Testing Procedure

The model was flown with various amounts of static margin for each value of rotational damping and a rating of longitudinal steadiness was assigned by the pilot to each condition tested. The model motion was observed with controls fixed and also during controlled flight. One measure of steadiness was the frequency with which elevator deflections had to be applied to keep the model flying smoothly in the center of the tunnel. For very steady conditions, elevator control was seldom necessary; for unsteady conditions, however, alternate up and down elevator deflections were required almost continuously. Another measure of steadiness was the magnitude of vertical motions of the model in the tunnel while the model was being controlled. Large vertical displacements and rapid motions were the usual indications of unsteadiness and slow, easily controlled motions of small magnitude were obtained in steady-flight conditions.

Motion-picture records were taken with a camera mounted at the side of the test section of the tunnel for some conditions to supplement the pilot's observations of steadiness. Most of these records were made of controlled model motions because elevator control was usually required to keep the model flying in the center of the tunnel.

Three differences between the method of controlling the longitudinal motions in model flight and in airplane flight should be noted:

(1) The model is controlled by abrupt elevator deflections of 2° to 5° or more, which are applied for very short periods of time; whereas, the airplane control can be applied slowly and smoothly. This difference probably makes the model flights more jumpy than those of an airplane with the same values of static margin and rotational damping.

(2) For the model, abrupt elevator control is given from a fixed neutral position and upon release the elevator returns to the neutral position. With this method of control it is impossible for longitudinal motions of the model to be induced by oscillations of the elevator itself as is sometimes the case for airplanes.

(3) The model is usually controlled to maintain a constant vertical position in the tunnel rather than a constant attitude as in the case of an airplane. This method of control introduces lag difficulties at times and causes motions that are probably well damped with

controls fixed to appear lightly damped when the elevator control is being used.

RANGE OF VARIABLES

During the investigation, the rotational damping in pitch and the static margin were varied while the weight of the model and the moment of inertia about the Y-axis were held constant. The rotational damping factor C_{m_q} was varied from -3.1 to -14.3 by use of horizontal tail areas that ranged from 0 to 24 percent of the wing area. (See table I.) The static margin was varied for each tail condition by shifting the center of gravity known distances ahead of the neutral point. The neutral points for the different tail conditions were determined from a consideration of the values of $\frac{dC_m}{dC_L}$ obtained in force tests of the model. The maximum variation of static margin for the different tail conditions was from 0.02 to 0.16.

The weight of the model was held constant at a value of approximately 6.1 pounds, which corresponds to a wing loading of 2.7 pounds per square foot for the model or to a wing loading of 27 pounds per square foot for an airplane 10 times the size of the model. The moment of inertia of the model for all test conditions was such that the ratio of the pitching radius of gyration to the wing span k_Y/b was 0.17. This value of k_Y/b is within the range of values for conventional airplanes and is only slightly below the average ratio obtained from values for over a hundred airplanes.

The flight tests were made over a range of lift coefficients from 0.4 to 0.7. The lowest lift coefficient obtainable (0.4) was established by the maximum airspeed of the tunnel. The highest lift coefficient (0.7) was limited by the maximum lift coefficient of the model. Most of the flight tests were made at a lift coefficient of approximately 0.5.

RESULTS

The results of the calculations made to determine the time to damp to one-half amplitude and the period of the longitudinal oscillations are presented in figures 3 and 4. Results are given for the short-period oscillation in figure 3 and for the long-period or phugoid oscillation in figure 4. The steadiness ratings assigned by the pilot to different flight conditions are shown in table II. Data from motion-picture records showing time histories of the vertical motion and pitching motion of the model with different amounts of rotational damping and static margin are presented in figures 5 to 7.

DISCUSSION

Effect of Variation of Static Margin

The ratings of table II show that the steadiness of the model decreased as the static margin was reduced for all values of rotational damping. The model was particularly unsteady at low values of static margin (below 0.04).

The model flew very steadily with large values of static margin, and only occasional elevator deflections were required to keep the model flying smoothly in the tunnel. The time histories at the bottom of figures 5 and 6 show that the vertical motions of the model during controlled flight with large static margins were slow, smooth, and of small magnitude.

With low values of static margin, however, the motions became faster, sharper, and larger, as shown by the upper time histories in figures 5 and 6. Table II shows that, with 0.02 static margin, the model was very unsteady with any amount of rotational damping. Flights at this condition were very jumpy, and strong tendencies toward longitudinal divergence were noted. Most flights with this amount of static margin ended in crashes because of the extreme difficulty experienced by the pilot in applying elevator control at the exact instant that it was needed to prevent longitudinal divergence. At times, because of unavoidable lag in the pilot's reactions, the control was applied in such a way as to reinforce rather than to oppose the divergent motions.

In this connection, it should be pointed out that the pitching velocities of the small-scale models tested in the NACA free-flight tunnel are more than three times as great as the pitching velocities of the corresponding airplanes. It is expected, therefore, that the airplane should be easier to fly than the model with the same amount of static margin, and it is not believed that an airplane corresponding to the model tested would necessarily exhibit poor flight characteristics similar to those that were noted in the tests of the model with 0.02 static margin.

The results of the calculations of dynamic longitudinal stability (figs. 3 and 4) show that reducing the static margin increases the period of both the phugoid and the short-period oscillation and reduces the damping of the phugoid but does not affect the damping of the short-period oscillation.

The only agreement noted between the calculations and the flight-test results was that the period of the short-period oscillation was approximately the same as the period of the controlled motion of the model. Theoretically, the damping of the short-period oscillation is heavy and does not vary with static margin. It is possible, however, that the short-period motion could be reinforced by elevator control movements or gust disturbances in such a way as to prevent it from damping quickly. If such conditions were present, an unsteady, lightly damped longitudinal motion having approximately the same period as the short-period oscillation might occur.

Effect of Variation of Rotational Damping

The ratings of table II show that variation of rotational damping had very little effect on the longitudinal steadiness of the model. Decreasing the rotational damping had virtually no effect on the steadiness at large values of static margin but decreased the steadiness slightly at low values of static margin. The time histories of figures 5 to 7 show that the vertical motions of the model during controlled flight with different values of C_{m_q} were roughly similar for a given value of static margin. With low values of static margin

(0.02 and 0.03), the longitudinal divergences were sometimes more violent with the tailless (low C_{m_q}) condition.

The small effects of changes in rotational damping on the longitudinal steadiness of the model indicate that a tailless airplane, in spite of its inherently low rotational damping in pitch, should have longitudinal steadiness characteristics similar to those of a conventional airplane with the same static margin.

In the investigation no quantitative data were obtained concerning the effect of changes in rotational damping on the elevator effectiveness required to maintain a given degree of controllability. It was noted in the flight tests, however, that as the horizontal tail area (and thus the elevator effectiveness) was reduced, the magnitude of the elevator control deflections required to keep the model flying satisfactorily in the tunnel did not increase in direct proportion to the reduction in elevator effectiveness. It thus appeared that, as the rotational damping in pitch was reduced, less powerful elevator control was required to obtain satisfactory flights with the model.

The calculations (figs. 3 and 4) show that reducing the rotational damping factor C_{m_q} increases the period of the short-period oscillation and decreases the period of the phugoid. Reducing the value of C_{m_q} reduces the damping of the short-period oscillation for all values of static margin and reduces the damping of the phugoid oscillation for the lower values of static margin.

CONCLUDING REMARKS

The results of the investigation to determine the effects on longitudinal steadiness of varying static margin and rotational damping are summarized in the following paragraphs. In the applications of these results to the full-scale airplane the small scale of the model and the method of control probably make the model tests conservative; that is, the steadiness of the airplane is expected to be somewhat greater than that of the model for given values of static margin and rotational damping.

1. The best longitudinal steadiness was noted at large values of static margin while the least steady conditions were obtained with very small values of static margin (0.03 or less).

2. Changes in rotational damping had little effect on longitudinal steadiness except that for low values of static margin (0.03 or less) the longitudinal divergences were sometimes more violent for conditions of low rotational damping.

3. The model test results indicated that a tailless airplane, in spite of its inherently low rotational damping in pitch, should have longitudinal steadiness characteristics similar to those of a conventional airplane with the same static margin, provided the static margin is greater than 0.03.

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2. Shortal, Joseph A., and Draper, John W.: Free-Flight-Tunnel Investigation of the Effect of the Fuselage Length and the Aspect Ratio and Size of the Vertical Tail on Lateral Stability and Control. NACA ARR No. 3D17, 1943.

3. Campbell, John P., and Mathews, Ward O.: Experimental Determination of the Yawing Moment Due to Yawing Contributed by the Wing, Fuselage, and Vertical Tail of a Midwing Airplane Model. NACA ARR No. 3F28, 1943.

TABLE I

CHARACTERISTICS OF MODEL USED IN NACA FREE-FLIGHT-TUNNEL

LONGITUDINAL-STABILITY INVESTIGATION

Condition	Horizontal tail							Complete model	
	Total area		Exposed area		Total span (ft)	Aspect ratio	Tail effectiveness factor, $\frac{dC_m}{di_t}$	Neutral point (percent M.A.C.)	Rotary damping factor, C_{m_q}
	(sq in.)	(Percent S)	(sq in.)	(Percent S)					
Tail 1	78.11	24.00	57.28	17.61	1.48	4.05	0.023	35	-14.3
Tail 2	52.07	16.00	37.35	11.50	1.21	4.05	.014	28	-10.4
Tail 3	26.04	8.00	16.34	5.02	.86	4.05	.006	18	-7.6
Tail off, untrimmed								12	-3.1
Tail off, trimmed								14	-3.1

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TABLE II

STEADINESS RATINGS[a] OBTAINED IN FLIGHT TESTS OF MODEL IN LONGITUDINAL-STABILITY INVESTIGATION MADE IN THE NACA FREE-FLIGHT TUNNEL

Tail	Total tail area (percent S)	C_{m_q}	Static margin, $\frac{-dC_m}{dC_L}$, chords														
			0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11	0.12	0.13	0.14	0.15	0.16
1	24	-14.3	D	C	-	B	-	B	-	A -	-	A	-	-	-	A +	A+
2	16	-10.4	-	C-	C+	-	B	-	B+	A-	-	A	-	-	A+	-	-
3	8	-7.6	D	C-	C+	B-	B	-	B+	-	A-	-	A	-	A+	-	-
None	0	-3.1	D	C-	C	-	B	B	B+	-	-	A	-	-	-	-	-

[a]

Symbol	Rating	Remarks
A	Good	Only occasional elevator control required. Motions slow and smooth.
B	Fair	Frequent elevator deflections required but model easily controlled.
C	Poor	Almost continuous attention required to elevator control. Motions faster and harder to control.
D	Very Poor	Continuous attention required to elevator and sometimes magnitude of motion increases despite control and causes crash. Vertical motions very jumpy.

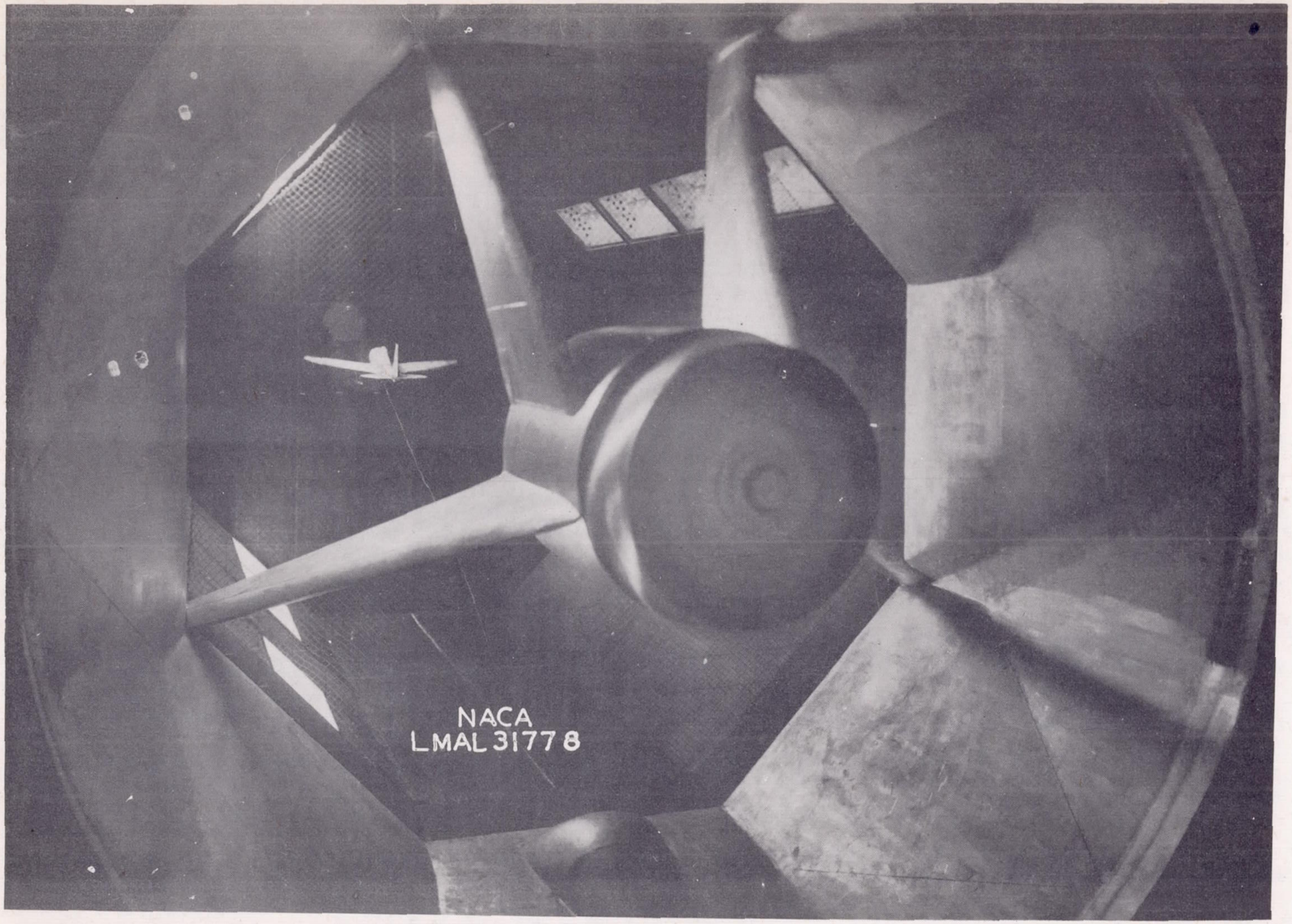
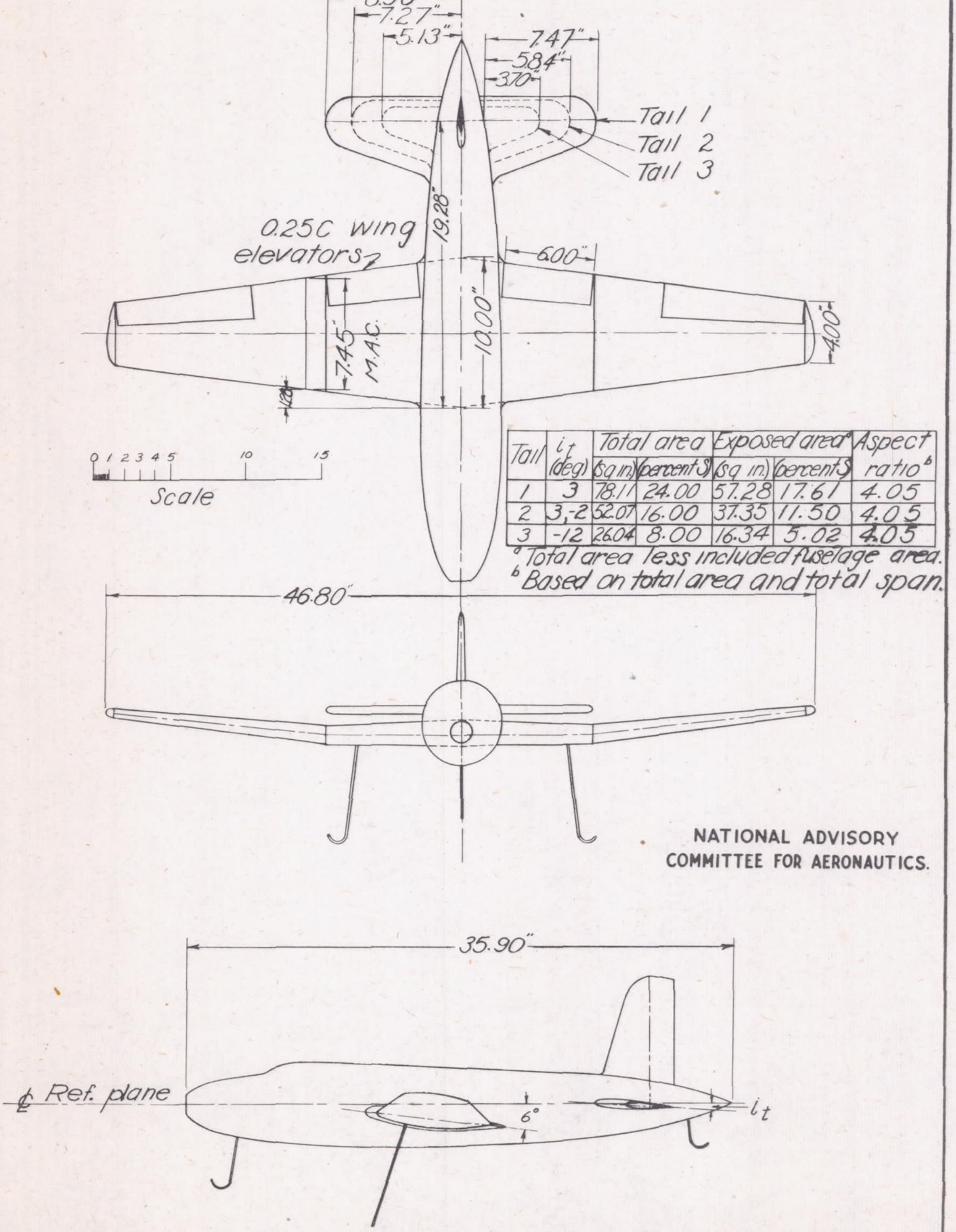


Figure 1.- Test section of the NACA free-flight tunnel showing a model in flight.



Tail	i_t (deg)	Total area (sq in.)	Total area (percent S)	Exposed area[a] (sq in.)	Exposed area[a] (percent S)	Aspect ratio[b]
1	3	78.11	24.00	57.28	17.61	4.05
2	3,-2	52.07	16.00	37.35	11.50	4.05
3	-12	26.04	8.00	16.34	5.02	4.05

[a] Total area less included fuselage area.
[b] Based on total area and total span.

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Figure 2.- Model used in free-flight-tunnel longitudinal-stability investigation.

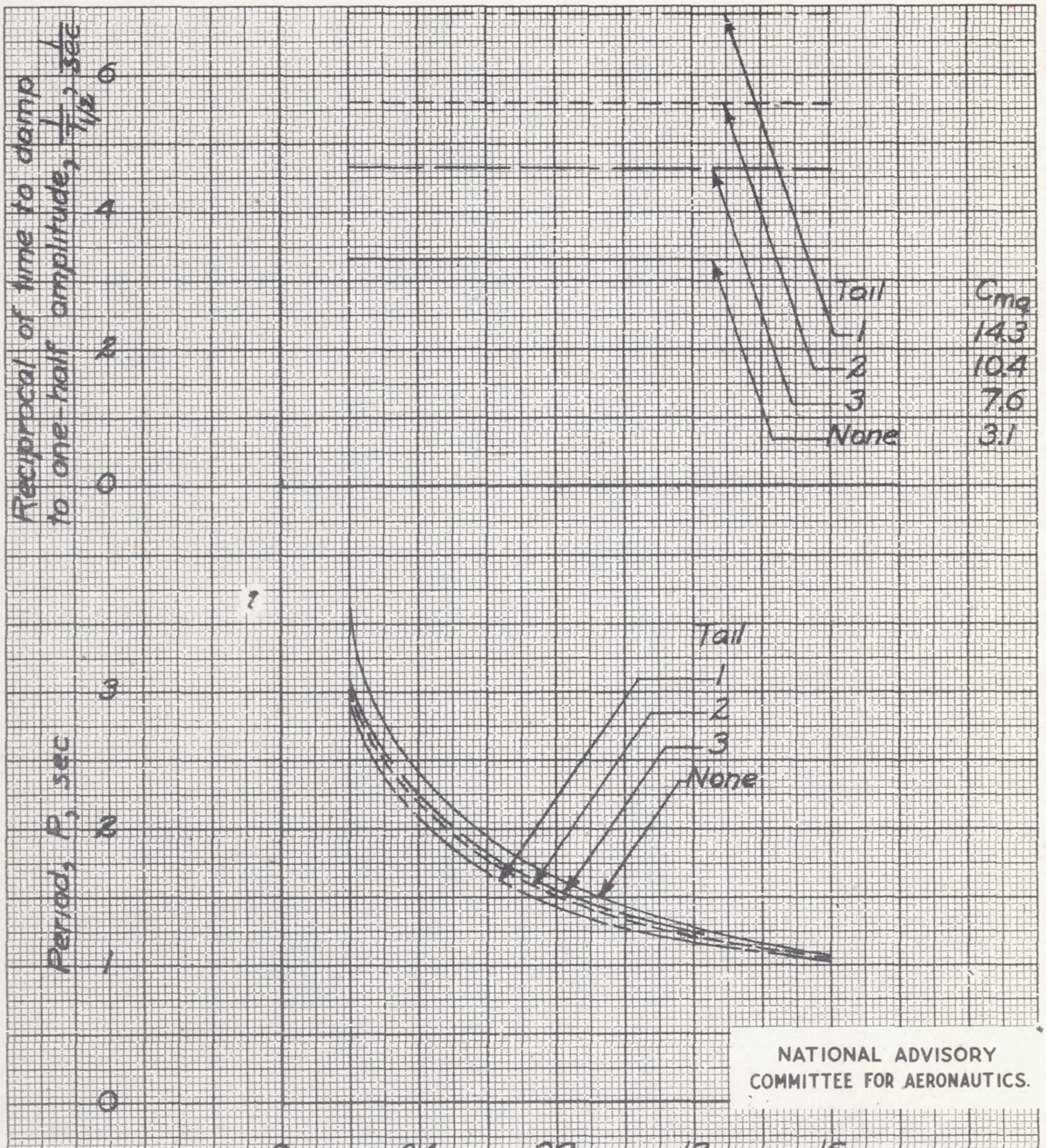

Figure 3.- Calculated characteristics of short-period longitudinal oscillation of model used in longitudinal-stability investigation in free-flight tunnel. $C_L = 0.5$.

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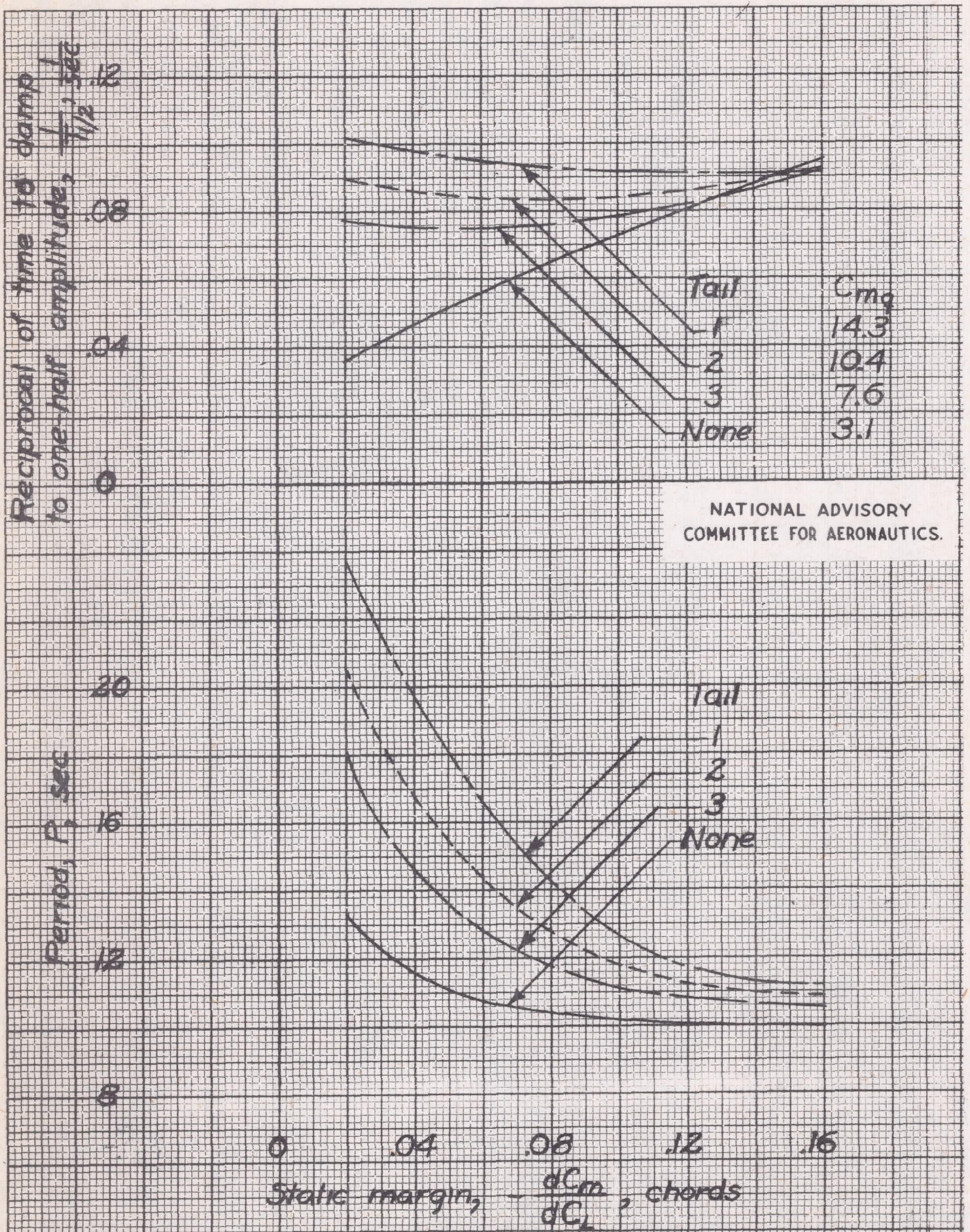

Figure 4.- Calculated characteristics of phugoid oscillation of model used in longitudinal-stability investigation in free-flight tunnel. $C_L = 0.5$.

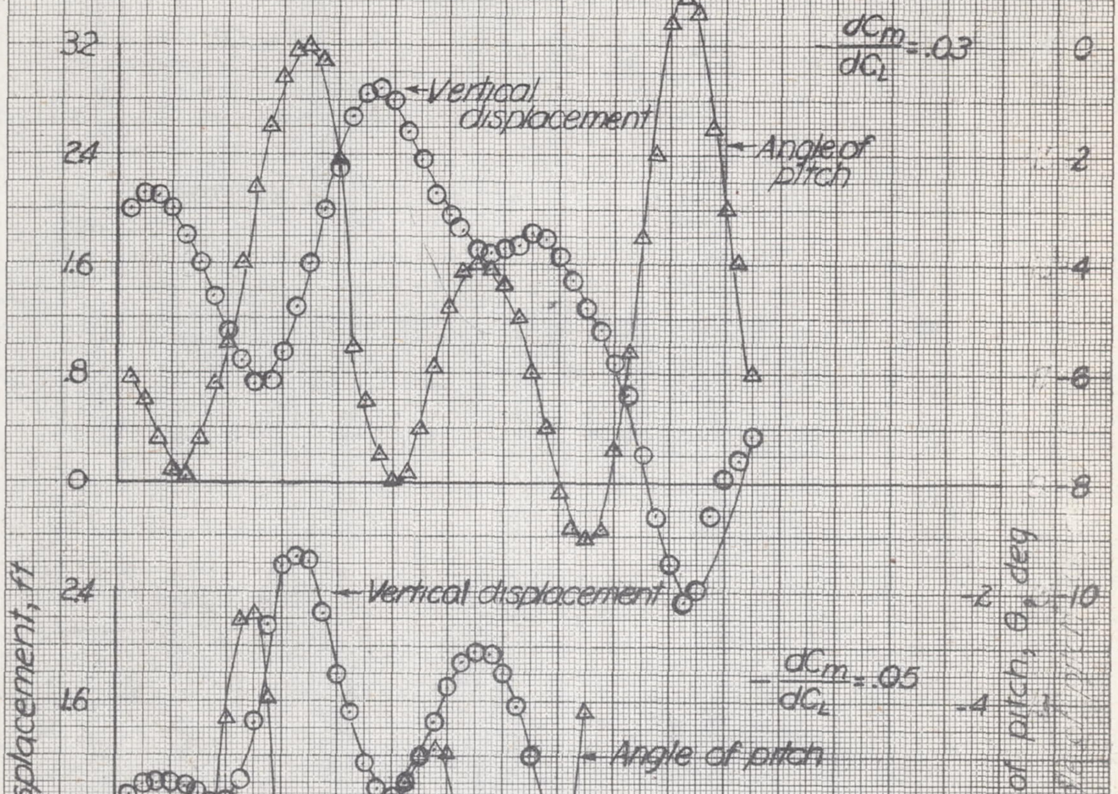

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Figure 5.- Typical motion-picture records of model motions. Large tail (tail 1); C_{m_q} = -14.3; C_L = 0.5; model controlled by elevator.

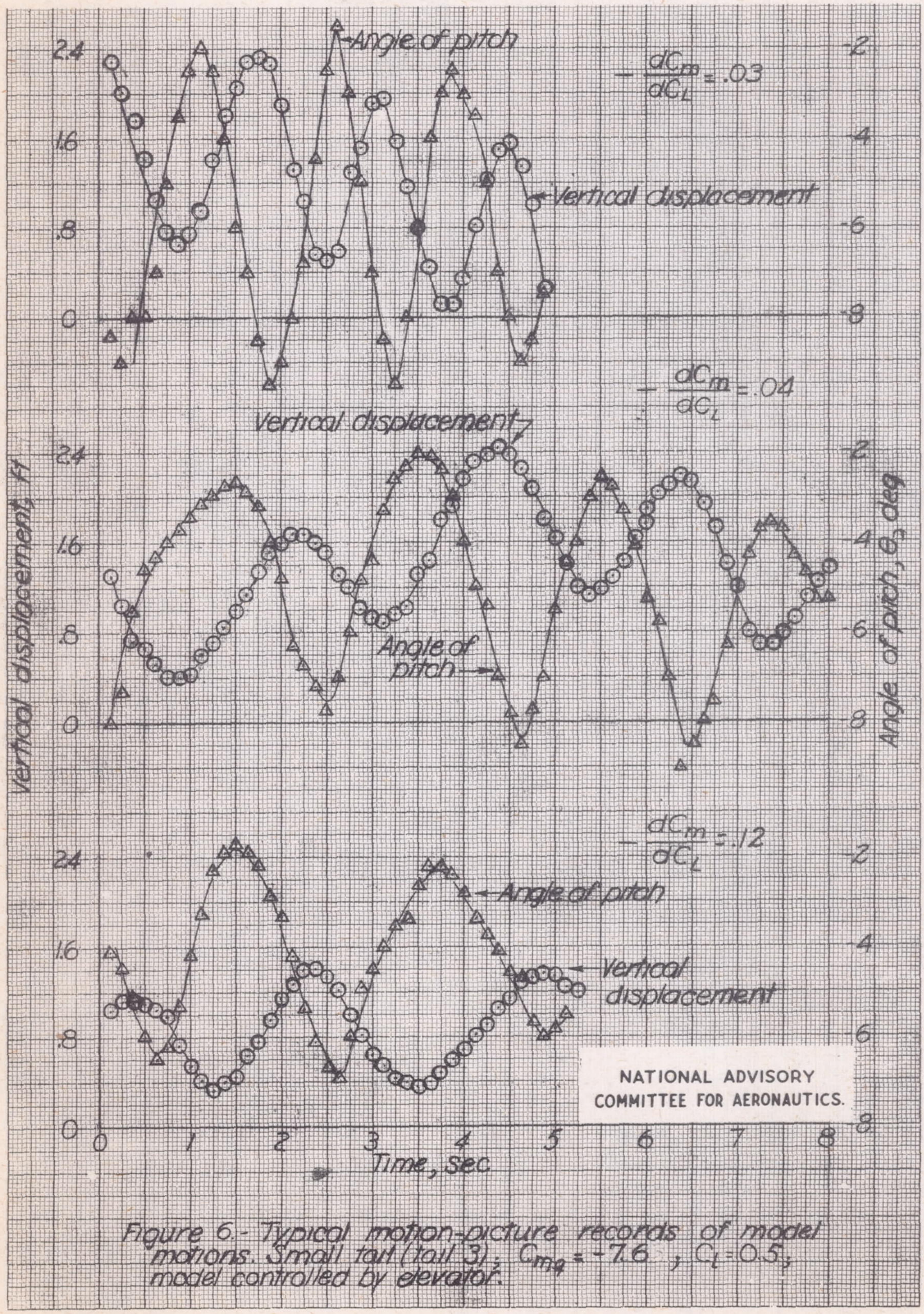

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Figure 6.- Typical motion-picture records of model motions. Small tail (tail 3), $C_{m_q} = -7.6$, $C_L = 0.5$; model controlled by elevator.

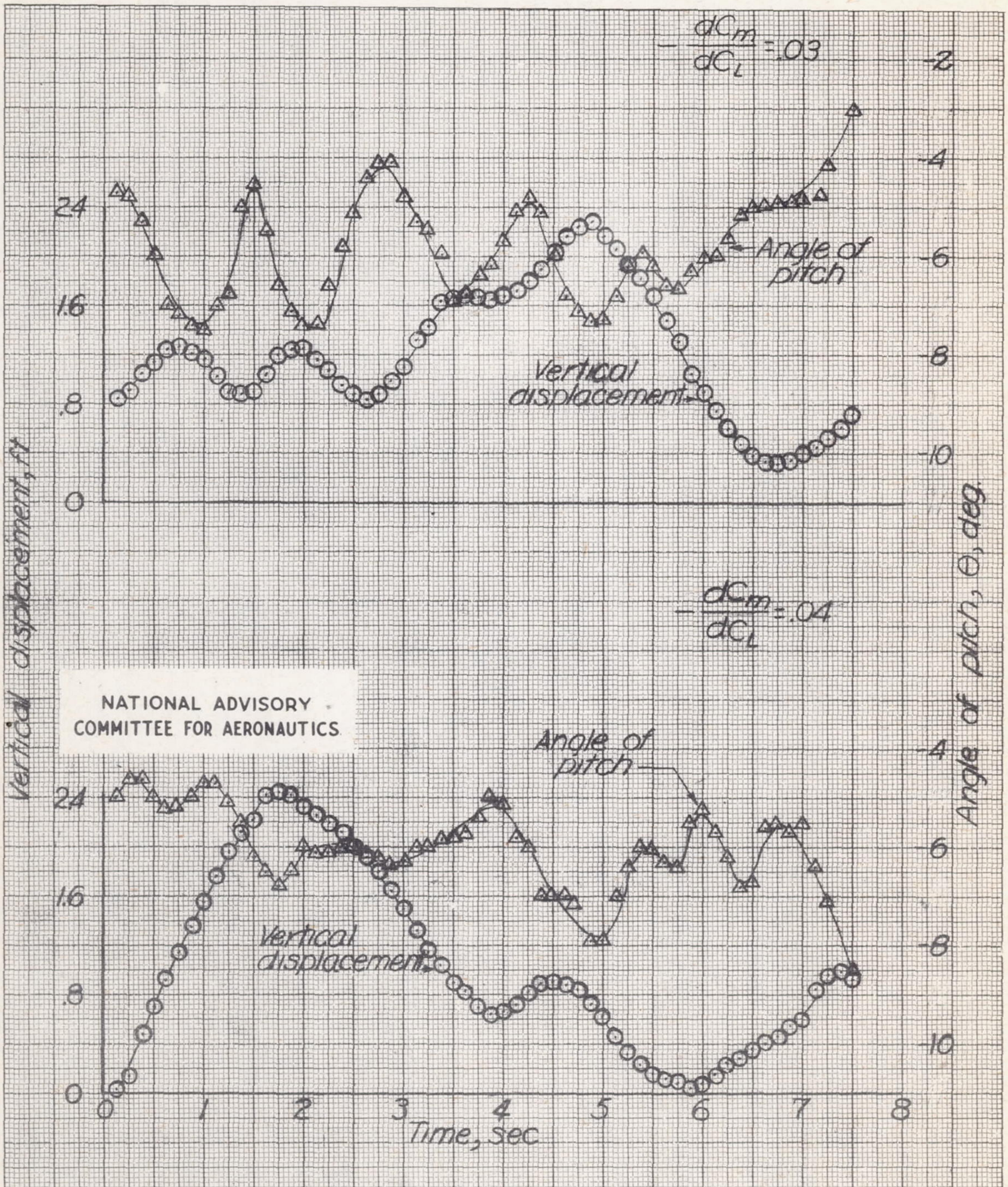

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Figure 7.- Typical motion-picture records of model motions. Tailless condition. $C_{m_q} = -3.1$; $C_L = 0.5$; model controlled by wing elevator.