RESEARCH MEMORANDUM

WIND-TUNNEL INVESTIGATION AT LOW SPEEDS OF THE PITCHING DERIVATIVES OF UNTAPERED SWEPT WINGS

By

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

A wind-tunnel investigation was conducted in straight and in pitching flow to determine the effects of independently varying aspect ratio and angle of sweep on the longitudinal rotary stability characteristics of a series of ten untapered wings. The wings had sweep angles of 0°, 45°, and 60° for each of three aspect ratios (1.34, 2.61, and 5.16) and a sweep angle of -45° for aspect ratio 2.61.

The investigation showed the effects of aspect ratio and sweep to be greatly interdependent. In every case the effect of varying angle of sweep increased as the aspect ratio increased.

The damping-in-pitch parameter generally became more negative with increasing aspect ratio or angle of sweep, except at the lowest sweep angles.

With increasing angle of sweep, the positive value of the lift due to pitching decreased slightly at the high aspect ratio. The effect of increasing aspect ratio on the lift due to pitching was either negligible or small.

The maximum damping-in-pitch value at zero lift was obtained for the high-aspect-ratio wing with 60° sweepback and amounted to about half of the value that would be expected for a conventional airplane.

Available theory is found to be quite reliable in predicting the trend of the variation of damping-in-pitch parameter with sweep and aspect ratio. Theoretical values of the damping in pitch, although somewhat greater in magnitude, were nearly proportional to experimental values. For the models tested, the application of an empirical factor to the theoretical values of the damping-in-pitch parameter resulted in good agreement between theory and experiment.

INTRODUCTION

When an airplane rotates about a lateral axis, as when entering climbing or diving flight, there are, in addition to the initial static forces and moments acting on the airplane, forces and moments resulting from the pitching motion of the airplane. The rotary stability derivatives associated with these additional forces and moments must be known before calculations can be made to determine the longitudinal dynamic stability of the airplane or the longitudinal motions of the airplane after a control displacement. Experimental determinations of these derivatives have been made by oscillating models in wind tunnels and by rotating models on whirling-arm devices. (See references 1 and 2.) Both of these test procedures gave results for the damping in pitch but could not be conveniently used to determine the other pitching derivatives. All the pitching derivatives can be determined rather simply, however, by the use of a test procedure wherein the model remains fixed and the air stream is curved. This method of testing is now being used at the Langley stability tunnel where a comprehensive investigation is being conducted to determine the rotary derivatives of wings of various plan forms.

The present paper contains the results of that part of the investigation that involved the testing in pitching flow of ten untapered wings of various aspect ratios and angles of sweep. Also included herein is a comparison between experimental data and available theory.

SYMBOLS

The results of these tests are presented in the form of standard NACA coefficients of forces and moments which are referred to the stability axes. (See fig. 1.) All moments are given about the quarter-chord point of the mean aerodynamic chord. The coefficients and symbols used herein are defined as follows:

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

C_m pitching-moment coefficient $\left(\frac{M}{\frac{1}{2}\rho V^2 S\bar{c}}\right)$

C_X longitudinal-force coefficient $\left(\frac{X}{\frac{1}{2}\rho V^2 S}\right)$

L lift, pounds

M pitching moment, about Y-axis, foot-pounds

X longitudinal force, pounds

ρ mass density of air, slugs per cubic foot

V free-stream velocity, feet per second

S wing area, square feet

b span of wing, measured normal to the plane of symmetry, feet

A aspect ratio $\left(b^2/S\right)$

c chord of wing, measured parallel to the plane of symmetry, feet

c_1 chord of wing, measured normal to the leading edge, feet

$\bar{c}$ mean aerodynamic chord, feet $\left(\frac{2}{S}\int_0^{b/2} c^2\,dy\right)$

y spanwise distance, measured from plane of symmetry, feet

x distance of quarter-chord point of any chordwise section from leading edge of root section, feet

$\bar{x}$ distance from leading edge of root chord to quarter chord of mean aerodynamic chord, feet $\left(\frac{2}{S}\int_0^{b/2} cx\,dy\right)$

α angle of attack, measured in plane of symmetry, degrees

Λ angle of sweep, positive for sweepback, degrees

a_o slope of section lift curve, per degree (calculations based on $a_o = 5.67$ in this paper)

q pitching angular velocity, radians per second

$qc/2V$ pitching-velocity parameter, radians

x' distance from moment reference point to aerodynamic center of mean aerodynamic chord, positive when moment reference point is upstream of the aerodynamic center, feet

C_{L_α} slope of lift curve $\left(\frac{\partial C_L}{\partial \alpha}\right)$

t time, seconds

$$C_{m_{\dot{\alpha}}} = \frac{\partial C_m}{\partial\left(\frac{d\alpha}{dt}\right)}$$

$$C_{L_q} = \frac{\partial C_L}{\partial\left(\frac{qc}{2V}\right)}$$

$$C_{m_q} = \frac{\partial C_m}{\partial\left(\frac{qc}{2V}\right)}$$

$$C_{X_q} = \frac{\partial C_X}{\partial\left(\frac{qc}{2V}\right)}$$

$$C_{m_{C_L}} = \frac{\partial C_m}{\partial C_L}$$

APPARATUS AND TESTS

The investigation was conducted in the 6- by 6-foot curved-flow test section of the Langley stability tunnel. A description of this test section and the method by which the curved flow is obtained may be found in reference 3.

In the yawing-flow procedure, described in reference 3, the model was mounted horizontally. The present pitching-flow procedure differed only in that the model was mounted vertically (fig. 2) to simulate pitching flight.

The models tested (fig. 3) constituted a series of ten untapered wings all of which had an NACA 0012 section in planes normal to the leading edge. These wings had sweep angles of 0°, 45°, and 60° for each of three aspect ratios (1.34, 2.61, and 5.16) and a sweep angle of -45° for aspect ratio 2.61. The models were rigidly mounted at the quarter-chord point of the mean aerodynamic chord on a single horizontal strut which contained a six-component electrical strain-gage balance. (See fig. 2.)

For mounting purposes, a cut-out which permitted an undesirable passage of air between the strain-gage unit and the wing was made in all the models except wings 5a, 6, 8, and 9. Three of the lower-aspect-ratio wings (1, 2, and 4) were fitted with faired canopies which covered the cut-out and effectively stopped the leakage. (See fig. 2.)

The tests were made at a dynamic pressure of 24.9 pounds per square foot which is equivalent to a Mach number of 0.13. The angle-of-attack range for each wing ran from approximately -4° to beyond the value for maximum lift.

In table I are presented for each wing the sweep angle, aspect ratio, test Reynolds number based on the chord parallel to the axis of symmetry, test Reynolds number based on the chord normal to the leading edge, and the values of $qc/2V$ equivalent to the four degrees of curvature at which the tests were made. The Reynolds number normal to the leading edge is given because recent thought indicates that boundary-layer thickness and separation depend on the air velocity and wing chord normal to the leading edge of the wing. (See reference 4.)

CORRECTIONS

Corrections for jet-boundary effects were obtained from unswept-wing theory (reference 5) and applied to the angle of attack. Lift and pitching-moment data were corrected for the effect of the static-pressure gradient peculiar to the curved-flow test section (reference 3). No corrections were made for the effects of blocking, support-strut tares, or for any effects of turbulence on the boundary-layer flow.

RESULTS AND DISCUSSION

General

The static longitudinal characteristics of the models tested (obtained from reference 6 and unpublished data) are given in figure 4. Since the longitudinal-force data obtained in pitching flow were not considered sufficiently accurate to permit a reliable determination of C_{X_q}, these data have been omitted from the present paper.

The values of C_{m_q} and C_{L_q} given in this paper were obtained by measuring the plotted slopes of C_m and C_L against $qc/2V$. Sample plots of this type for the 45° sweptback wing with 2.61 aspect ratio (wing 5) are given in figure 5. In general, no consistent nonlinear trends of the coefficients were evident for the test range of $qc/2V$. The slopes of the curves were defined satisfactorily.

Pitching Moment Due to Pitching Velocity

The variation of the pitching stability derivative C_{m_q} (an important indication of the damping of the pitching motion) with lift coefficient is given in figure 6.

In the present investigation, the values of C_{m_q} for each of the wings, with the exception of the high-aspect-ratio, highly swept wings, were nearly constant through the lower lift range. The rapid changes with lift coefficient in the values of C_{m_q} for the high-aspect-ratio, highly swept wings are believed to have been caused by variations in the aerodynamic centers of these wings. The pitching-moment curves of figure 4 show the existence of such variations at lift coefficients corresponding to those at which the variations in C_{m_q} occurred.

The experimental values of C_{m_q} at zero lift are compared in figures 7 and 8 with values derived, for wings of the same plan forms, from the theoretical equation

$$C_{m_q} = -a_o \cos \Lambda \left\{ \frac{A\left[\frac{1}{2}\frac{x'}{c} + 2\left(\frac{x'}{c}\right)^2\right]}{A + 2\cos\Lambda} + \frac{1}{24}\left(\frac{A^3 \tan^2\Lambda}{A + 6\cos\Lambda}\right) + \frac{1}{8} \right\}$$

given in reference 7. The value of x', the distance from the moment reference point to the aerodynamic center of the mean aerodynamic chord, was in this investigation assumed to be zero. The equation gives a good indication of trends, but the values are numerically high. These values might be expected to be high since the induction factor $\frac{A}{A + 6\cos\Lambda}$ was obtained from lifting-line theory which indicates too high a lift load for the aspect-ratio range considered. By multiplying the value of the equation by an empirical factor 0.67, good agreement was reached between theory and experiment, especially at the higher aspect ratios. It should be noted, however, that such an empirical factor cannot be expected to apply for all possible configurations, for it would be too large at very low aspect ratios (as indicated in fig. 7) and too small at very high aspect ratios for which the factor should approach 1.0.

A comparison of the results for C_{m_q} (previously unpublished and limited in scope to wing 5) obtained by the oscillation technique (reference 1) with those obtained by the curved-flow procedure is given in figure 9. The oscillation results, through most of the lift range, indicate a higher damping than was found by the curved-flow procedure. This higher damping probably results from the fact that the oscillation technique involves an additional derivative $C_{m_{\dot{\alpha}}}$ (not taken into account in fig. 9) which would be expected to be of such a sign as to increase the indicated C_{m_q}. The two experimental procedures check very well with regard to the trend of the variation of C_{m_q} with lift.

Effect of aspect ratio.- The effect of aspect ratio upon C_{m_q} is shown in figure 7 to be negligible for the unswept wings. As the sweepback angle was increased, however, aspect ratio had an increasing effect on the magnitude of C_{m_q}. This interdependence of aspect ratio and sweep is indicated by the equation given for C_{m_q}. For the cases considered the term containing x'/c and $(x'/c)^2$ can be neglected at least for low lift coefficients. The derivative C_{m_q}, therefore, tends to be increased by sweep through the term $\frac{1}{24} \frac{A^3 \tan^2 \Lambda}{A + 6 \cos \Lambda}$ and tends to be decreased by sweep through the factor $a_o \cos \Lambda$. At very low aspect ratios the two effects may be almost equal in magnitude, in which case they would cancel one another and result in a negligible sweep effect. At high aspect ratios, however, the term $\frac{1}{24} \frac{A^3 \tan^2 \Lambda}{A + 6 \cos \Lambda}$ may be considerably more important than the factor $a_o \cos \Lambda$, in which case the expected result of an increase in the angle of sweep would be a negative increase in C_{m_q}. Whenever an increment in C_{m_q} developed because of an increase in aspect ratio, the change was in the negative direction.

Effect of sweep.- As discussed in the previous paragraph, the effect of sweep was largely dependent upon aspect ratio. At the lowest aspect ratio (1.34), sweep had an almost negligible effect on C_{m_q} (fig. 8); at the higher aspect ratios, however, increasing the sweep of a wing resulted in an increase in the damping in pitch - a result similar to that attained by increasing the tail length of an airplane. For the 60° sweptback wing with aspect ratio of 5.16, the value of C_{m_q} at zero lift, which was the maximum value obtained, amounted to about half the value that would be expected for a conventional airplane (reference 1).

It may be noted that, according to the theory of reference 7, if x'/c is a constant (an assumption on which the theoretical values contained herein were based) the effect of sweep on C_{m_q} is the same regardless of the direction of sweep. The pitching-moment results for the sweptforward wing, however, were different from those for the sweptback wing. (See fig. 4.) Over most of the lift range, the $C_{m_{C_L}}$ slope for the sweptback wing was positive while the $C_{m_{C_L}}$ for the sweptforward wing was negative.

The value of x'/c then must have been negative for the sweptback wing and positive for the sweptforward wing. This difference in x'/c, as can be seen from its application in the equation, may account for at least a part of the difference in the experimental values of C_{m_q} for the sweptback and sweptforward wings having the same geometric properties.

Lift Due to Pitching Velocity

The sample variations of C_L with $qc/2V$, presented in figure 5, are of low magnitude and appear to be somewhat erratic. It would be expected then that a comparison between the experimental values of lift due to pitching C_{L_q} shown in figure 10 and values calculated by use of the following equation (reference 7)

$$C_{L_q} = \left(\frac{1}{2} + 2\frac{x'}{c}\right) C_{L_\alpha}$$

would not be very conclusive. Such a comparison (figs. 11 and 12) shows, however, that at zero lift, the experimental and calculated values of C_{L_q} are in qualitative agreement, and that because of the low magnitude of the values, the theory probably is sufficiently reliable for calculations.

The variation of C_{L_q} with increase of aspect ratio was negligible on the basis of the present investigation. (See fig. 11.) The effect of sweep upon C_{L_q} was negligible at the low aspect ratio but became larger at the higher aspect ratios at which a slight decrease in C_{L_q} with increase in sweep was noted. (See fig. 12.)

CONCLUSIONS

The results of low-speed tests made in pitching flow in the Langley stability tunnel to determine the effect of independently varying angle of sweep and aspect ratio upon longitudinal rotary derivatives of untapered wings indicate the following conclusions:

1. In general, the trends of the effects of varying aspect ratio and sweep as given by available theory were substantiated in the present investigation. Both experimental and theoretical results indicate that the effects of aspect ratio and sweep on the pitching derivatives are

greatly interdependent. Theoretical values of the damping in pitch, although somewhat higher in magnitude, were nearly proportional to the experimental values.

2. With the moment reference point at or near the wing aerodynamic center, the damping-in-pitch parameter was practically unaffected by an increase in aspect ratio for unswept wings. As the sweep angle increased, however, an increase in aspect ratio caused an increase in the damping in pitch. With constant aspect ratio, increasing the angle of sweep generally increased the damping in pitch. The maximum damping-in-pitch value obtained at zero lift amounted to about half the value that would be expected for a conventional airplane.

3. The effect on the lift due to pitching of changing aspect ratio or sweep was either negligible or small. The lift due to pitching decreased slightly with an increase in sweep, but the change was noticeable only at the higher aspect ratios.

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TABLE I

DESCRIPTION OF MODELS AND TEST CONDITIONS

Wing	Sweep (deg)	Aspect ratio	Reynolds number based on $\bar{c}$ and V	Reynolds number based on c_1 and $V \cos \Lambda$	Pitching-velocity parameter, $\frac{qc}{2V}$
5a	-45	2.61	1,100,000	550,000	0, .0123, .0260, .0342
1	0	1.34	1,580,000	1,580,000	0, .0177, .0374, .0492
4	0	2.61	1,100,000	1,100,000	0, .0124, .0262, .0345
7	0	5.16	780,000	780,000	0, .0086, .0183, .0241
2	45	1.34	1,560,000	780,000	0, .0174, .0370, .0486
5	45	2.61	1,100,000	550,000	0, .0123, .0260, .0342
8	45	5.16	770,000	385,000	0, .0086, .0183, .0241
3	60	1.34	1,560,000	390,000	0, .0173, .0368, .0484
6	60	2.61	1,080,000	270,000	0, .0122, .0258, .0339
9	60	5.16	760,000	190,000	0, .0086, .0183, .0241

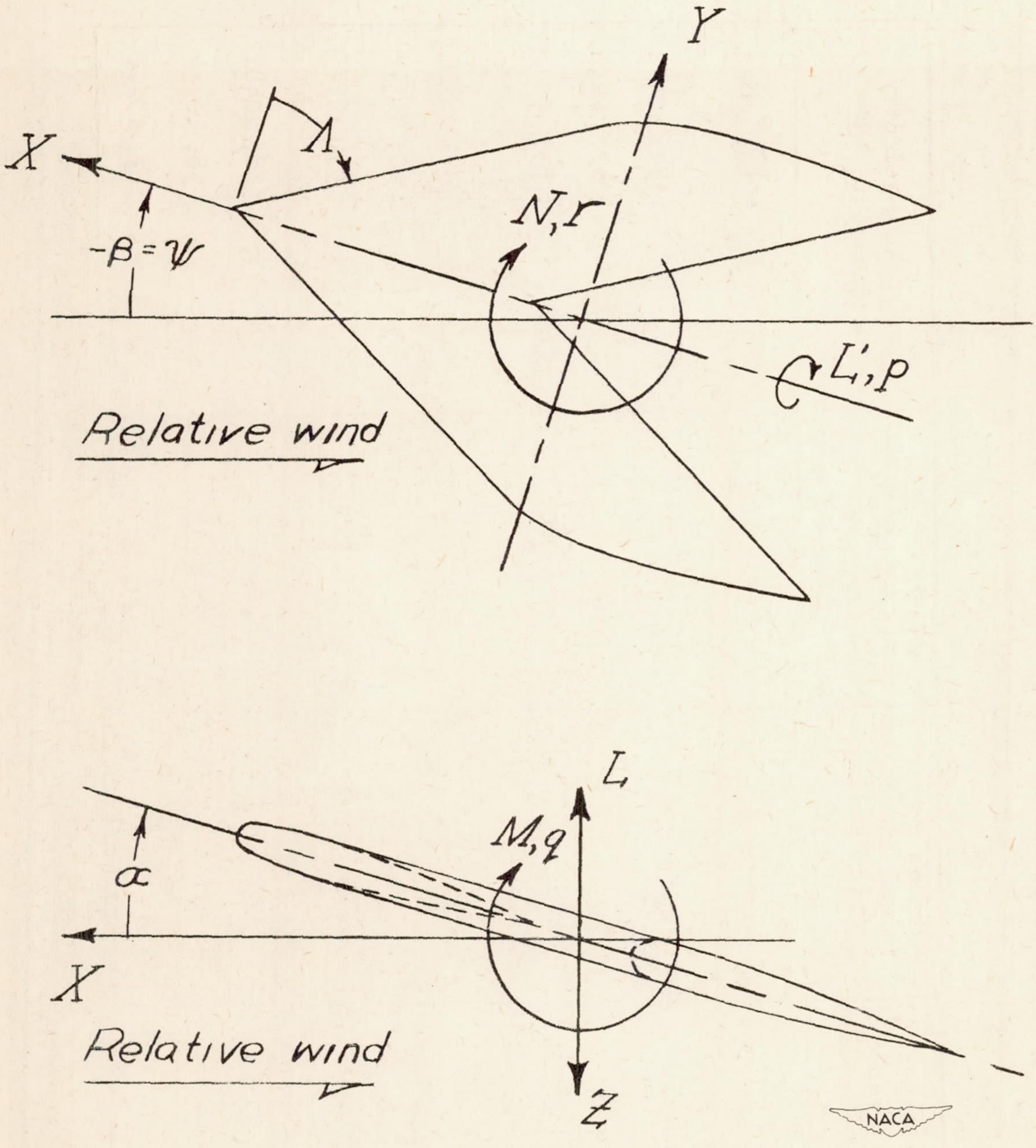


Figure 1.- Stability-axes system. Positive values of forces, moments, and angles are indicated.

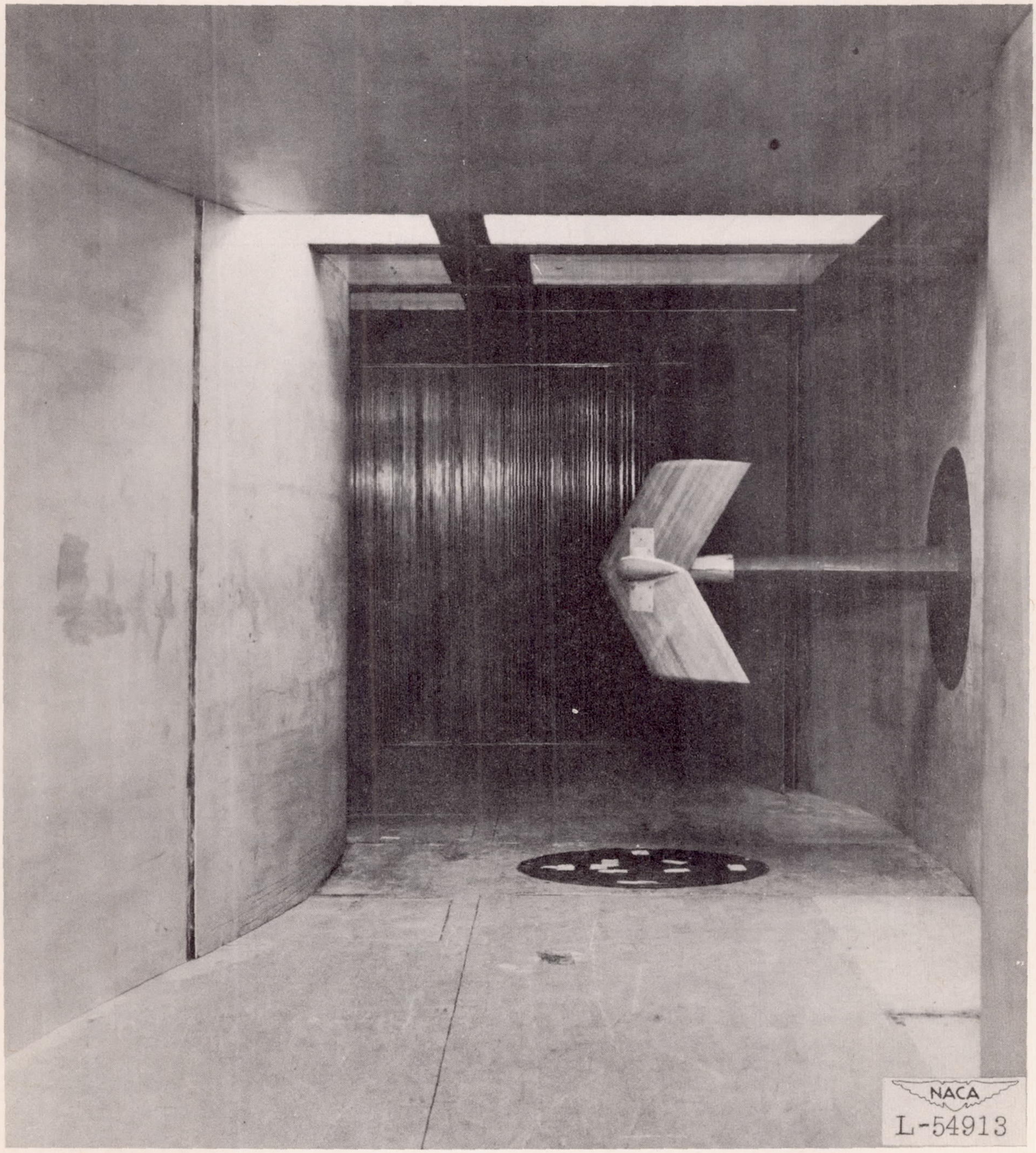
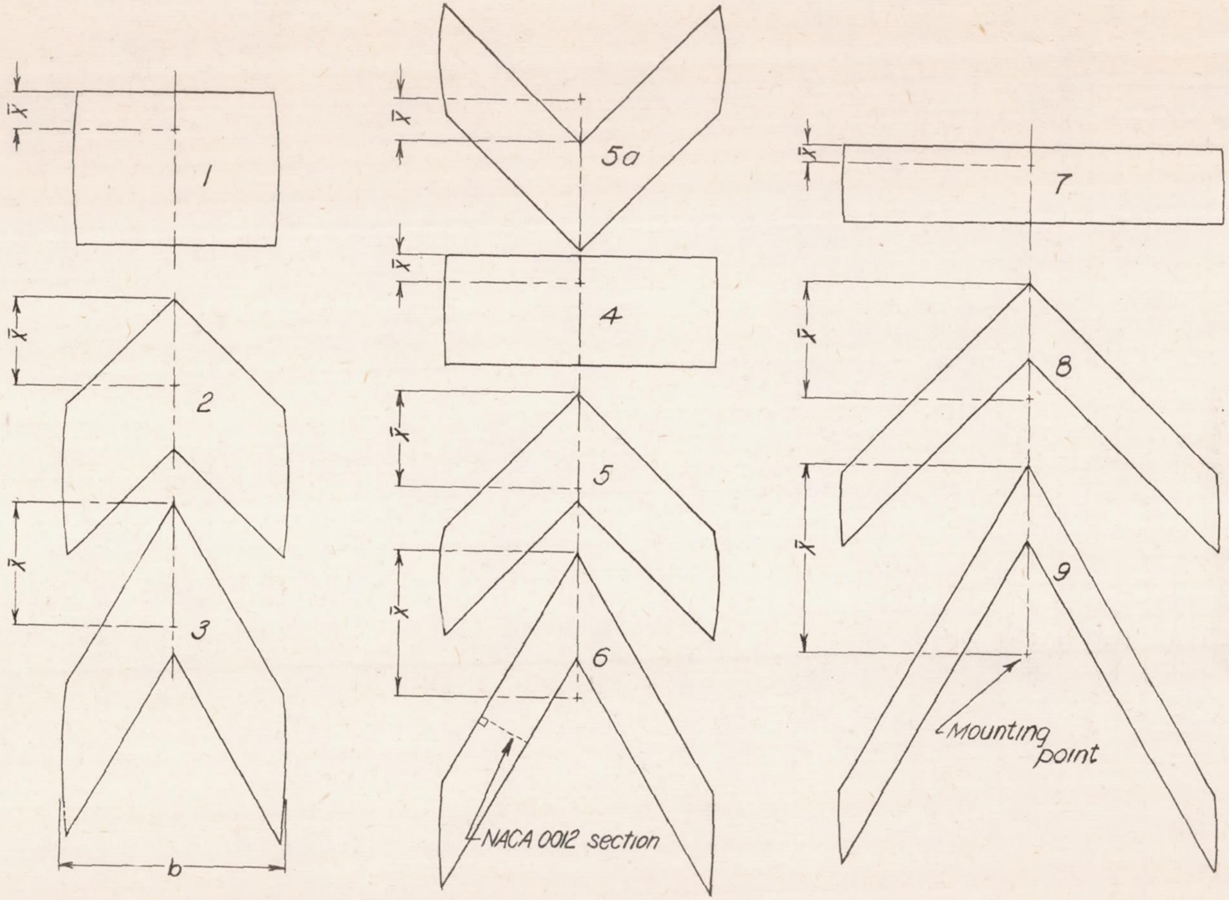


Figure 2.- Model mounted for pitching-flow tests in the Langley stability tunnel.



A	Wing	Λ (deg)	S (ft²)	b (ft)	$\bar{c}$ (ft)	$\bar{x}$ (ft)
1.34	1	0	3.64	2.21	1.68	0.41
	2	45	3.62	2.20	1.66	.96
	3	60	3.64	2.21	1.65	1.36

A	Wing	Λ (deg)	S (ft²)	b (ft)	$\bar{c}$ (ft)	$\bar{x}$ (ft)
2.61	5a	-45	3.56	3.05	1.17	-0.47
	4	0	3.60	3.08	1.18	.30
	5	45	3.56	3.05	1.17	1.05
	6	60	3.53	3.05	1.16	1.60

A	Wing	Λ (deg)	S (ft²)	b (ft)	$\bar{c}$ (ft)	$\bar{x}$ (ft)
5.16	7	0	3.52	4.26	0.83	0.21
	8	45	3.50	4.26	.83	1.26
	9	60	3.56	4.28	.83	2.06

Figure 3.- Plan forms of swept wings tested.

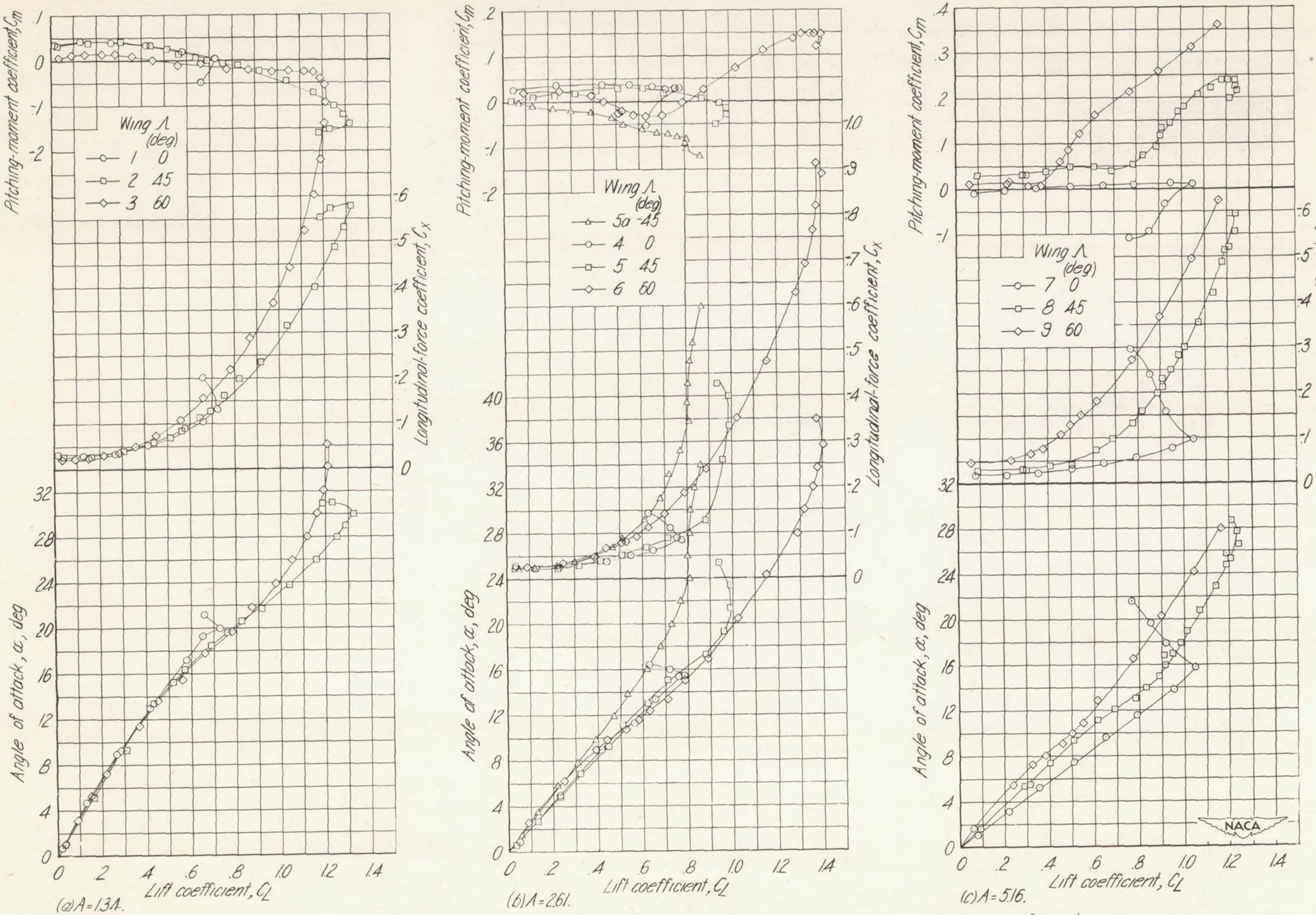


Figure 4.- Variation with lift coefficient of the static longitudinal aerodynamic characteristics of a series of swept wings.

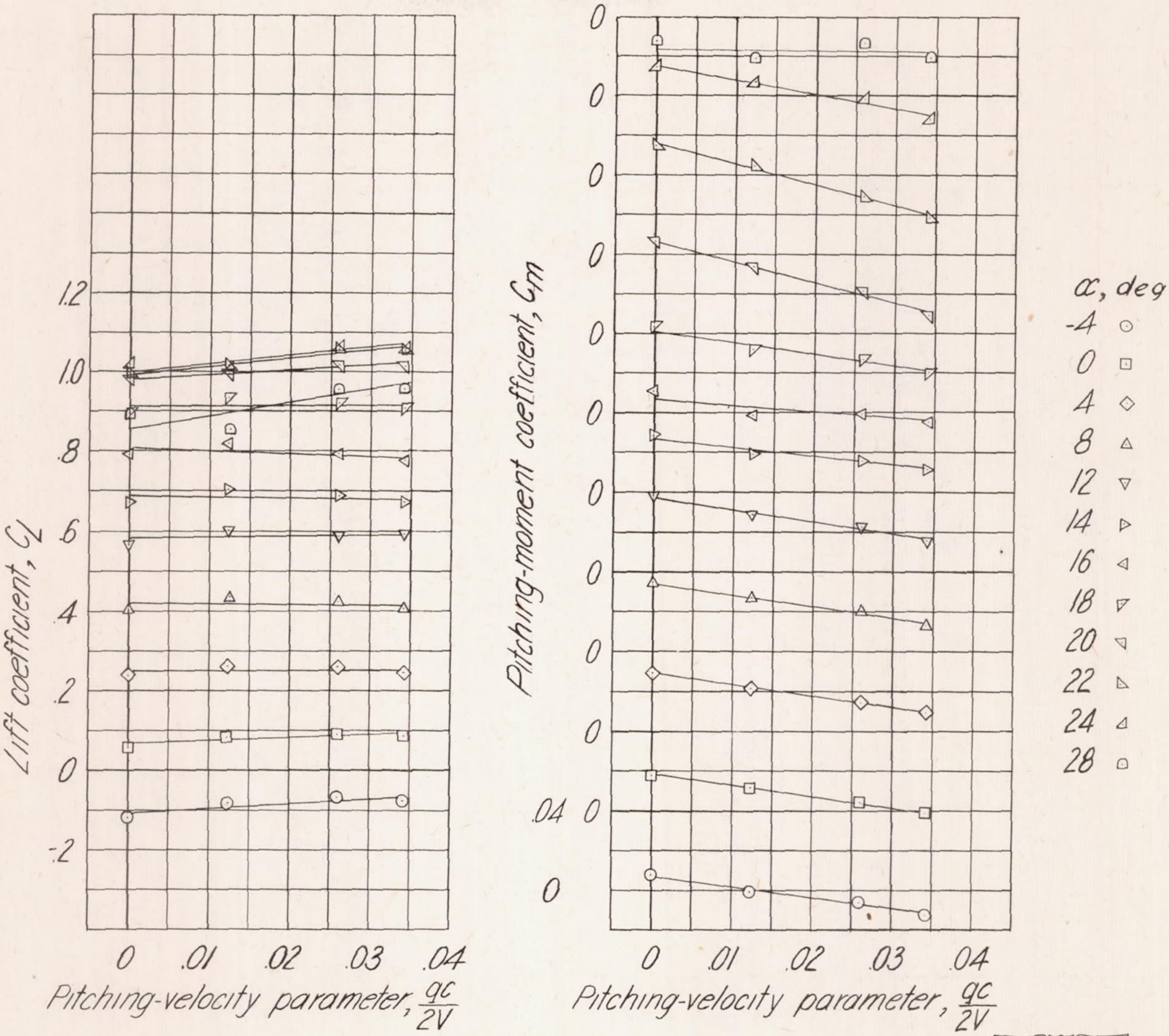


Figure 5.- Sample plots showing variation of C_L and C_m with pitching-velocity parameter $\frac{qc}{2V}$. Wing 5.

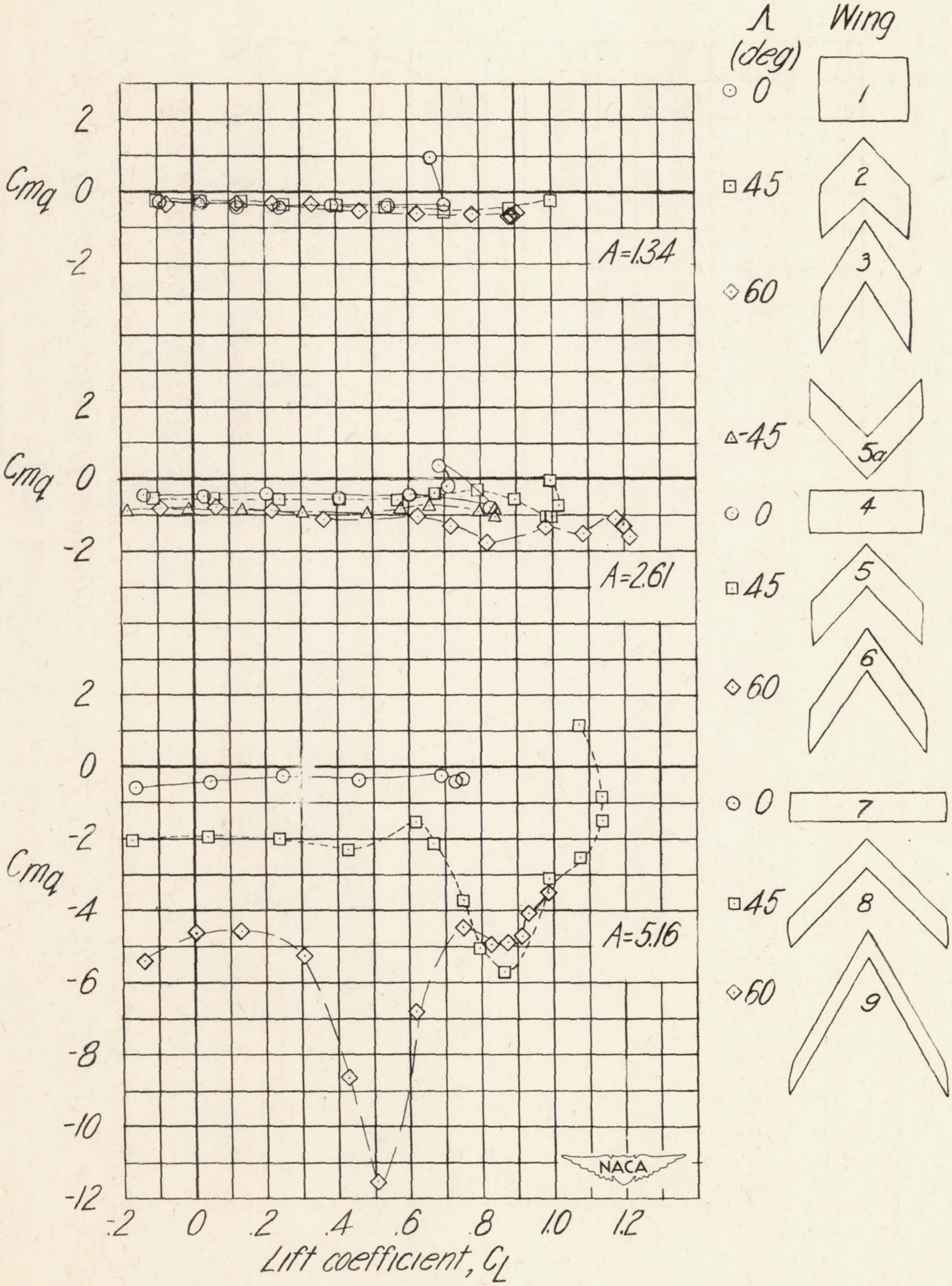


Figure 6.- Variation of damping-in-pitch parameter with lift coefficient.

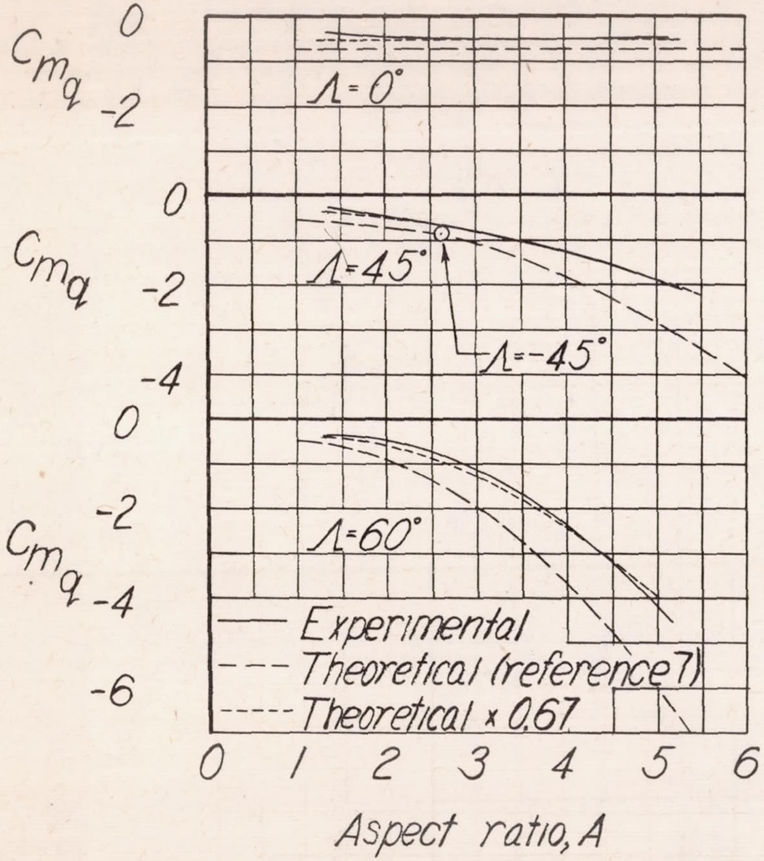


Figure 7.- Variation of damping-in-pitch parameter with aspect ratio. $C_L = 0$; $\frac{\bar{x}}{c} = 0$.

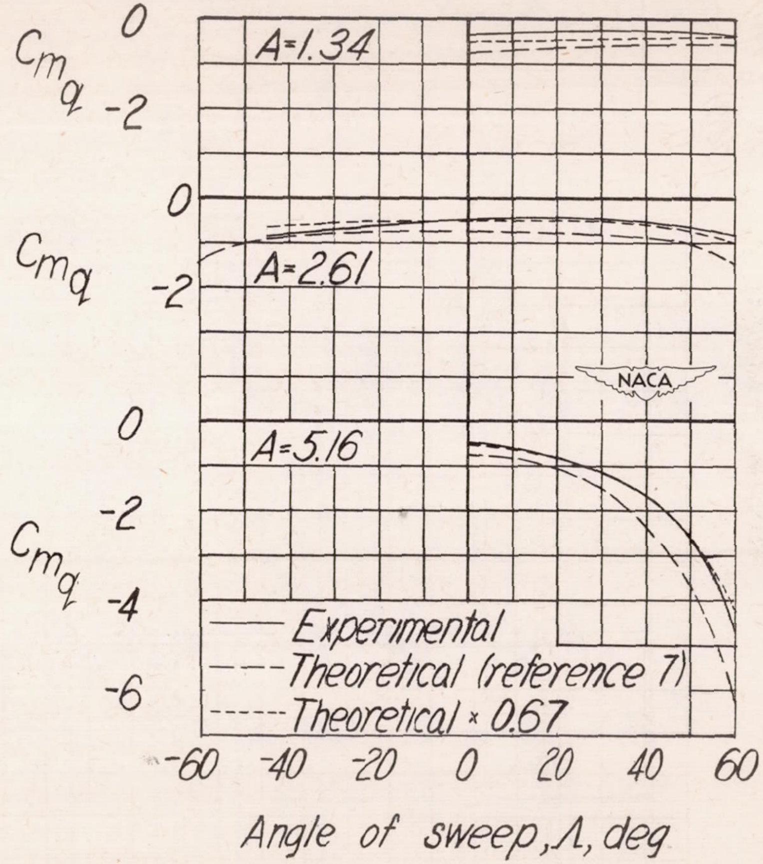


Figure 8.- Variation of damping-in-pitch parameter with sweep. $C_L = 0$; $\frac{\bar{x}}{c} = 0$.

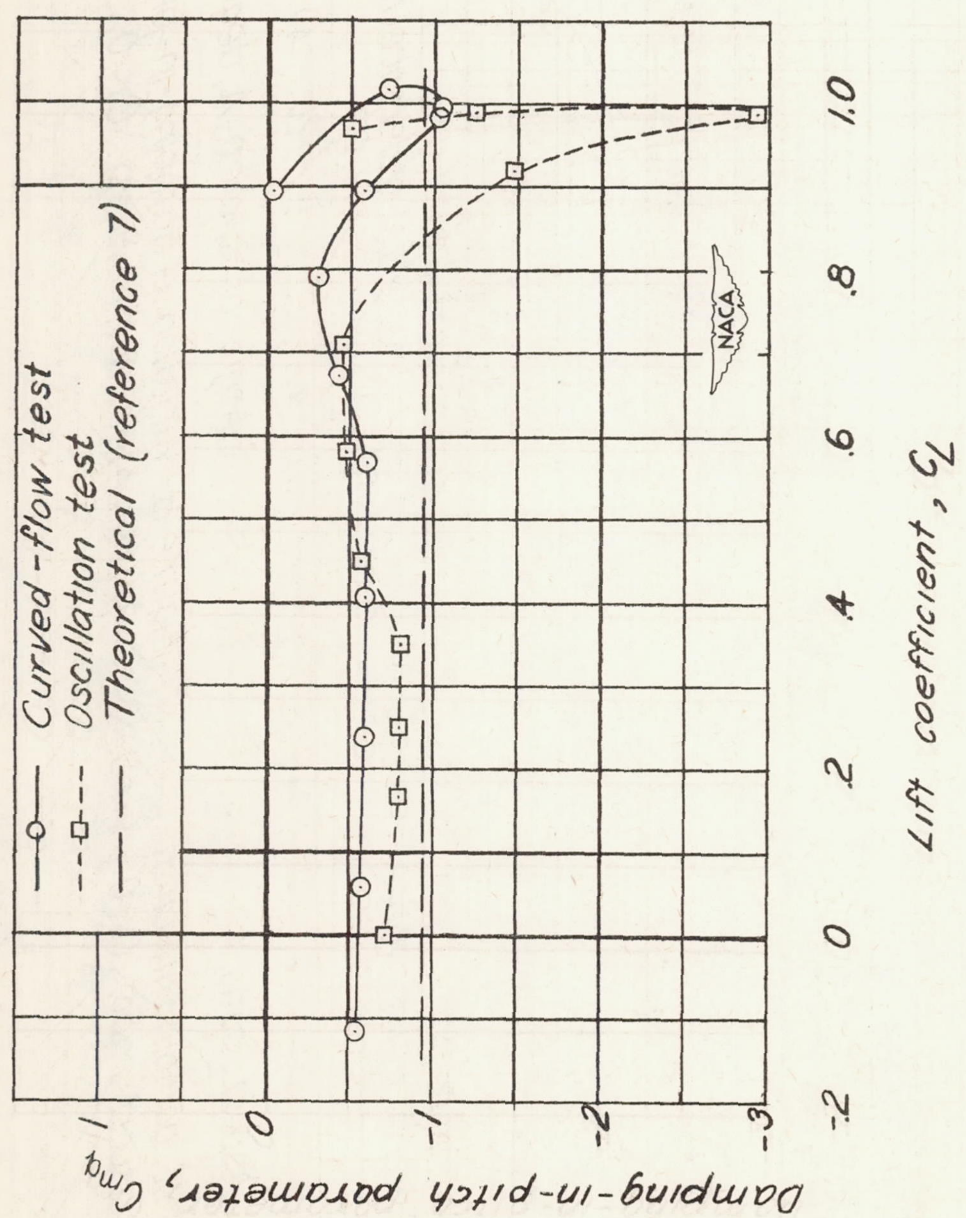


Figure 9.- Comparison of experimental and calculated values of C_{m_q}. Wing 5.

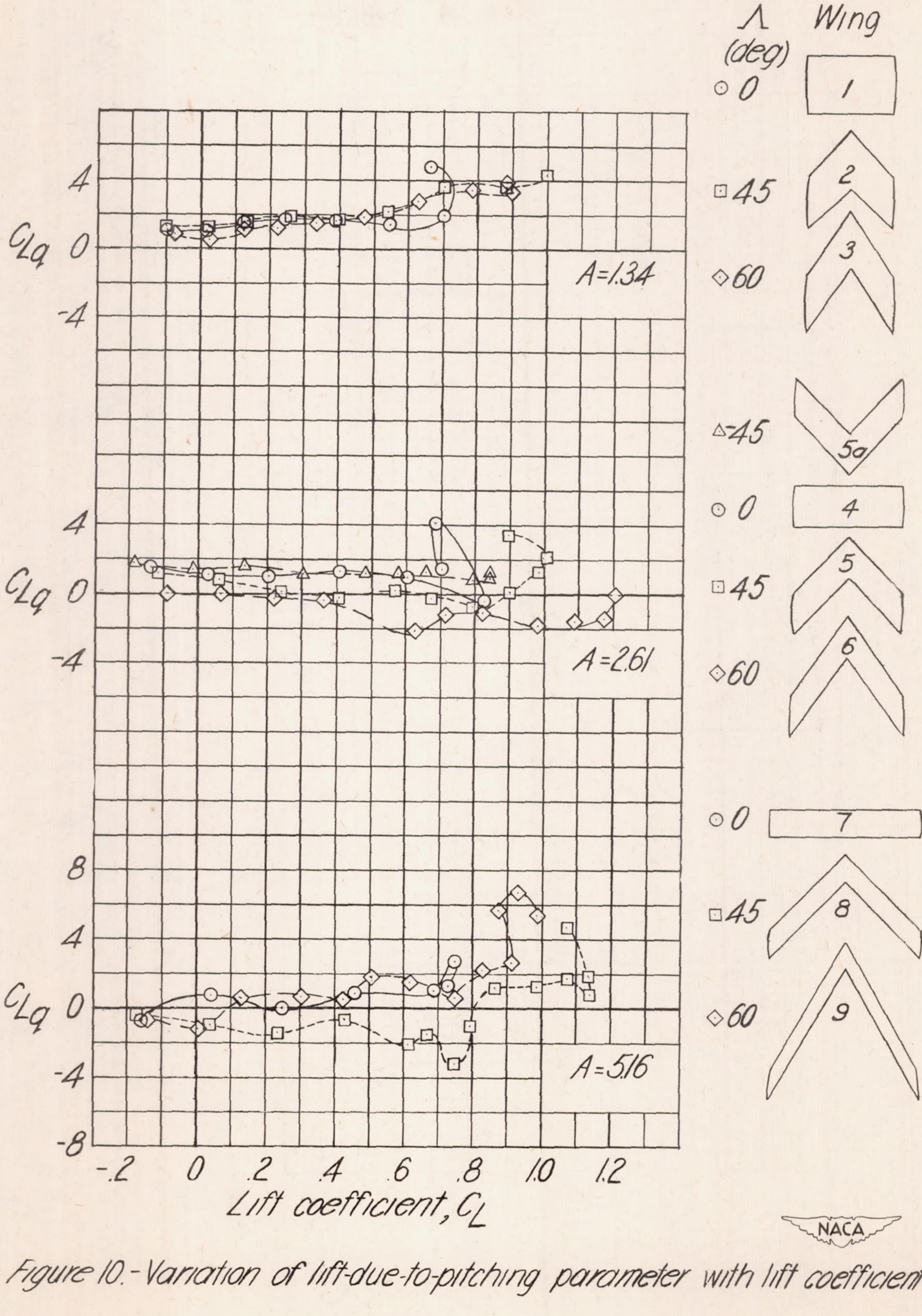


Figure 10.- Variation of lift-due-to-pitching parameter with lift coefficient.

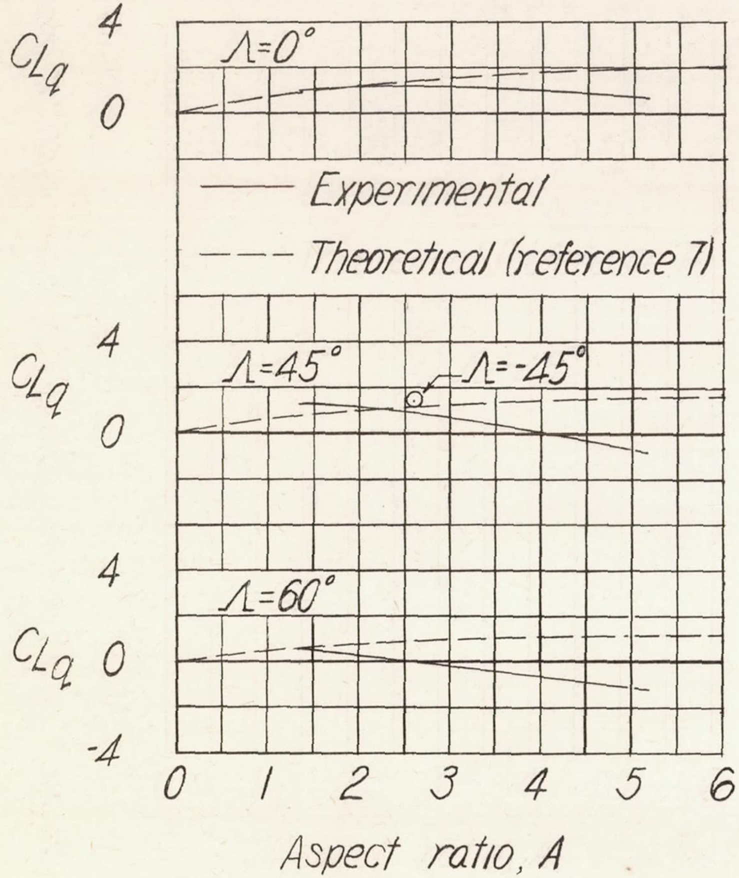


Figure 11.- Variation of lift due to pitching with aspect ratio. $C_L = 0$; $\frac{X}{c} = 0$.

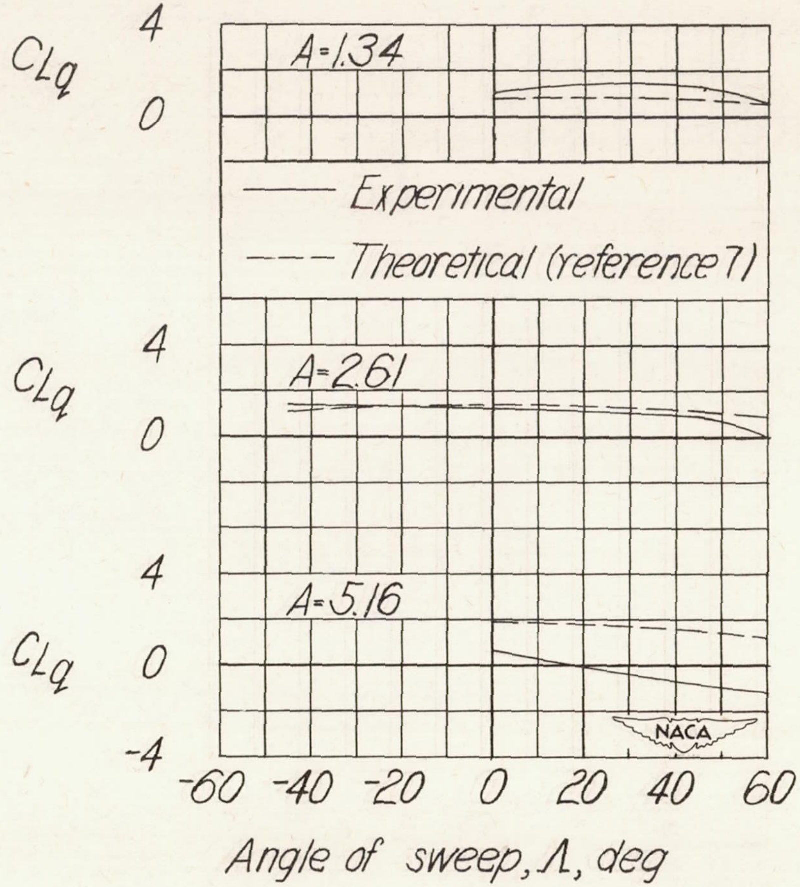


Figure 12.- Variation of lift due to pitching with sweep. $C_L = 0$; $\frac{X}{c} = 0$.