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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

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INVESTIGATION OF STABILITY AND CONTROL CHARACTERISTICS OF AN AIRPLANE MODEL WITH SKEWED WING IN THE LANGLEY FREE-FLIGHT TUNNEL

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SUMMARY

An investigation to determine the stability and control characteristics of an airplane model with a skewed wing has been made in the Langley free-flight tunnel. The wing of the model was pivoted in such a way that it could be rotated as a unit with respect to the fuselage so that one side of the wing was swept forward and the other side swept back. With an arrangement of this type the wing of an airplane could be set at right angles to the fuselage for take-off, landing, and low-speed flight and could be rotated to some large angle of skew to permit flight at high speeds.

In the investigation, flight tests, force tests, and damping-in-roll tests were made on the model with the wing set at angles of skew from 0° to 60°. This investigation was of an exploratory nature and was intended to provide only a preliminary and qualitative indication of whether such a design could be flown.

The results of the investigation indicated that it was possible to skew the wing as a unit to angles as great as 40° without encountering serious stability and control difficulties. At an angle of skew of 60°, however, the aileron control became unsatisfactorily weak. The aileron rolling effectiveness was not reduced by skewing the wing from 0° to 40° because the damping in roll decreased approximately the same amount as the aileron rolling moments. The force tests showed that for a skew angle of 40° the ailerons produced large pitching moments, but in the flight tests no pitching tendencies were observed in aileron rolls, apparently because the lift forces on the wing produced by rolling introduced pitching moments that were equal and opposite to the aileron pitching moments. The model did not exhibit the undesirably large variation of effective dihedral with lift coefficient that is characteristic of wings with large amounts of sweepback or sweepforward. Skewing the wing as a unit, however, did introduce large changes in lateral trim which varied with lift coefficient and skew angle.

INTRODUCTION

Theoretical and experimental investigations have shown that compressibility effects on a wing can be delayed by sweeping the wing forward or backward. In order to obtain a large increase in the Mach number at which compressibility effects occur, the use of angles of sweep of 40° or more is necessary, but these large angles of sweep introduce serious stability and control problems at moderate and high lift coefficients. For example, large angles of sweep produce undesirably large variations of effective dihedral and pitching-moment coefficient with lift coefficient. Also a rapid increase in drag occurs at moderate lift coefficients which is detrimental to take-off and climb performance and which complicates the landing problem.

In order to gain the advantages of sweep at high speeds without experiencing the difficulties introduced by sweep at low speeds, it has been proposed that an airplane be equipped with a wing pivotally attached to the fuselage so that it can be set at right angles to the fuselage for take-off, landing, and low-speed flight and at some angle of sweep for flight at high speeds. In one suggested design the wing is skewed or pivoted as a unit so that one side of the wing is swept forward and the other side swept back. In order to ascertain the low-speed stability and control characteristics of such a design an investigation has been conducted in the Langley free-flight tunnel. This investigation consisted in flight tests, force tests, and damping-in-roll tests of a model equipped with a pivoted wing that could be set at various angles of skew from 0° to 60°.

This investigation was of an exploratory nature and was intended to provide only a preliminary and qualitative indication of whether such a design could be flown. No attempt is therefore made in this paper to give a complete and comprehensive discussion of the stability and control problems involved in skewed-wing designs. Tests at higher scale of skewed-wing models more representative of high-speed airplane designs will probably be needed before an accurate and detailed analysis can be made of the stability and control characteristics of this type of airplane.

SYMBOLS AND COEFFICIENTS

The forces and coefficients were measured with reference to the stability axes. A diagram of these axes showing the positive directions of forces and moments is presented as figure 1, which shows the wing in the symmetrical (unskewed) condition. For skewed condition the axes are determined by the fuselage rather than by the wing.

C_L	lift coefficient $\left(\frac{\text{Lift}}{qS}\right)$
C_D	drag coefficient $\left(\frac{\text{Drag}}{qS}\right)$
M	pitching moment
L	rolling moment
N	yawing moment
C_m	pitching-moment coefficient $\left(\frac{M}{qS\bar{c}}\right)$
C_l	rolling-moment coefficient $\left(\frac{L}{qSb}\right)$
C_n	yawing-moment coefficient $\left(\frac{N}{qSb}\right)$
C_Y	lateral-force coefficient $\left(\frac{\text{Lateral force}}{qS}\right)$
S	wing area, square feet
$\bar{c}$	mean aerodynamic chord of unskewed wing, feet
b	span of unskewed wing, feet
q	dynamic pressure, pounds per square foot $\left(\frac{1}{2}\rho V^2\right)$
V	airspeed, feet per second
ρ	mass density of air, slug per cubic foot
β	angle of sideslip, degrees
ψ	angle of yaw, degrees; for force-test data equals $-\beta$
ζ	skew angle (angle through which wing is rotated with respect to the fuselage), degrees
δ_a	aileron deflection, degrees
δ_e	elevator deflection, degrees
δ_r	rudder deflection, degrees
ϕ	angle of roll, degrees

α	angle of attack, degrees
X	longitudinal axis
Y	lateral axis
Z	normal axis
k_X	radius of gyration of model about X-axis, feet
k_Z	radius of gyration of model about Z-axis, feet
$\frac{pb}{2V}$	aileron-rolling-effectiveness factor or helix angle generated by wing tip in roll, radians
p	rolling angular velocity, radians per second
C_{l_β}	effective-dihedral parameter; rate of change of rolling-moment coefficient with angle of sideslip, per degree $\left(\partial C_l/\partial\beta\right)$
C_{n_β}	directional-stability parameter; rate of change of yawing-moment coefficient with angle of sideslip, per degree $\left(\partial C_n/\partial\beta\right)$
C_{l_p}	damping-in-roll parameter; rate of change of rolling-moment coefficient with rolling-angular-velocity factor $\left(\dfrac{\partial C_l}{\partial\frac{pb}{2V}}\right)$

APPARATUS AND MODEL

The flight tests and force tests were conducted in the Langley free-flight tunnel, a complete description of which is given in reference 1. A photograph of the tunnel test section with the model in flight is presented as figure 2. All force tests were made on the free-flight-tunnel balance (reference 2) which measures forces and moments about the stability axes.

The values of the damping-in-roll derivative C_{l_p} were determined by rotation tests in the Langley 15-foot free-spinning tunnel by the method described in reference 3.

A sketch of the model used in the tests is presented as figure 3, and a photograph of the model is presented as figure 4. The model fuselage consisted of a boom on which was mounted the rotatable wing and fixed horizontal and vertical tails. The wing was mounted by a pivot at the 50-percent-chord point so that it could be skewed to any angle up to 60°. In all tests the wing was skewed so that the right side was swept back and the left side swept forward, as shown in figure 3. The dimensional and mass characteristics of the model are given in table I.

TESTS

Force tests were made to determine the static stability and aileron control characteristics of the model with skew angles of 0°, 20°, 40°, and 60°. Force tests were also made to determine the longitudinal stability of the model with horizontal tail off for skew angles of 0°, 40°, and 60°. No control-effectiveness tests were made for elevator and rudder. All force tests were made at a dynamic pressure of 1.9 pounds per square foot which corresponds to a test Reynolds number of 179,000 at 0° skew based on the mean aerodynamic chord.

All rolling-moment and yawing-moment data obtained in the tests with different skew angles are based on the span of the unskewed wing and all pitching-moment data are based on the mean aerodynamic chord of the unskewed wing. All test data are referred to the normal center of gravity at 20 percent of the mean aerodynamic chord of the unskewed wing unless otherwise noted on the figures. If it is desired, the moments can be based on the span and chord of the skewed wing by using the values given in table I for the different skew angles.

Rotation tests were made to determine the damping in roll for the model with skew angles of 0°, 20°, 40°, and 60° at a lift coefficient of 0.5. All damping-in-roll tests were made at a dynamic pressure of 3.0 pounds per square foot which corresponds to a Reynolds number of 226,000 at 0° skew.

Flight tests of the model with the center of gravity at 0.20 mean aerodynamic chord of the unskewed wing were made at a lift coefficient of approximately 0.6 for skew angles of 0°, 10°, 20°, 30°, 40°, 50°, and 60°. In addition, for the same center-of-gravity location, flight tests were made over a lift-coefficient range from 0.3 to 1.0 for 0° and 40° skew. Further flight tests were made with 40° skew at lift coefficients from 0.6 to 0.9, and the center of gravity was moved successively back to 0.25, 0.30, and 0.35 mean aerodynamic chord of the unskewed wing. In the flight tests, abrupt deflections of approximately ±18° aileron (total 36°), ±5° rudder, and ±5° elevator were used for controlling the model. Reference 1 describes the flight-testing technique used in the Langley free-flight tunnel.

RESULTS AND DISCUSSION

Force-Test Results

Longitudinal stability.- The results of the force tests made to determine the longitudinal stability characteristics of the model are presented in figures 5 to 7. The data of figure 5 show that as the skew angle of the model was increased from 0° to 60°, the static longitudinal stability (as indicated by the slope of the pitching-moment curve) progressively decreased until at 60° skew the model was longitudinally unstable at lift coefficients above 0.7.

The data of figure 6 show that with the horizontal tail off the reduction in longitudinal stability with increasing skew was even more pronounced. A comparison of the data of figures 5 and 6 indicates that the addition of the horizontal tail greatly reduced the variation in longitudinal stability over the lift range for the 40° and 60° skewed wings.

The data of figures 5 and 6 show the expected reduction in lift-curve slope with increasing skew. The slopes of the lift curves are approximately proportional to the cosine of the angle of skew.

The force-test data of figure 7 show the longitudinal stability and trim characteristics of the model with 40° skew for the most forward and rearward center-of-gravity locations used in flight tests. Those data show that for the most rearward center-of-gravity location the model was either statically longitudinally unstable or about neutrally stable over the entire lift-coefficient range.

Lateral stability.- The results of the force tests made to determine the lateral-stability characteristics of the model at a lift coefficient of 0.6 at zero angle of yaw are shown in figure 8. The effects of skew on the directional-stability parameter C_{n_β} and on the effective dihedral parameter C_{l_β} as determined by the slopes of the curves between ±10° in figure 8 can be summarized as follows:

Skew angle	C_{n_β}	C_{l_β}
0°	0.0034	-0.0006
40°	.0033	-.0008
60°	.0023	-.0006

The values of C_{l_β} for the model are considerably smaller than the values normally encountered at a lift coefficient of 0.6 on wings with large amounts of sweepback.

The lateral-trim changes caused by skewing the wing from 0° to 40° and 60° can be seen from the data for zero angle of yaw in figure 8 and from the lateral-component data of figures 5 and 6. The data of figure 8 for a lift coefficient of 0.6 show that with increasing skew an increasing positive (right) lateral force and an increasing negative (left) rolling moment occurred. Changing the skew from 0° to 40° caused a negative (left) yawing moment but a further increase in skew to 60° produced a positive (right) yawing moment. The data of figures 5 and 6 show that the changes in lateral trim varied considerably with angle of attack.

If the pivot point of the wing were shifted forward the change in rolling moments with skew at low lift coefficients would be reduced because the area of the left wing would be increased with increasing skew.

Lateral control.- The results of the force tests made to determine the aileron effectiveness are shown in figures 9 and 10. These results show that the aileron effectiveness in producing rolling moment was somewhat reduced by skewing the wing to 40° and was greatly reduced by skewing the wing to 60°. When deflected the ailerons at the 40° and 60° skew angles also produced sizable pitching moments. The pitching moment produced by the ailerons was much greater at 40° skew angle than at 60°, apparently, because of the reduced effectiveness of the ailerons in producing lift at 60° skew.

The data in figure 10, which show the independent contributions of the right and left ailerons to the aerodynamic moments, indicate that the left (leading) aileron was most affected by skew angle, and that at 40° and 60° skew its effectiveness in producing rolling moment was somewhat less than that of the right (trailing) aileron. This difference can be attributed to the increase in wing area ahead of the trailing aileron.

Rotation-Test Results

The results of the damping-in-roll tests are shown in figure 11 together with the rolling effectiveness of the ailerons based on the rolling-moment data of figure 9. These data show that the damping in roll was reduced by skew to such an extent that the ailerons remained effective to angles of skew greater than 40°.

The damping-in-roll data based on the projected span at each skew angle (rather than on the span of the wing with 0° skew) are presented in figure 12 for the purpose of comparing the data with calculations made by the simple relation presented in reference 3. This figure shows that the damping in roll varied approximately as the cosine of the skew angle, as would be expected from the data of reference 3 for conventionally swept-back wings.

Flight-Test Results

In the flight tests of the model with the center of gravity at 0.20 mean aerodynamic chord the general flight characteristics were satisfactory and remained essentially unchanged as the wing was skewed from 0° to 40° by 10°-increments. With the wing skewed 50° the flight characteristics of the model were satisfactory except that the aileron effectiveness was noticeably reduced and some difficulty was consequently experienced in controlling the model. With 60° skew the aileron effectiveness was even further reduced and was inadequate for maintaining sustained flights of sufficient length to permit judging the other stability and control characteristics of the model. These flight-test results are in agreement with the force-test results of figures 10 to 12 in regard to the reduction in aileron effectiveness with 60° skew.

No pronounced changes in stability and control were apparent with skew angles up to 40° but sizable changes in lateral trim were noted. When the skew angle was increased from 0° to 40° while the flight lift coefficient was held constant at about 0.6, use of a total of about 17° right aileron trim and 3° right rudder setting was necessary to maintain lateral trim, (that is, to keep the wing level and the fuselage at zero sideslip). As the flight lift coefficient was increased at 40° skew, however, progressively smaller amounts of aileron and rudder trim were required until at a lift coefficient of 1.0 no trim was needed. These trim changes were indicated by the force-test results of figures 5, 6, and 8.

When the skew angle was changed from 0° to 40°, only slight changes in elevator setting (not over 3°) were required to maintain the same flight lift coefficient. With 40° skew, however, the glide-path angle was 2° or 3° higher than with 0° skew over the lift-coefficient range from about 0.3 to 1.0. This result is substantiated by the force-test data of figure 5 which indicate that the drag at 40° skew is higher than that at 0° skew at a given lift coefficient. The force-test results in figure 5 show that at lift coefficients greater than 1.0 the drag at a given lift coefficient (and hence the glide-path angle) for the 40° skew angle became increasingly greater than that of the unskewed wing.

In the flight tests of the 40° skewed wing satisfactory flights were made over a lift-coefficient range from 0.3 to 1.0 with static margins (static longitudinal stability) from large values to very small values. The flight characteristics appeared to be slightly better at the lower lift coefficients. No pronounced changes in the longitudinal stability characteristics were noted as the static margin was progressively decreased by moving the center of gravity from 0.20 to 0.25 and 0.30 mean aerodynamic chord. With the center of gravity at 0.35 mean aerodynamic chord, however, the model appeared to be longitudinally unstable and continuous application of elevator control was required to keep the model flying. The force-test data of figure 7 indicate static longitudinal instability for the foregoing condition.

In the flight tests no pitching motions with aileron control were noted for any skew angle, lift coefficient, or center-of-gravity location. This result appears to disagree with the force-test results of figures 9 and 10 which showed sizable pitching moments with aileron deflection for 40° skew. This apparent discrepancy is explained by the fact that during a steady aileron roll, lift forces due to rolling are produced which are equal and opposite to the lift forces produced by the ailerons. These lift forces due to rolling produce pitching moments that are equal and opposite to the aileron pitching moments and hence eliminate the pitching tendencies in a steady aileron roll. No flights were made to determine the effects of these aileron pitching moments in a steady sideslip.

CONCLUSIONS

The results of the investigation in the Langley free-flight tunnel to determine the stability and control characteristics of an airplane model with a skewed wing are summarized as follows:

1. In general, the results indicate that an airplane wing can be skewed as a unit to angles as great as 40° without encountering serious stability and control difficulties.

2. Longitudinal stability and control:

(a) The longitudinal stability and control characteristics were satisfactory in flights made with 40° skew over a lift-coefficient range from 0.3 to 1.0 even for very low values of static margin.

(b) Only a slight change in longitudinal trim occurred with increasing skew but an appreciable increase occurred in the glide angle required at a given lift coefficient.

3. Lateral stability:

(a) The values of effective dihedral for the wing skewed as a unit were considerably less than those encountered on wings with large amounts of sweepforward or sweepback.

(b) Skewing the wing caused sizable changes in the lateral trim which varied with lift coefficient and skew angle.

4. Lateral control:

(a) The aileron control effectiveness was only slightly reduced by skew for angles less than 40° because the damping in roll decreased approximately the same amount as the aileron rolling moments. At 50° skew, however, the aileron control effectiveness was noticeably reduced, and at 60° it was so weak that sustained flights could not be made.

(b) The force tests indicated that for 40° skew angle the ailerons produced large pitching moments. In the flight tests, however, no pitching tendencies were observed in aileron rolls, apparently because the lift forces on the wing produced by rolling introduced pitching moments that were equal and opposite to the aileron pitching moments.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., July 23, 1946

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1. Shortal, Joseph A., and Osterhout, Clayton J.: Preliminary Stability and Control Tests in the NACA Free-Flight Wind Tunnel and Correlation with Full-Scale Flight Tests. NACA TN No. 810, 1941.

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. Bennett, Charles V., and Johnson, Joseph L.: Experimental Determination of the Damping in Roll and Aileron Rolling Effectiveness of Three Wings Having 2°, 42°, and 62° Sweepback. NACA TN No. 1278, 1947.

TABLE I

DIMENSIONAL AND MASS CHARACTERISTICS OF MODEL USED IN SKEWED-WING INVESTIGATION

Weight, lb	4.73 to 5.03
Wing:	
Area, sq ft	2.67
Span, ft	
0° skew	4.00
40° skew	3.07
60° skew	2.00
Mean aerodynamic chord, ft	
0° skew	.70
40° skew	.91
60° skew	1.40
Aspect ratio (0° skew)	6.0
Sweepback of 0.25-chord line, deg	3.0
Dihedral, deg	0
Taper ratio (ratio of tip chord to root chord)	0.50
Root chord, ft (0° skew)	0.90
Tip chord, ft (0° skew)	0.45
Loading, lb per sq ft	1.78 to 1.89
Radii of gyration (for 0° skew):	
k_X, ft	0.625
k_Z, ft	0.844
Ailerons:	
Type	Plain
Area	
Sq ft	0.19
Percent S	7
Span, percent b	44

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TABLE I

DIMENSIONAL AND MASS CHARACTERISTICS OF MODEL USED IN SKEWED-WING INVESTIGATION - Concluded

Horizontal Tail:	
Area	
Sq ft	0.53
Percent S	20
Aspect ratio	4
Tail length, hinge line to center of gravity, ft	2
Vertical tail:	
Area	
Sq ft	0.4
Percent S	15
Aspect ratio	2
Tail length, hinge line to center of gravity, ft	2

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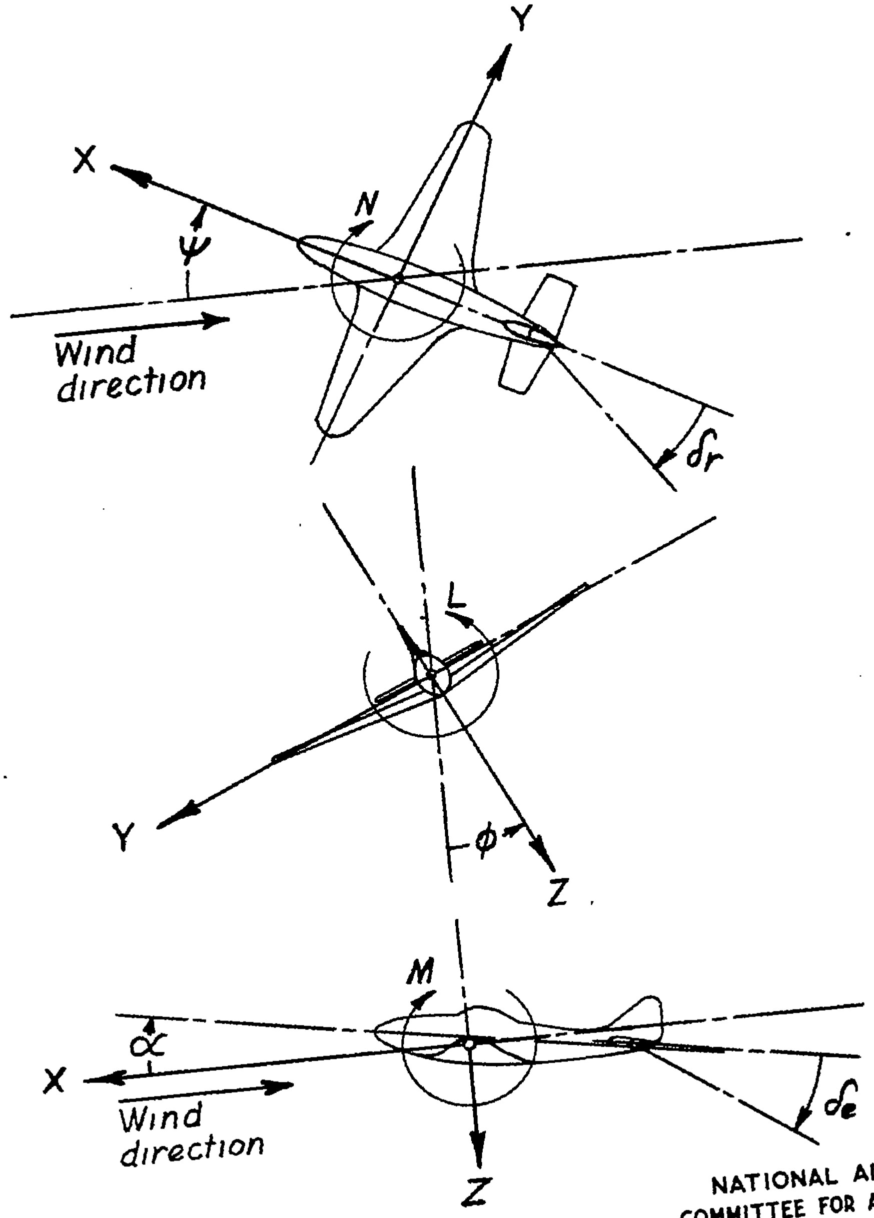

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Figure 1.—The stability system of axes is defined as an orthogonal system of axes having their origin at the center of gravity and in which the Z-axis is in the plane of symmetry and perpendicular to the relative wind, the X-axis is in the plane of symmetry and perpendicular to the Z-axis, and the Y-axis is perpendicular to the plane of symmetry. Arrows indicate positive directions of moments, forces, and control-surface deflections.

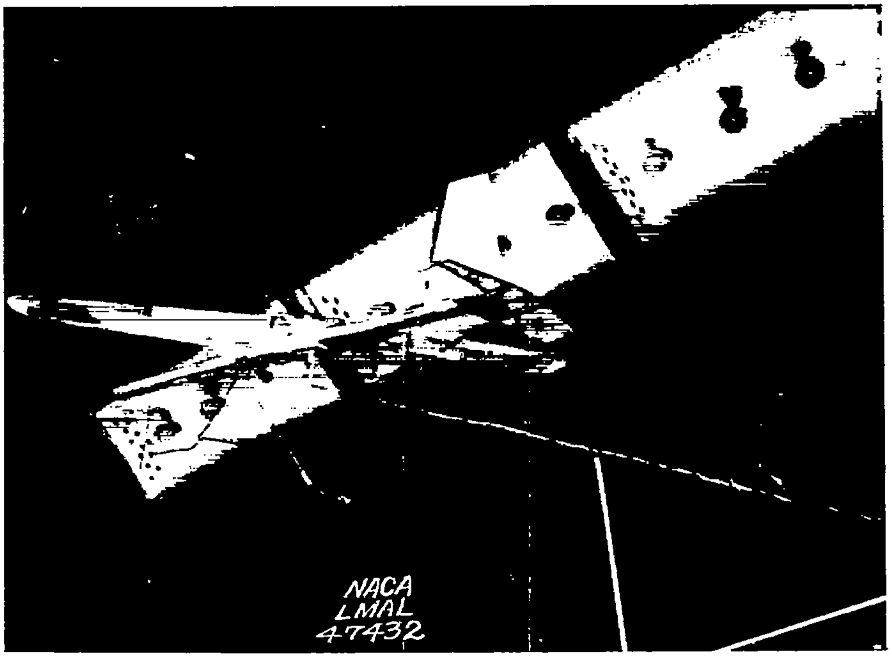

Figure 2.- Model with skewed wing flying in Langley free-flight tunnel. 40° skew.

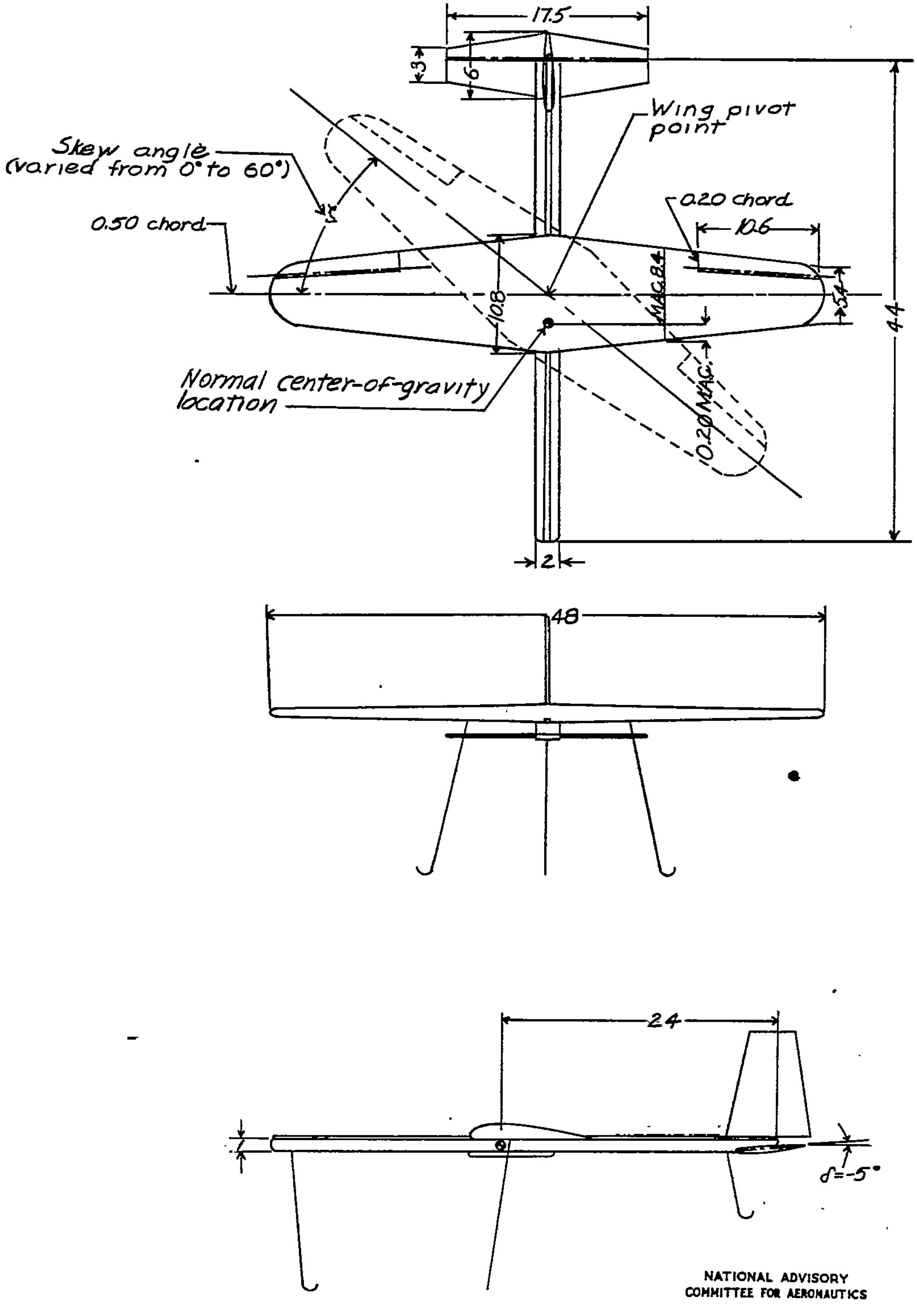

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Figure 3.-Three-view sketch of model used in adjustable-skewed-wing investigation. (All dimensions in inches.)

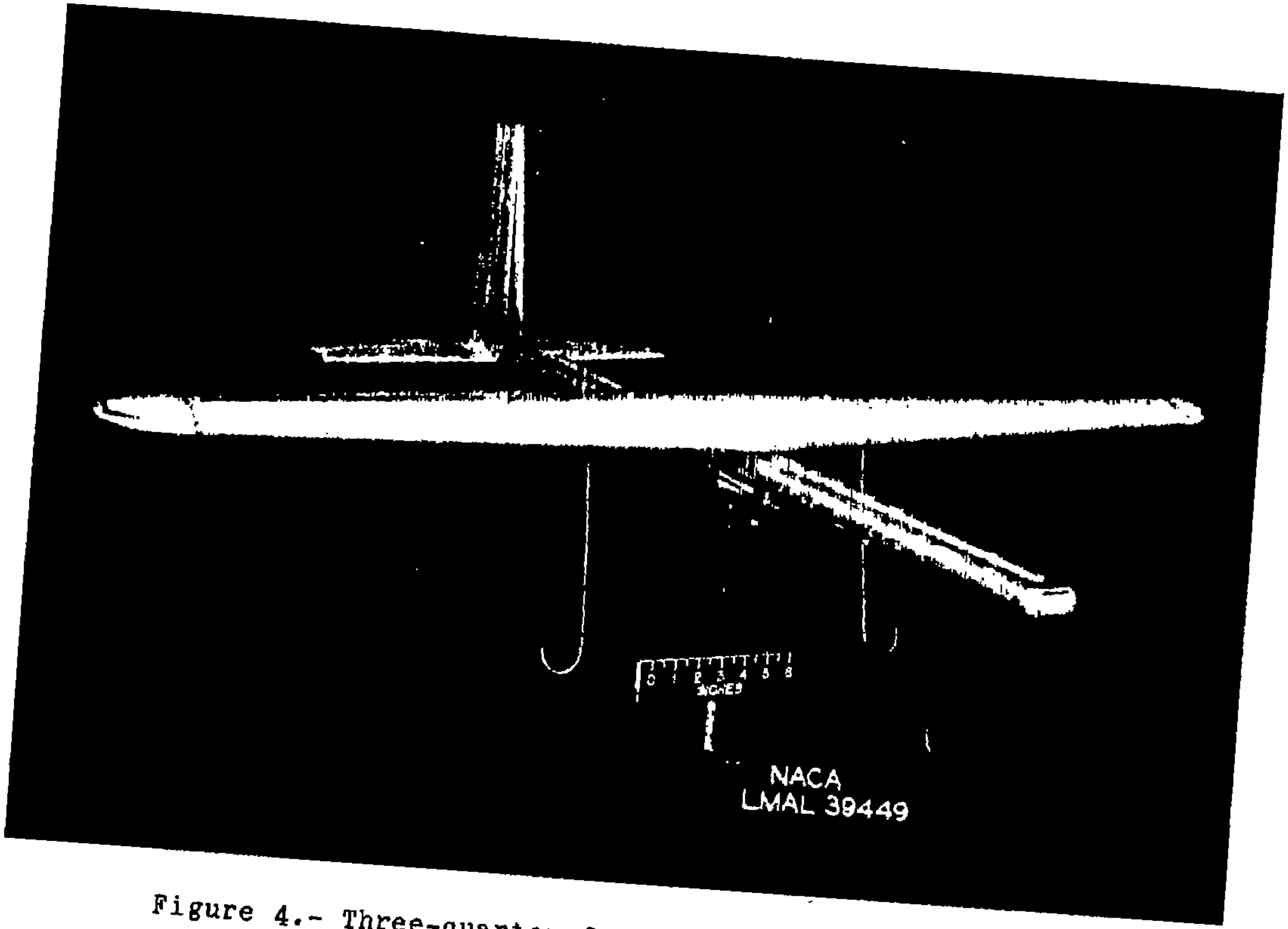

Figure 4.- Three-quarter front view of model used in skewed-wing investigation. 0° skew.

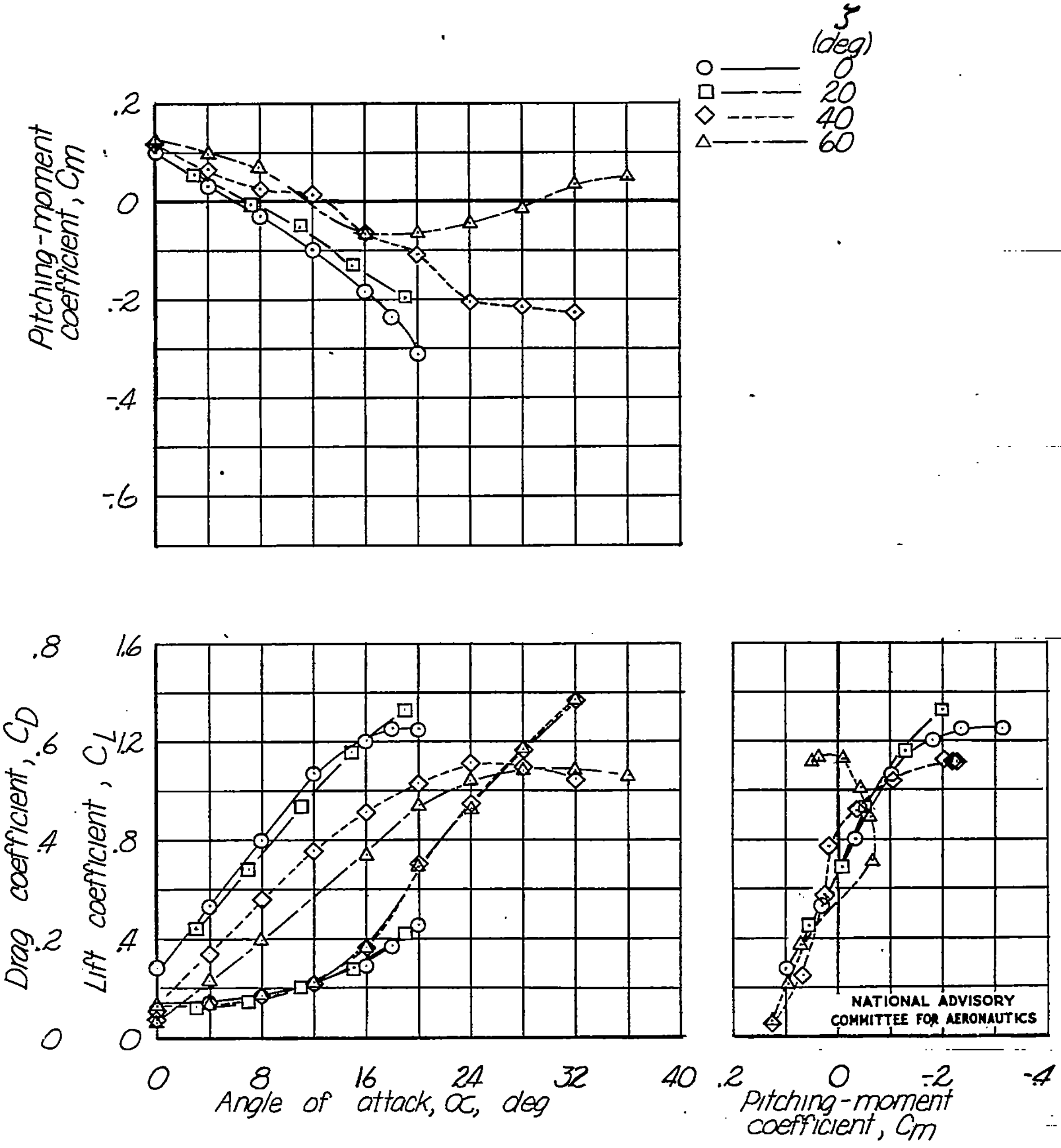

Figure 5.- Effect of skew angle on the aerodynamic characteristics of the complete skewed-wing model.

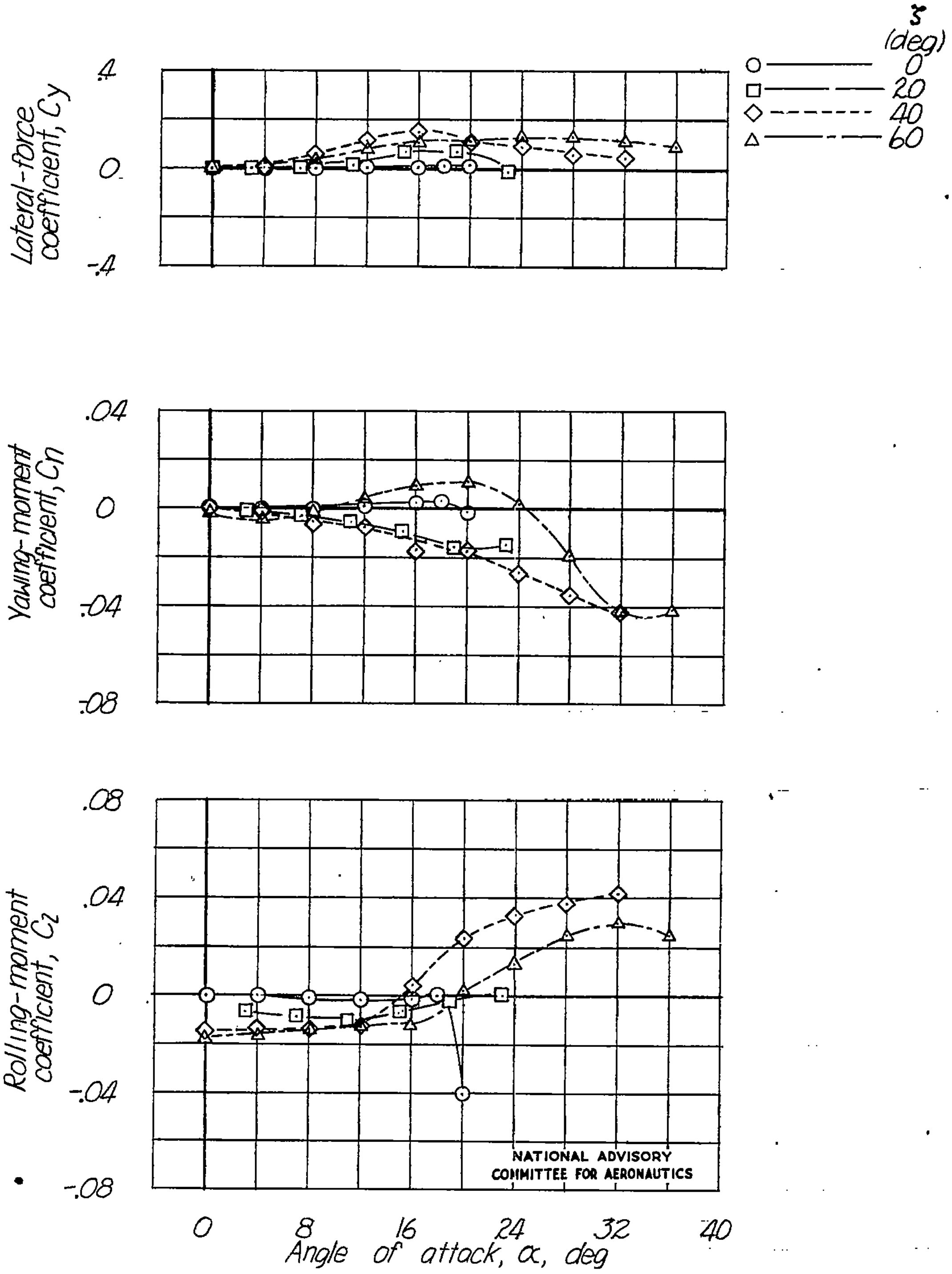

Figure 5.- Concluded.

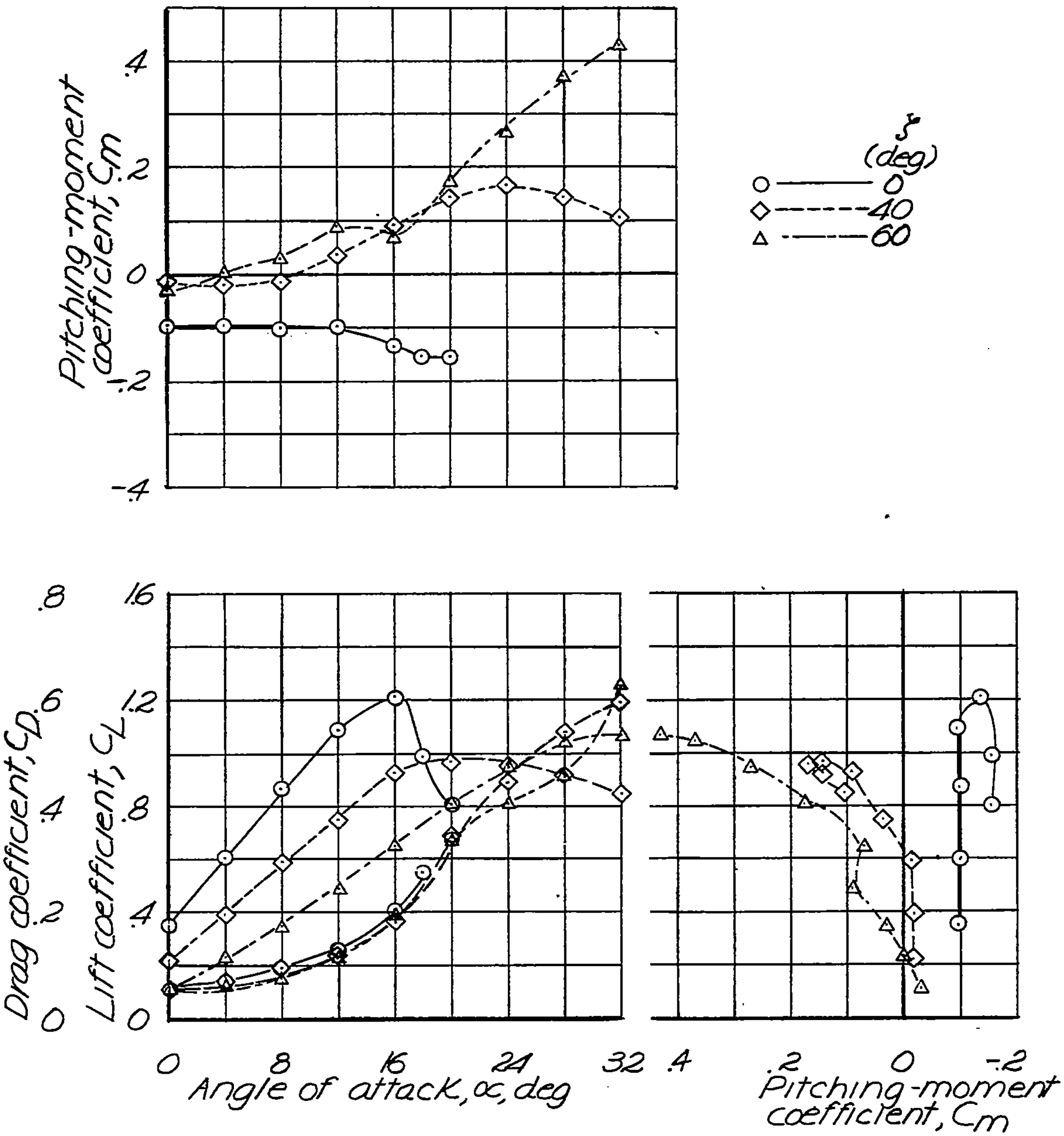

Figure 6.- Effect of skew angle on the aerodynamic characteristics of the skewed-wing model with the horizontal tail removed.

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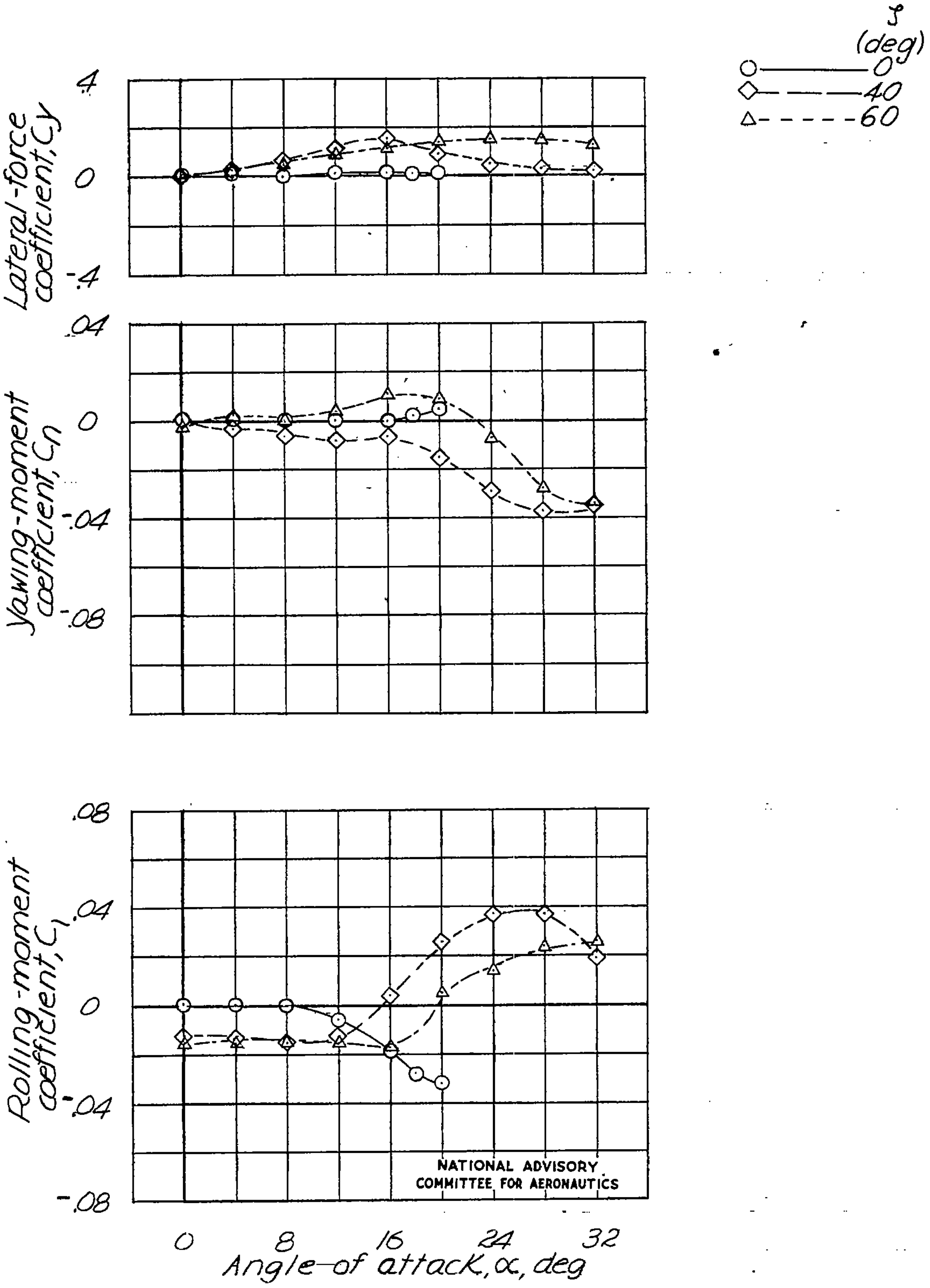


Figure 6.- Concluded.

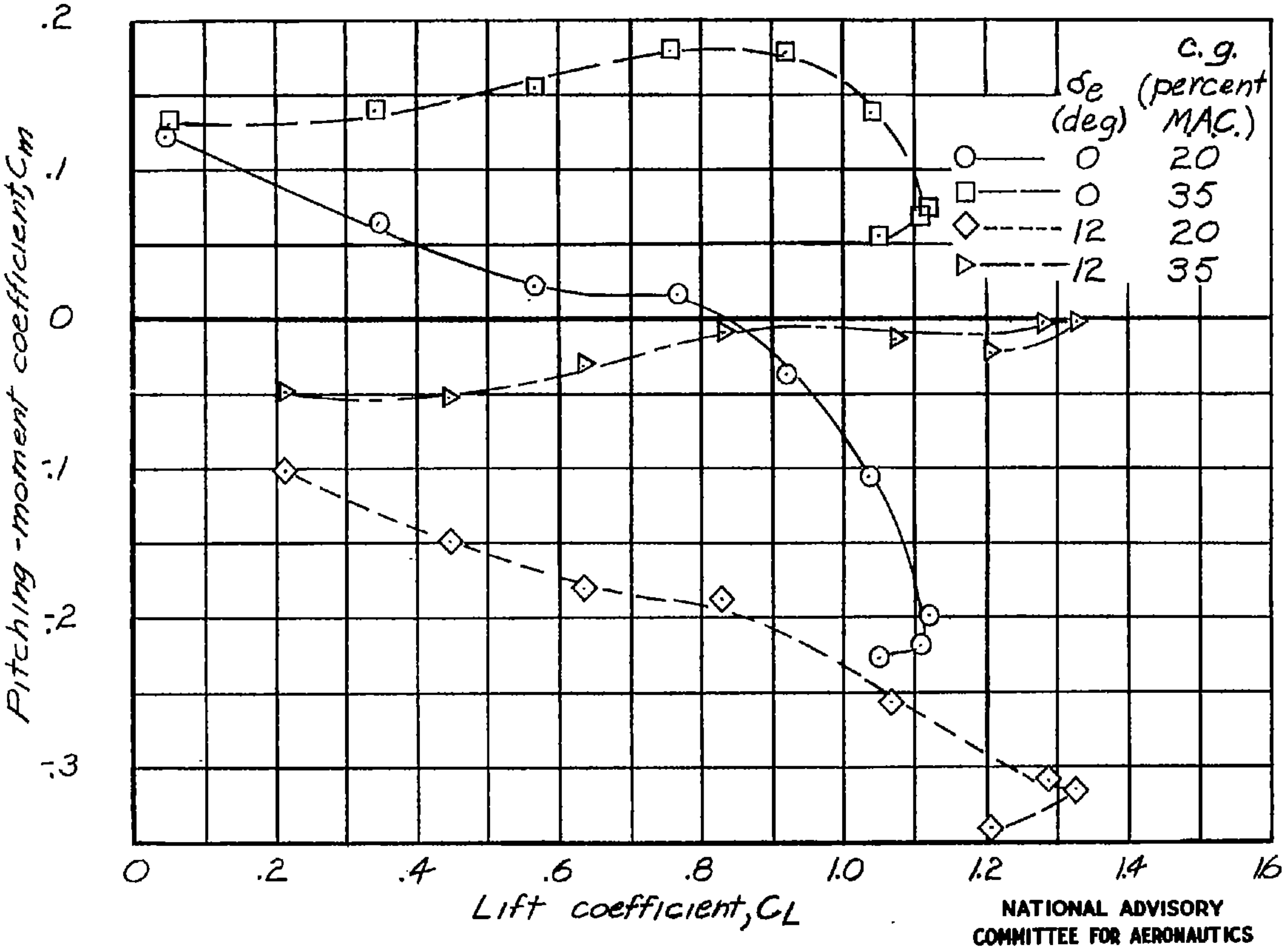


Figure 7.- Effect of elevator deflection and center-of-gravity location on the static longitudinal stability and trim of the complete skewed-wing model with 40° skew.

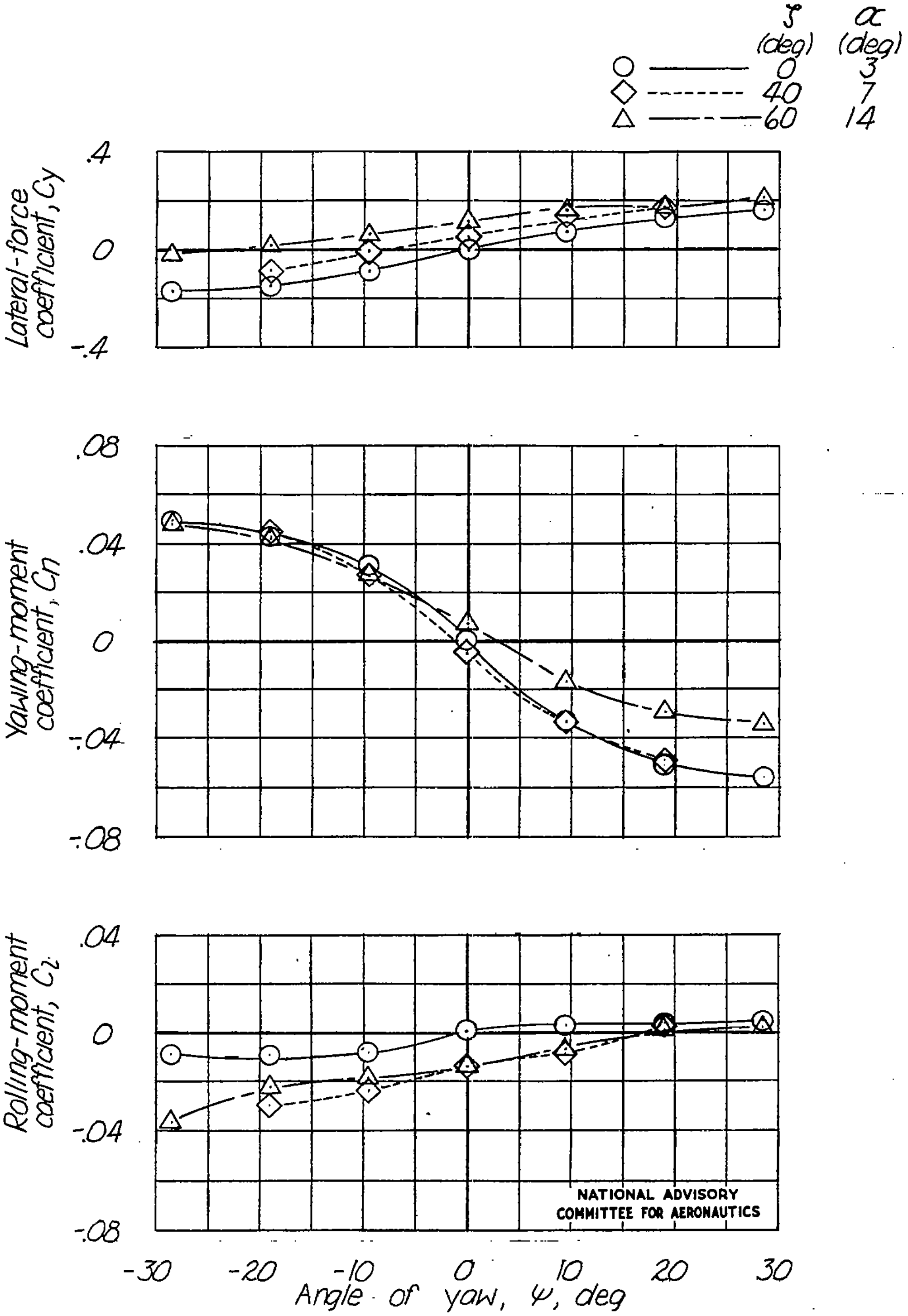


Figure 8.- Effect of skew angle on the lateral stability and trim characteristics of the complete skewed-wing model. C_L approximately 0.6.

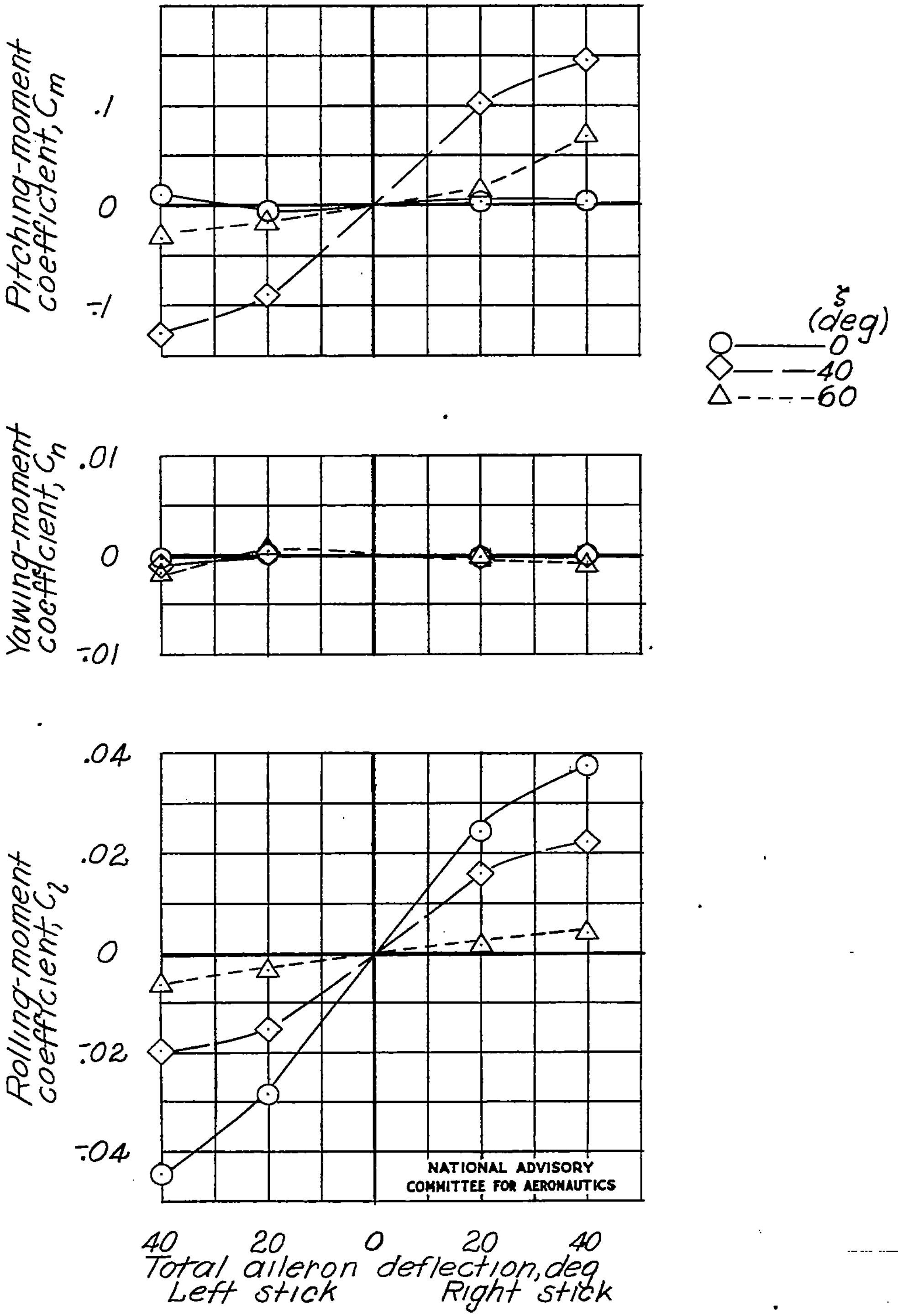
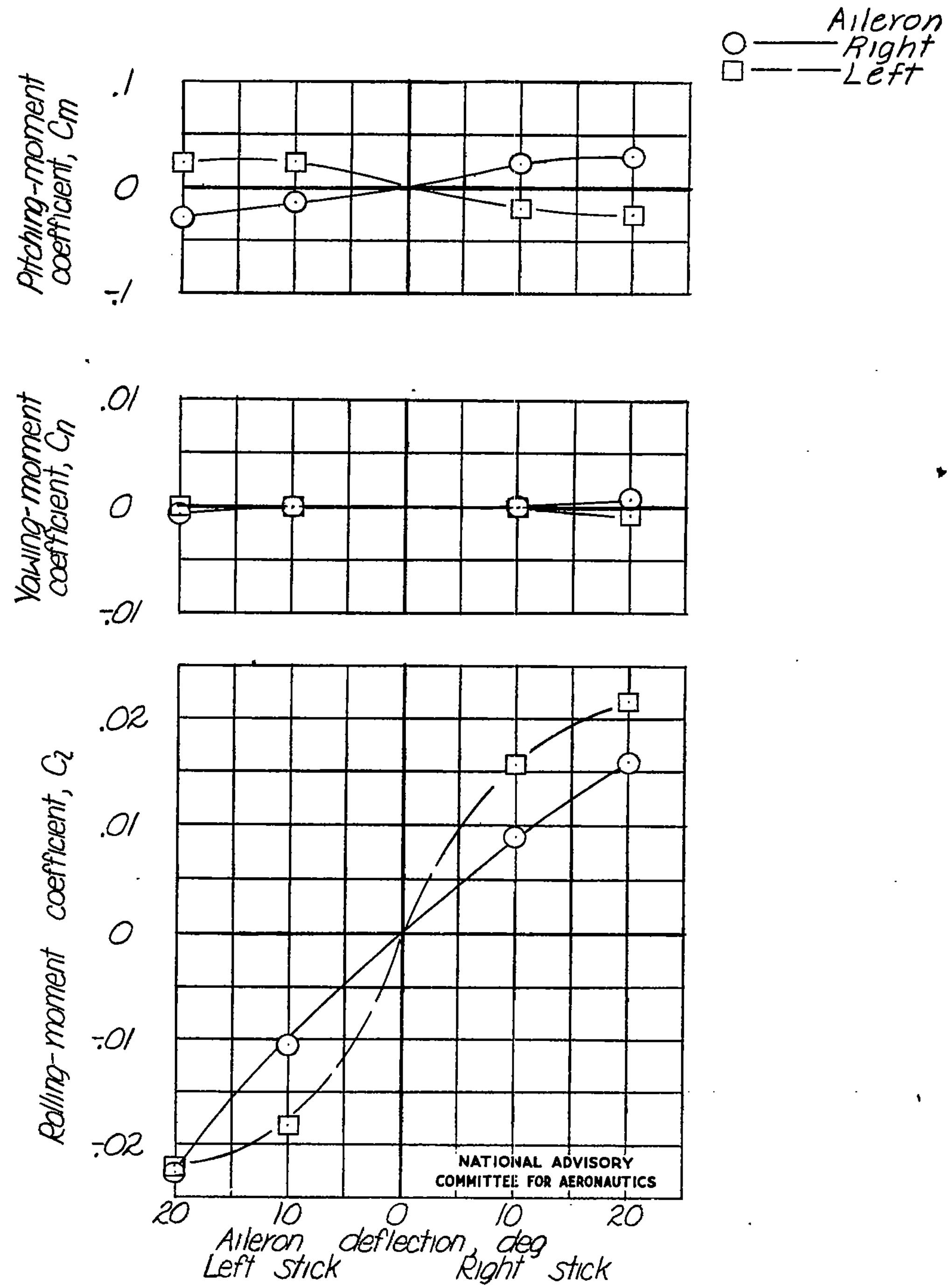
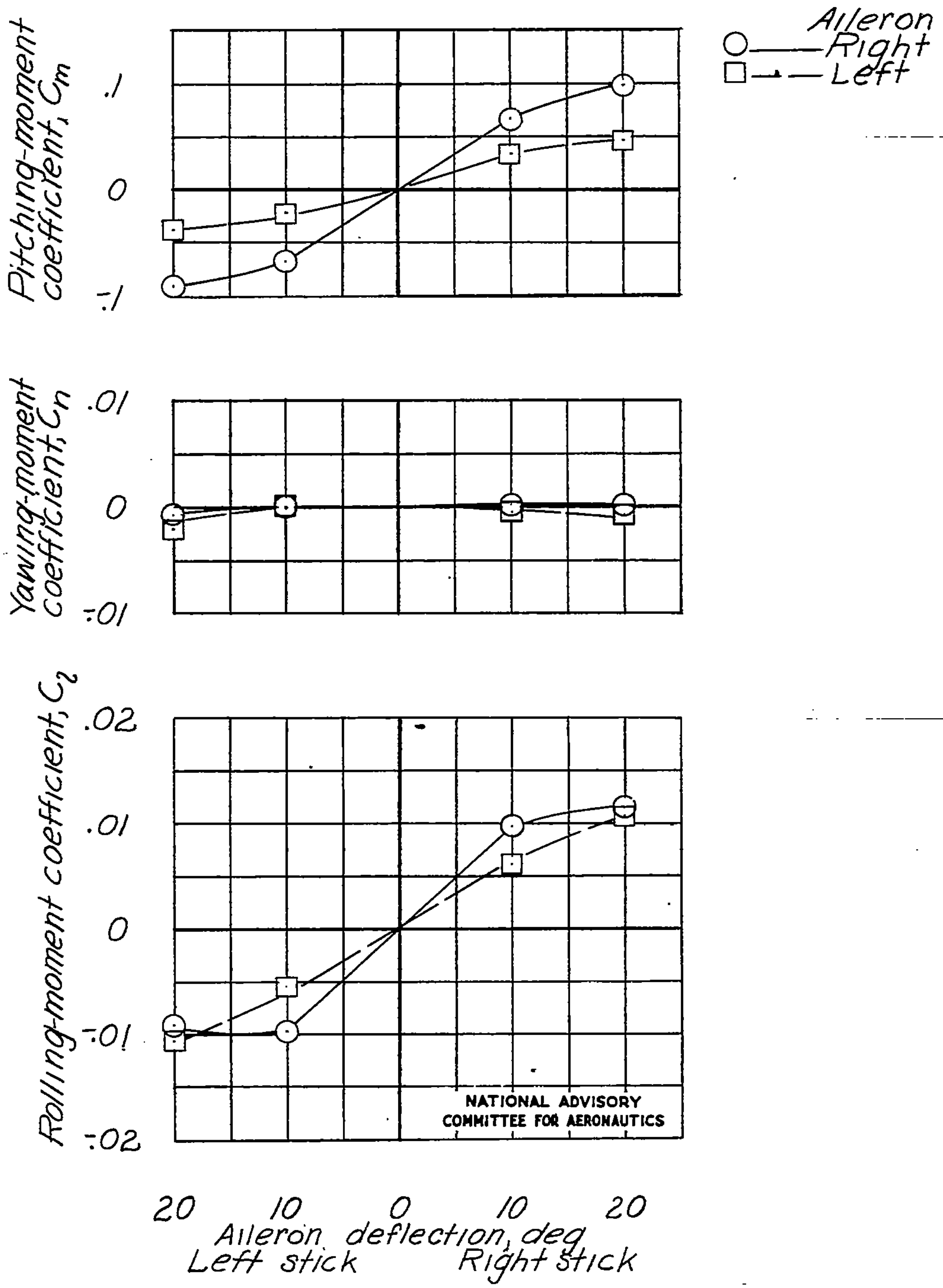


Figure 9.- Effect of skew angle on aileron effectiveness of the skewed-wing model. Both ailerons deflected with equal up and down travel. $C_L = 0.6$.



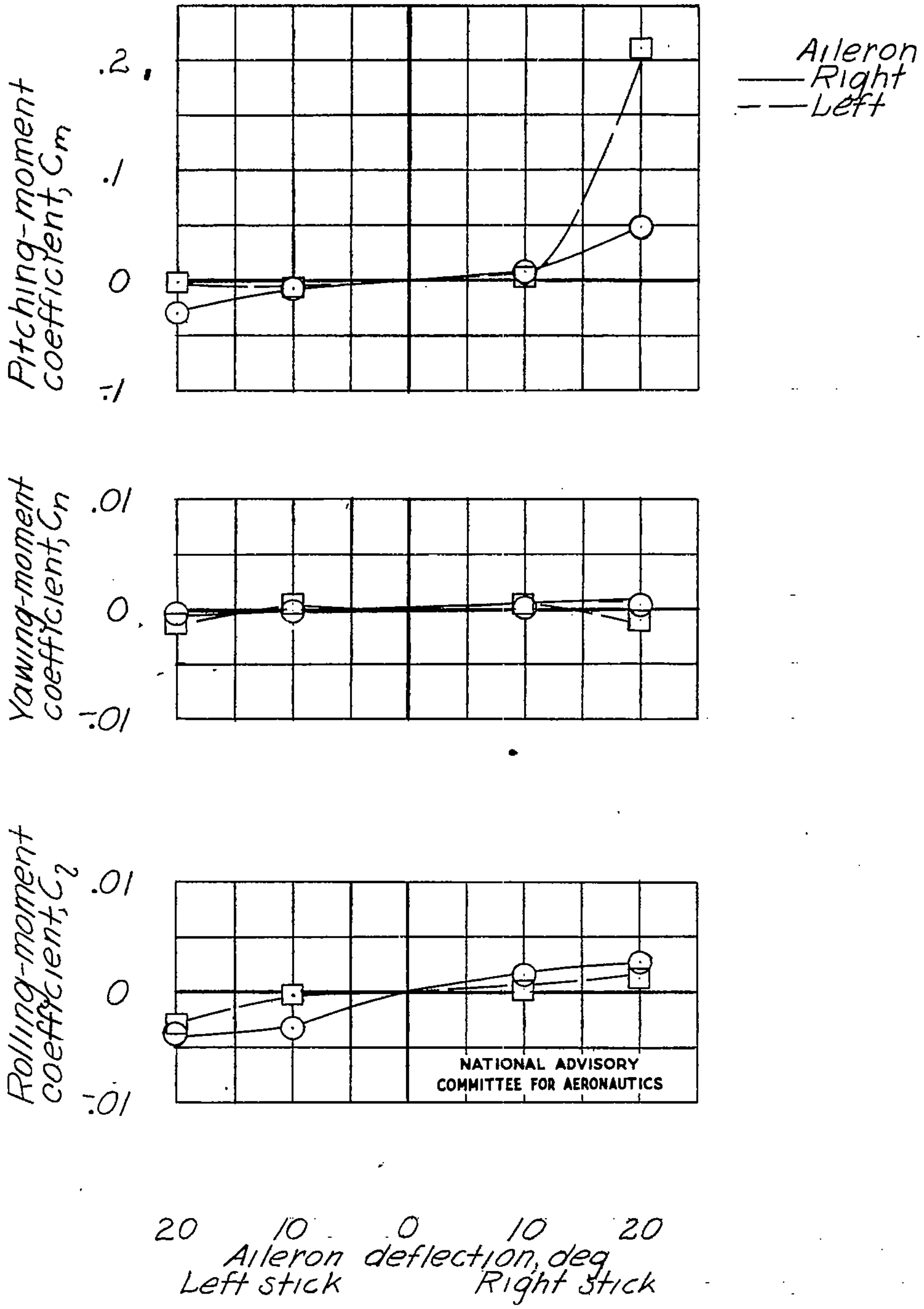
(a) $\zeta = 0°$.

Figure 10.- Effect of skew angle on the aileron effectiveness of the skewed-wing model. Ailerons deflected individually. $C_L = 0.6$.



(b) $\zeta = 40°$

Figure 10.-Continued.



(c) $\delta = 60°$.

Figure 10.-Concluded.

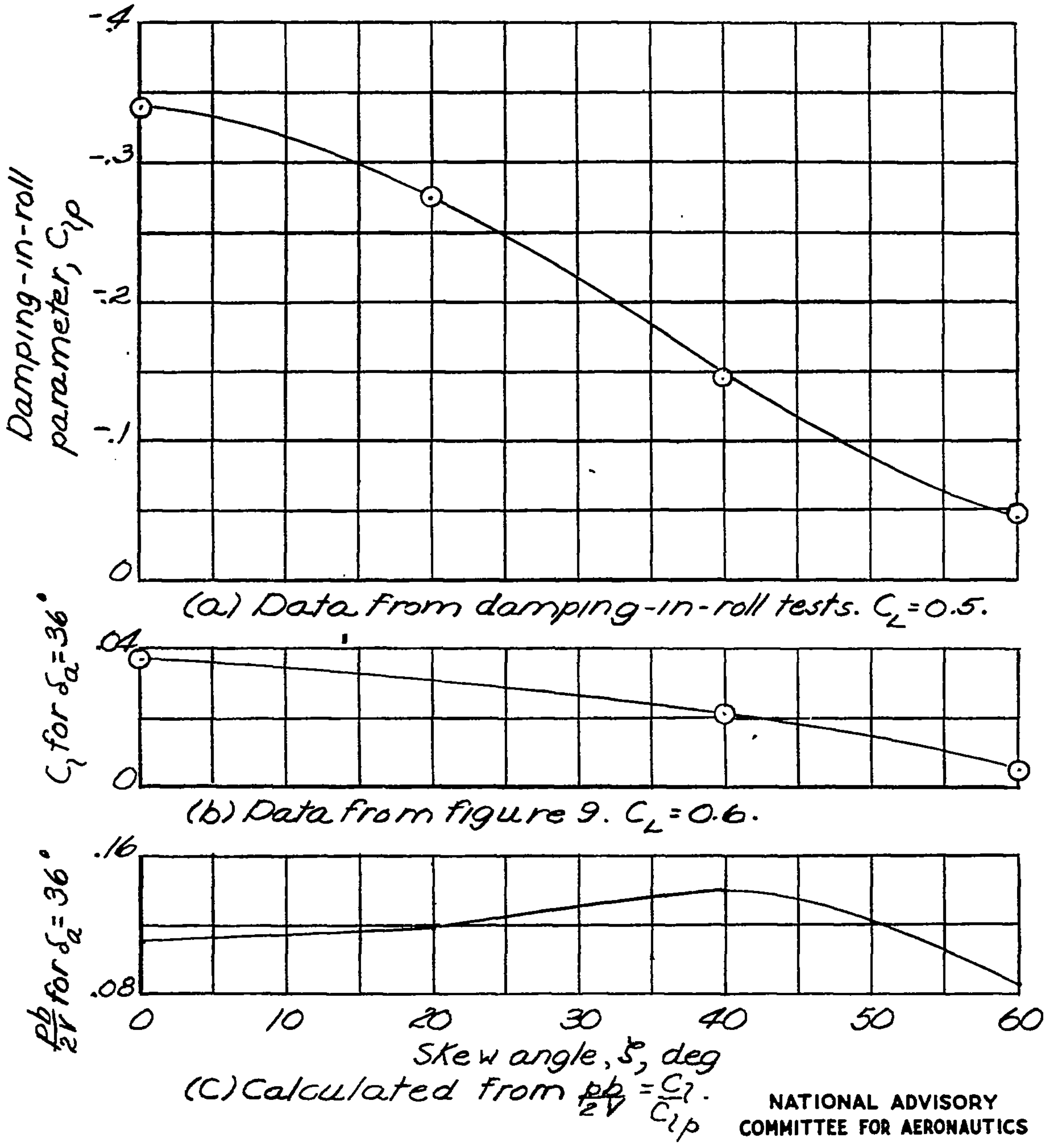


Figure 11.- Effect of skew angle on damping in roll and aileron rolling effectiveness.

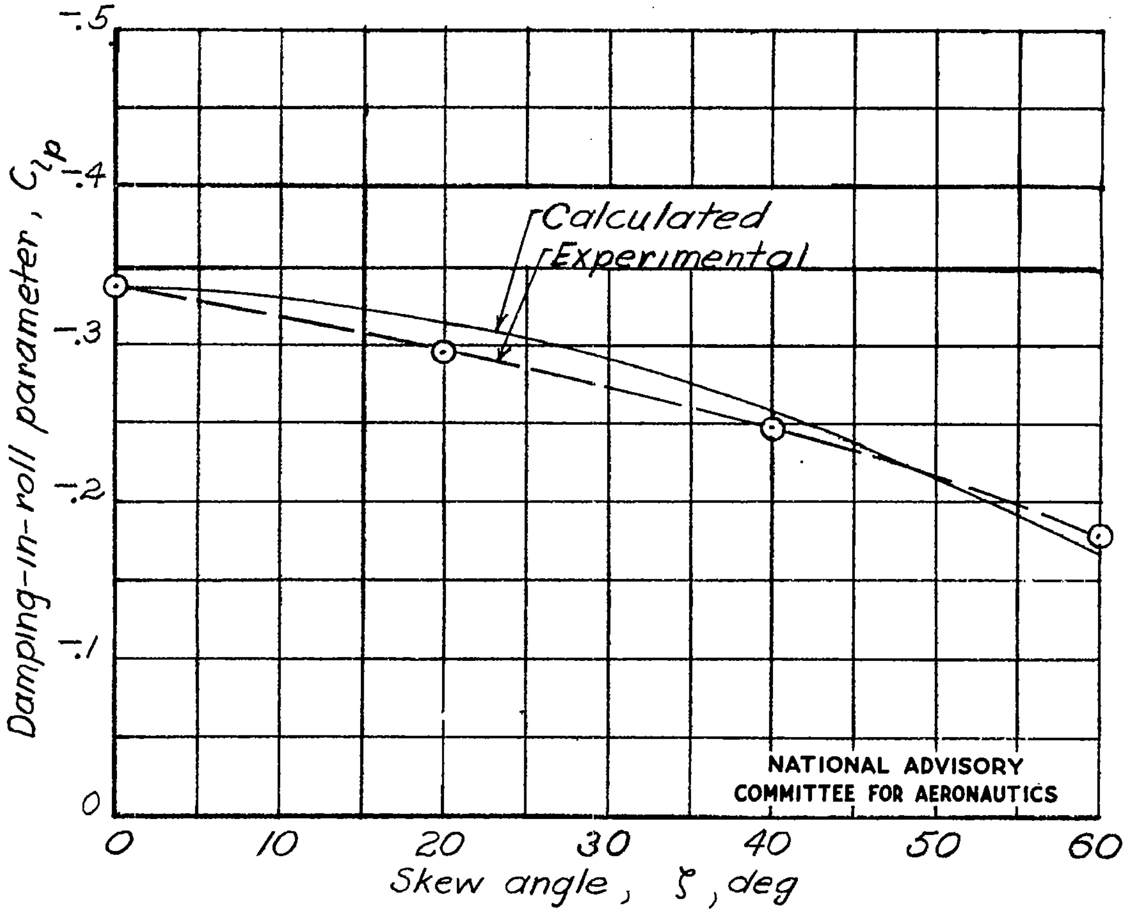


Figure 12.- Variation of damping-in-roll parameter C_{l_p} with skew angle. Experimental data for each skew angle is based on projected span ($b \cos \zeta$). Calculated curve was obtained by use of formula from reference 3, $C_{l_p} = C_{l_{p(\zeta=0)}} \cos \zeta$.