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# RESEARCH MEMORANDUM

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PRELIMINARY INVESTIGATION AT LOW SPEEDS OF  
SWEPT WINGS IN YAWING FLOW

By

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Langley Field, Va.

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## RESEARCH MEMORANDUM

## PRELIMINARY INVESTIGATION AT LOW SPEEDS OF

## SWEPT WINGS IN YAWING FLOW

By Alex Goodman and David Feigenbaum

## SUMMARY

A wind-tunnel investigation was conducted to determine the rotary stability characteristics in yawing flow of a series of untapered wings having angles of sweep of  $-45^\circ$ ,  $0^\circ$ ,  $45^\circ$ , and  $60^\circ$ . The curved-flow equipment of the Langley stability tunnel was used for the greater part of the tests. For comparison purposes, a free-oscillation method was used to obtain the damping in yaw for the same wings. At low lift and moderate lift coefficients, results obtained by these two methods were in fair agreement. At high lift coefficients, however, consistent values of the damping in yaw could not be obtained for the swept wings by the oscillation method used.

The results of the yawing-flow tests indicated that the values of the rotary derivatives agreed fairly well with simple sweep theory for a moderate range of lift coefficients. For this range of lift coefficients, the values of the damping in yaw became more negative and those of the rolling moment due to yawing more positive with increasing lift coefficient, while those of the lateral force due to yawing were small in magnitude. Near maximum lift coefficient the values of the damping in yaw and the lateral force due to yawing became more positive for the sweptback wings and more negative for the sweptforward wing. The rolling moment due to yawing, however, showed opposite tendencies; namely, the values for the sweptforward wing became highly positive while those for the sweptback wings changed sign and became negative near maximum lift coefficient.

## INTRODUCTION

A systematic investigation is being conducted at the Langley stability tunnel to determine the rotary stability characteristics of various airplane wings and complete airplane configurations. For the most part, the measurements are being made by means of the rolling-flow and curved-flow technique in which the model is held stationary while the air stream is made to roll or curve about the model. This technique makes it possible to obtain certain rotary derivatives which have not been obtained experimentally heretofore. Results on the static

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stability and rolling characteristics for a series of swept wings and for a complete airplane configuration have been presented in references 1 and 2, respectively. The present report gives the results of a preliminary investigation of the rotary derivatives in yawing flow for the same series of swept wings as reported in reference 1.

Some tests of the same wings were made by means of the free-oscillation technique of reference 3 for comparison with the curved-flow results.

### SYMBOLS

The data are presented in the form of standard NACA coefficients of forces and moments which are referred in all cases to the stability axes, with the origin at the quarter-chord point of the mean geometric chord of the models tested. The positive directions of the forces, moments, and angular displacements are shown in figure 1. The coefficients and symbols used herein are defined as follows:

$C_L$  lift coefficient  $\left(\frac{L}{qS}\right)$

$C_Y$  lateral-force coefficient  $\left(\frac{Y}{qS}\right)$

$C_l$  rolling-moment coefficient  $\left(\frac{L'}{qSb}\right)$

$C_n$  yawing-moment coefficient  $\left(\frac{N}{qSb}\right)$

L lift

Y lateral force

$L'$  rolling moment about X-axis

N yawing moment about Z-axis

q dynamic pressure  $\left(\frac{1}{2}\rho V^2\right)$

$\rho$  mass density of air

V free-stream velocity

S wing area

b span of wing, measured perpendicular to axis of symmetry

- c chord of wing, measured parallel to axis of symmetry
- $\bar{c}$  mean geometric chord  $\left( \frac{2}{S} \int_0^{b/2} c^2 db \right)$
- x distance of quarter-chord point of any chordwise section from the leading edge of the root section
- $\bar{x}$  distance from the leading edge of the root chord to the quarter chord of the mean geometric chord  $\left( \frac{2}{S} \int_0^{b/2} cx db \right)$
- A aspect ratio  $\left( \frac{b^2}{S} \right)$
- $\alpha$  angle of attack, measured in plane of symmetry
- $\Lambda$  angle of sweep, positive for sweepback
- $\frac{rb}{2V}$  lateral flight-path curvature (for constant sideslip; ratio of semispan to radius of curvature)
- r yawing angular velocity, radians per second
- $C_{l_\alpha}$  lift-curve slope  $\left( \frac{\partial C_L}{\partial \alpha} \right)$
- $C_{Y_r}$  lateral force due to yawing  $\left( \frac{\partial C_Y}{\partial \frac{rb}{2V}} \right)$
- $C_{n_r}$  damping in yaw  $\left( \frac{\partial C_n}{\partial \frac{rb}{2V}} \right)$
- $C_{l_r}$  rolling moment due to yawing  $\left( \frac{\partial C_l}{\partial \frac{rb}{2V}} \right)$

## APPARATUS AND TESTS

The tests of the present investigation were conducted in the 6- by 6-foot curved-flow test section of the Langley stability tunnel in which curved flight may be simulated approximately by holding the model fixed while causing the air to flow about it in a curved path. This allows measurements of the rotary characteristics to be made with much greater accuracy than has been possible by other techniques, such as the various oscillation and whirling-arm methods. The proper flow

curvature and velocity gradient are obtained by curving the flexible walls of the tunnel and by inserting, upstream of the model, screens made up of parallel wires with variable spacing. (See fig. 2.) The wires are distributed in such a manner that energy is removed from the air stream at an increasing rate as the radius of the stream decreases.

The curved flow does not reproduce exactly the conditions of an airplane flying in a curved path, since there is a lateral static-pressure gradient inevitably associated with the centrifugal force of a curved stream. The static-pressure gradient causes a lateral buoyancy and perhaps some lateral flow within the boundary layer on the model. A fairly reliable correction can be made for this buoyancy force, but the effects of the flow in the boundary layer cannot be evaluated accurately at the present time. In addition to the pressure gradient caused by the curvature, the wire screens can be expected to cause a turbulence gradient across the tunnel, the effects of which cannot yet be accurately evaluated. Studies of aerodynamic characteristics in straight flow have shown that at least at low lift coefficients, the effects of turbulence and flow in the boundary layer are usually relatively small. It is believed that these effects would also be of little importance in the determination of the rotary derivatives possibly at high lift coefficients.

The models tested consisted of four untapered wings of approximately the same area, all of which had equal chords (10 in.) and NACA 0012 sections in planes normal to the leading edge. (See fig. 3.) These wings are the ones used in the tests of reference 1. The wings had sweep angles of  $-45^\circ$ ,  $0^\circ$ ,  $45^\circ$ , and  $60^\circ$ , and the corresponding aspect ratios were 2.61, 5.16, 2.61, and 1.34, respectively. The models were rigidly mounted at the quarter-chord point of the mean geometric chord on a single strut. (See fig. 4.) The moments were measured by a strain-gage moment unit mounted at the top of the support strut. The forces were measured by strain gages mounted on the strut below the moment unit. This arrangement necessitated making cut-outs in the wings in order to accommodate the moment unit. Such cut-outs had not been required for the tests reported in reference 1. It was necessary to provide a slight clearance between the moment unit and the wing, which resulted in air leakage for all except the unswept wing for which the cut-out was covered with a sealed fairing at the top surface of the wing.

All tests were run at a dynamic pressure of 24.9 pounds per square foot which corresponds to a Mach number of 0.13. The test Reynolds numbers based on the mean geometric chord of the models are:

Sweepback (deg)	Reynolds number
-45	1,100,000
0	780,000
45	1,100,000
60	1,560,000

The yawing-flow tests were made at constant sideslip and at four different wall curvatures corresponding to the values of  $rb/2V$  shown in the following table:

Sweepback (deg)	Lateral-flight-path curvature $\frac{rb}{2V}$
-45	0, -0.0316, -0.0670, -0.0883
0	0, -0.0442, -0.0937, -0.1234
45	0, -0.0316, -0.0670, -0.0883
60	0, -0.0229, -0.0485, -0.0639

For each  $rb/2V$ , each model was tested through an angle-of-attack range from approximately zero lift up to and beyond maximum lift. All the models were tested at a given tunnel-wall curvature before resetting the walls. This necessitated the removal and remounting of the models for each tunnel-wall curvature.

For comparison purposes, the free-oscillation method and procedure of reference 3 were used to obtain the damping in yaw  $C_{n_r}$  for the same wings.

#### CORRECTIONS

The following corrections for jet-boundary effects and lateral static-pressure gradient were applied to the data:

$$\Delta C_l = KC_{l_t}$$

$$\Delta\alpha = 57.3 \delta_w \left(\frac{S}{C}\right) C_L$$

$$\Delta C_Y = 4.0 \frac{v}{bS} \left(\frac{rb}{2V}\right)$$

where

- $\delta_w$  boundary-correction factor obtained from reference 4
- C tunnel cross-section area
- $C_{L_t}$  uncorrected rolling-moment coefficient
- K correction factor from reference 5 modified for application to these tests
- v volume of model

The data have not been corrected for the effects of blocking, support-strut tares, or for any effects of turbulence or static-pressure gradient on the boundary-layer flow.

## RESULTS AND DISCUSSION

### Lift Characteristics

The lift characteristics of the wings under the conditions of the present tests are presented in figure 5. These characteristics are very nearly the same as those presented in reference 1 except at high angles of attack. The differences may be accounted for by the wing cut-outs, the difference in support-strut interference, and the difference in tunnel cross section.

### Yawing Characteristics

Basic data.— Plots of the lateral-force, yawing-moment, and rolling-moment coefficients against the lateral flight-path curvature  $rb/2V$  are presented in figures 6 to 9. No data are presented for the lift, drag, and pitching-moment coefficients since no consistent variations in these coefficients with  $rb/2V$  could be determined. The data presented in figures 6 to 9 have in all cases been faired by straight lines which are considered to represent the best average of the test points. In general, the data seem to indicate no consistent deviations from linearity over the test range of  $rb/2V$ . The test points show a certain amount of random scatter from linearity, but this is believed to be caused by certain errors inherent in the test procedure which required a separate test run for each angle of attack and each curvature.

Yawing derivatives.— An unpublished application of simple sweep theory indicates that for constant geometric aspect ratio  $\partial C_{n_r} / \partial C_L^2$  and  $\partial C_{l_r} / \partial C_L$  do not vary with sweep angle. The lateral-force derivative  $C_{Y_r}$ , however, is a function of both sweep angle and the aspect ratio and may be expressed by the following equation:

$$C_{Y_r} = C_L^2 \left( \frac{2 - \frac{A}{\cos \Lambda}}{2\pi A} \right) \tan \Lambda$$

In figure 10 the variation of  $C_{Y_r}$  with lift coefficient determined from the yawing-flow tests is compared with the theoretical variation. The magnitudes of this derivative are so small that they are probably of very little significance, but the experimental data show the same general trends at low lift coefficients as the theoretical curves. There is a negative displacement of the experimental points from the theoretical values, which is probably caused by an incomplete correction for the lateral static-pressure gradient. In the case of the sweptback wings there is a sudden departure from the general trend at about the lift coefficient at which the lift-curve slope suddenly increases. (See fig. 5) Near maximum lift the values of  $C_{Y_r}$  of the sweptforward wing became more negative; those of the sweptback wings became more positive; while those of the unswept wing remained about the same.

Theoretical values of  $\partial C_{n_r} / \partial C_L^2$  were obtained by extrapolating the data of reference 6 to low aspect ratios and using theoretical values of  $C_{L_\alpha}$ . The effects of the profile drag on  $C_{n_r}$  have been included in the theoretical values plotted in figure 11. Experimental values of  $C_{n_r}$  from both yawing-flow and free-oscillation tests are compared with these theoretical values in figure 11. At low lift coefficients the two experimental methods agree very well in all cases. Some differences between the values of  $C_{n_r}$  obtained by the two methods may be attributed to the unsteady-flow conditions which exist on an oscillating wing. The values of the damping in yaw  $C_{n_r}$  from oscillation tests were determined by using the procedure of reference 3. This procedure assumes that the variation of  $C_n$  with  $\psi$  is linear over the range of amplitudes used. At the high angles of attack, tests showed that the variations of  $C_n$  with  $\psi$  were nonlinear, even for small values of  $\psi$ , particularly for the swept wings. Because of the nonlinearity of the variation of  $C_n$  with  $\psi$  and because near the stall the flow conditions over an oscillating

wing are unstable, consistent values of  $C_{n_r}$  could not be obtained at these angles by the oscillation test procedure. Results of the oscillation test therefore are presented only for the angle-of-attack range for which the procedure is applicable.

In general, for the low lift-coefficient range, the two experimental methods agree very well with theory. As in the case of  $C_{Y_r}$  near maximum lift, the value of  $C_{n_r}$  for the sweptforward wing became more negative; those of the sweptback wings more positive; while those of the unswept wing remained about the same. Theoretical values of  $\partial C_{l_r} / \partial C_L$  also were obtained by extrapolating the data of reference 6 to low aspect ratios and using theoretical values of  $C_{L_\alpha}$ . Figure 12 presents a comparison of the values of  $C_{l_r}$  obtained by the yawing-flow method with the theoretical values. The theoretical and experimental variations of  $C_{l_r}$  with  $C_L$  agree rather well at low lift coefficients, although the experimental values are again more negative than the theoretical values. At some moderate lift coefficients a sudden change in the slope  $\partial C_{l_r} / \partial C_L$  occurs. The lift coefficient at which change of slope occurs decreases as the angle of sweep increases. At high lift coefficients, the values of  $C_{l_r}$  for the sweptforward wing became highly positive, while those for the sweptback wings changed sign and became negative.

### CONCLUSIONS

The results of low-scale tests made in yawing flow to determine the yawing derivatives at constant sideslip of a series of untapered swept wings having equal chords in planes normal to the leading edge and approximately equal areas indicate the following conclusions:

1. At low lift and moderate lift coefficients, the values of the damping in yaw determined by the curved-flow method are in fair agreement with those obtained by the free-oscillation method. At high lift coefficients consistent results could not be obtained for the swept wings by the oscillation method used.
2. At low lift and moderate lift coefficients the values of the damping in yaw became more negative with increasing lift coefficient and were in fair agreement with simple sweep theory. Near maximum lift coefficient this derivative became positive for the sweptback wings and highly negative for the sweptforward wing.
3. Values of the rolling moment due to yawing became more positive with increasing lift coefficient and were in fair agreement with simple sweep theory over a range of lift coefficients that decreased with increasing sweep angle. At high lift coefficients, the values of this

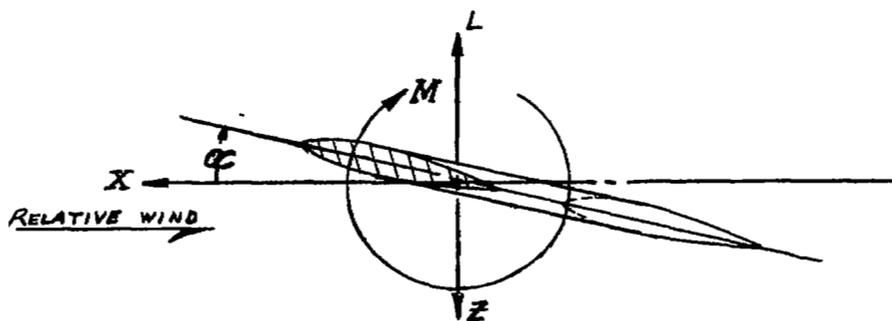
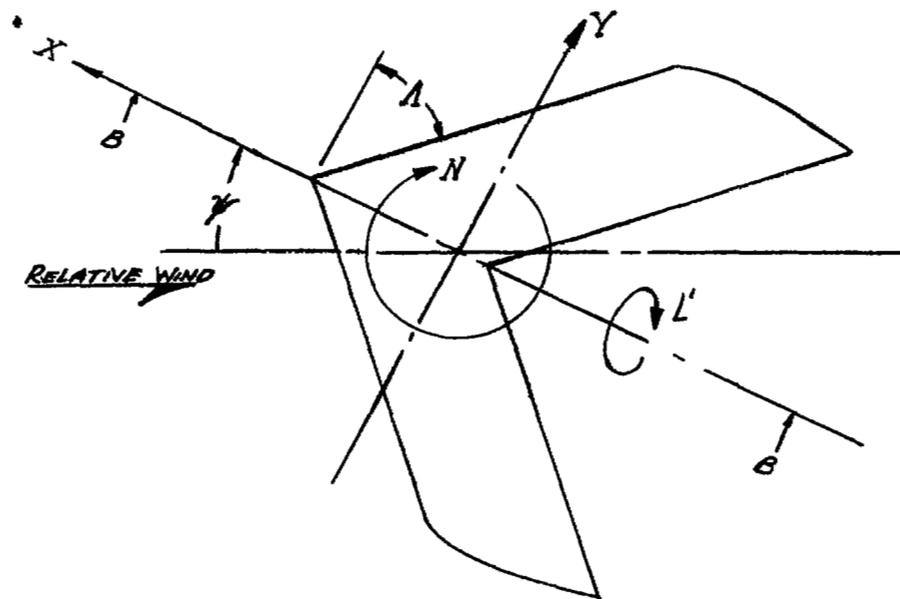
derivative for the sweptforward wing became highly positive, while those for the sweptback wings changed sign and became negative.

4. The lateral force due to yawing was small in magnitude but showed trends which were generally in agreement with the simple sweep theory. Near maximum lift coefficient the tendencies shown by this derivative were similar to those indicated by the damping in yaw.

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SECTION B-B

Figure 1.- System of axes used. Positive values of forces, moments, and angles are indicated.

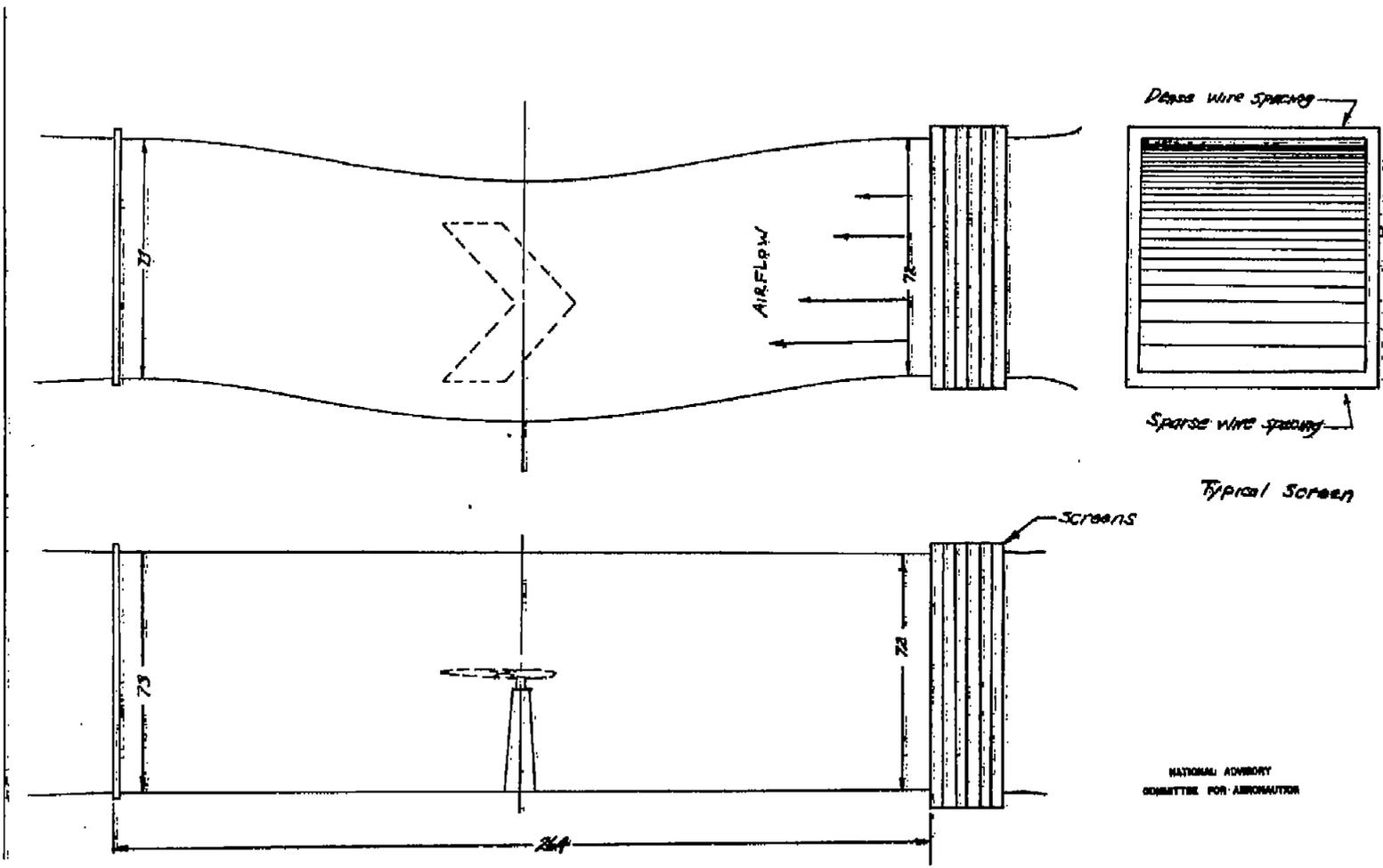


Figure 2.- Curved flow test section of the Langley stability tunnel.

$\Lambda$ (deg)	$A$	$S$ (ft. <sup>2</sup> )	$b$ (ft.)	$\bar{x}$ (ft.)
-45	2.61	3.56	3.05	-0.460
0	5.16	3.52	4.26	0.208
45	2.61	3.56	3.05	1.050
60	1.34	3.64	2.21	1.360

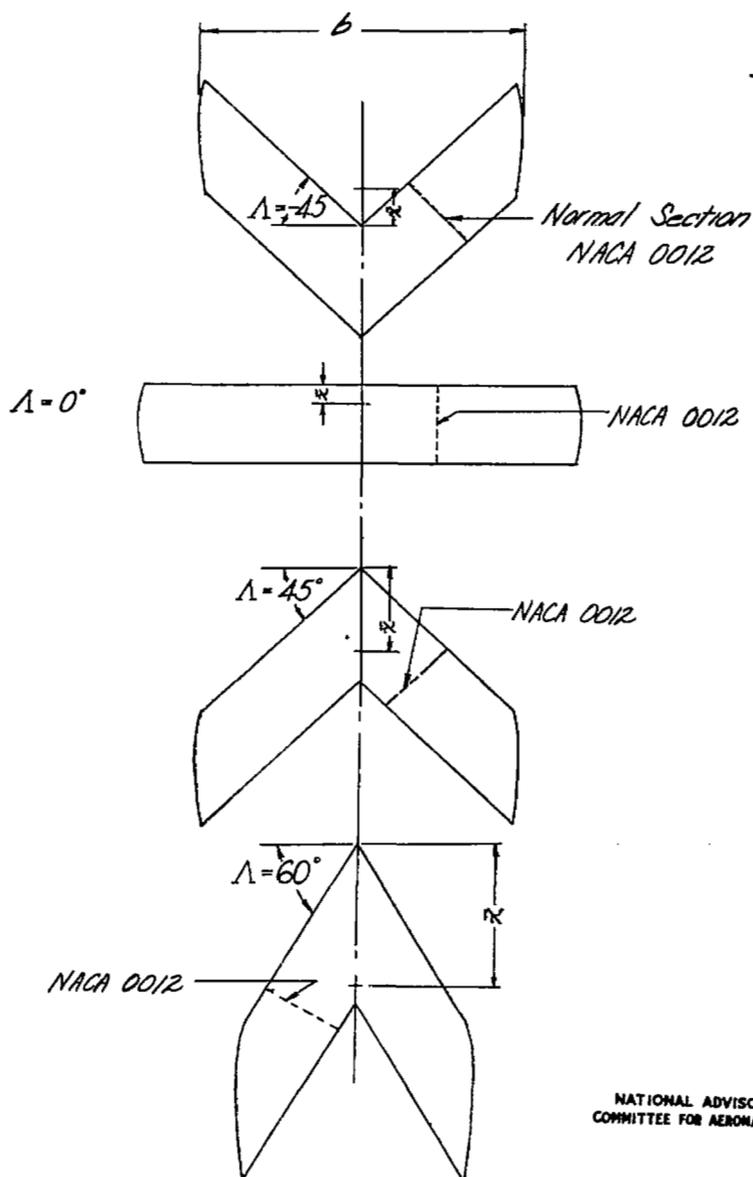


Figure 3.- Plan forms of the swept wings tested.

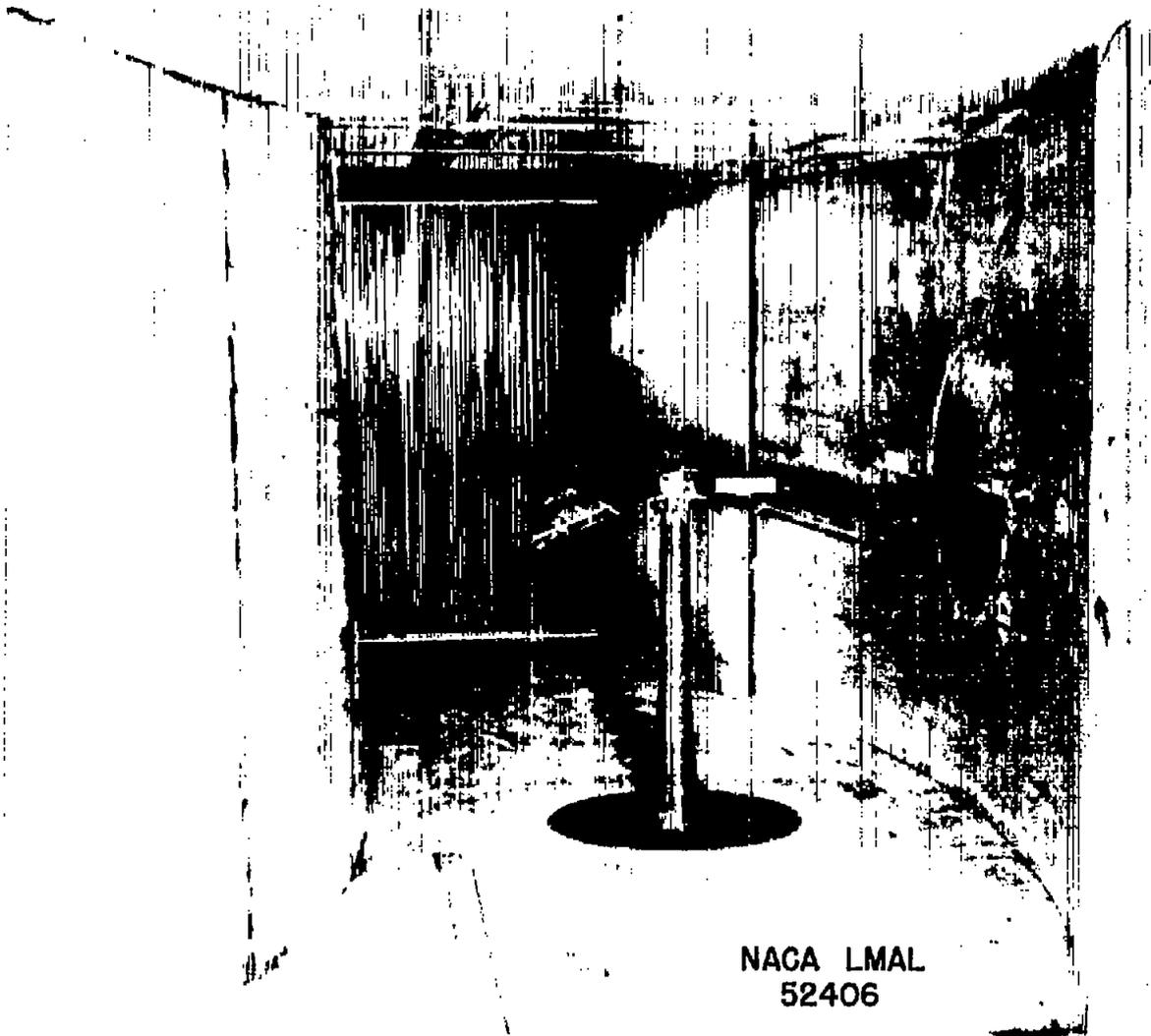


Figure 4.-  $45^{\circ}$  sweptback wing mounted on strain-gage strut in curved-flow test section of the Langley stability tunnel.

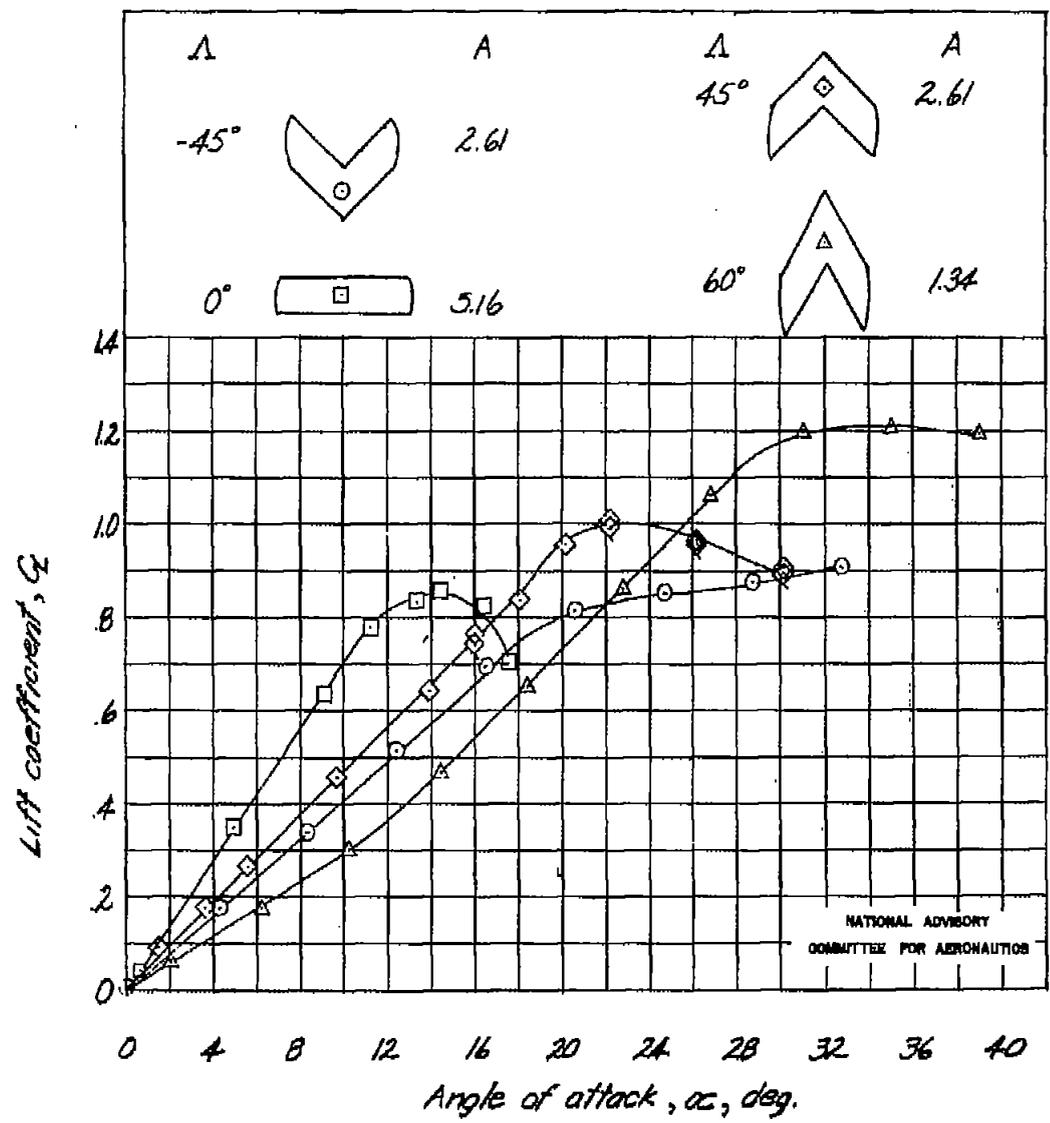


Figure 5.- Variation of lift coefficient with angle of attack for several swept wings.

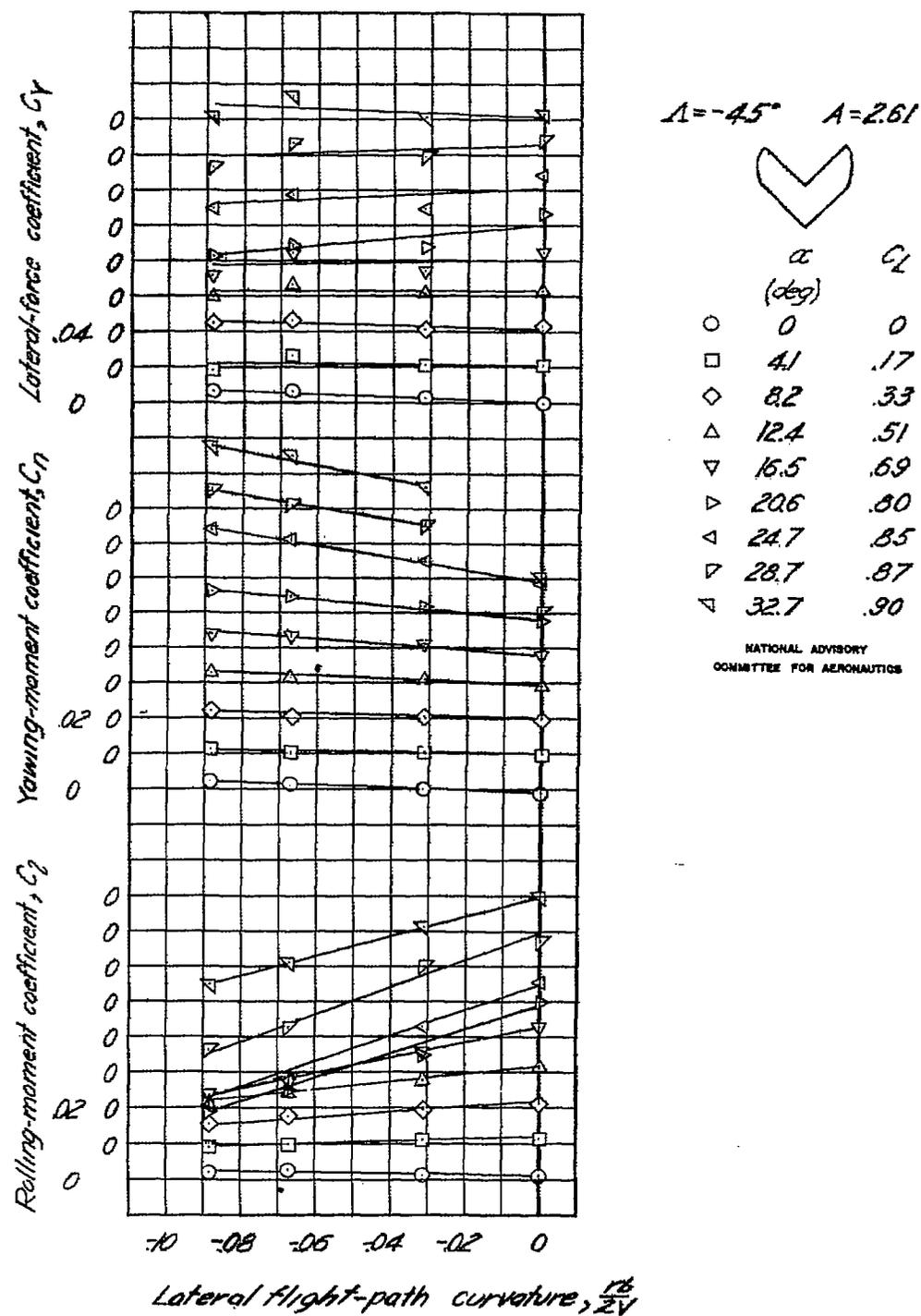


Figure 6.- Variation with lateral flight-path curvature of the lateral characteristics for a  $45^\circ$  sweptforward wing.

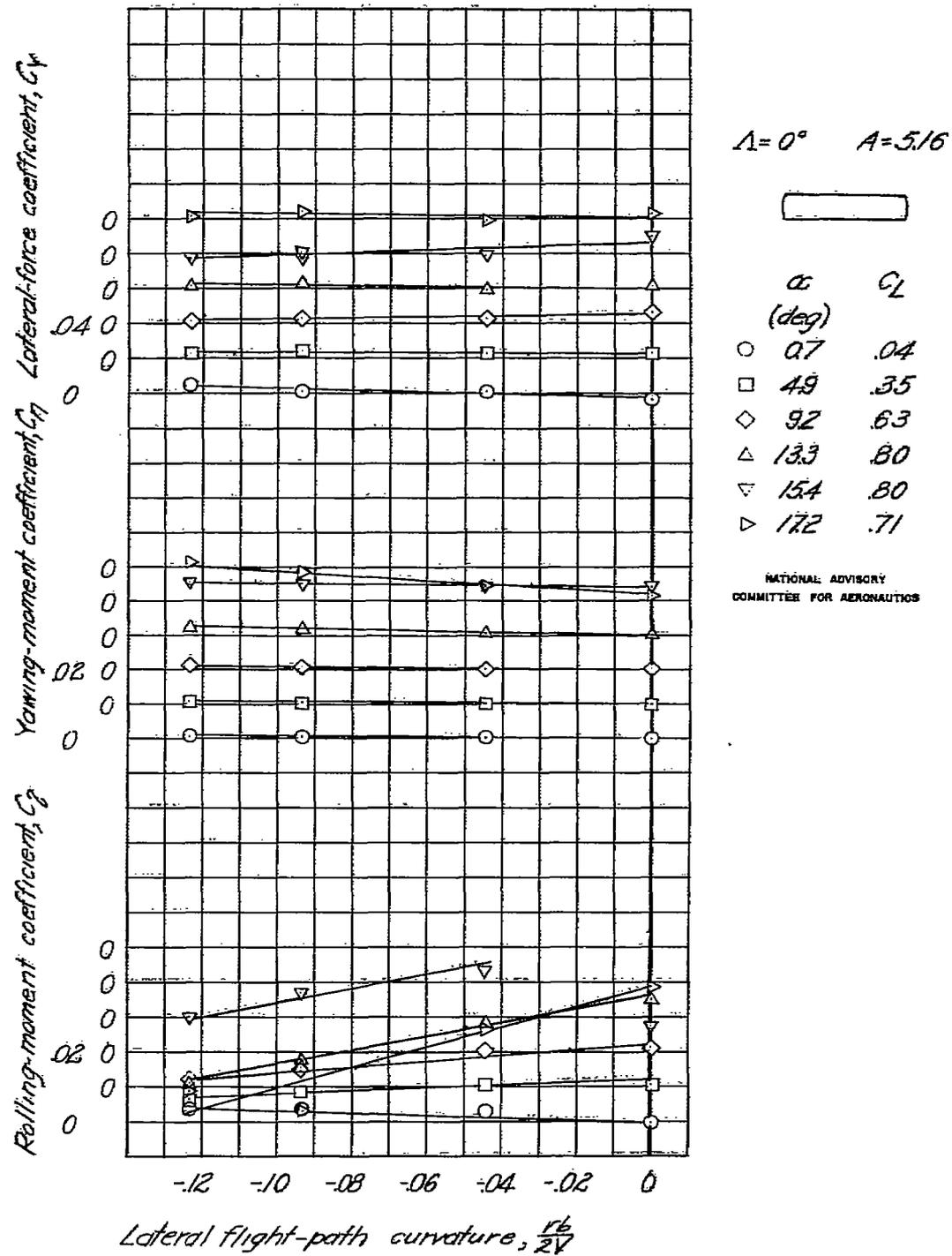


Figure 7.- Variation with lateral flight-path curvature of the lateral characteristics for a  $0^\circ$  sweptback wing.

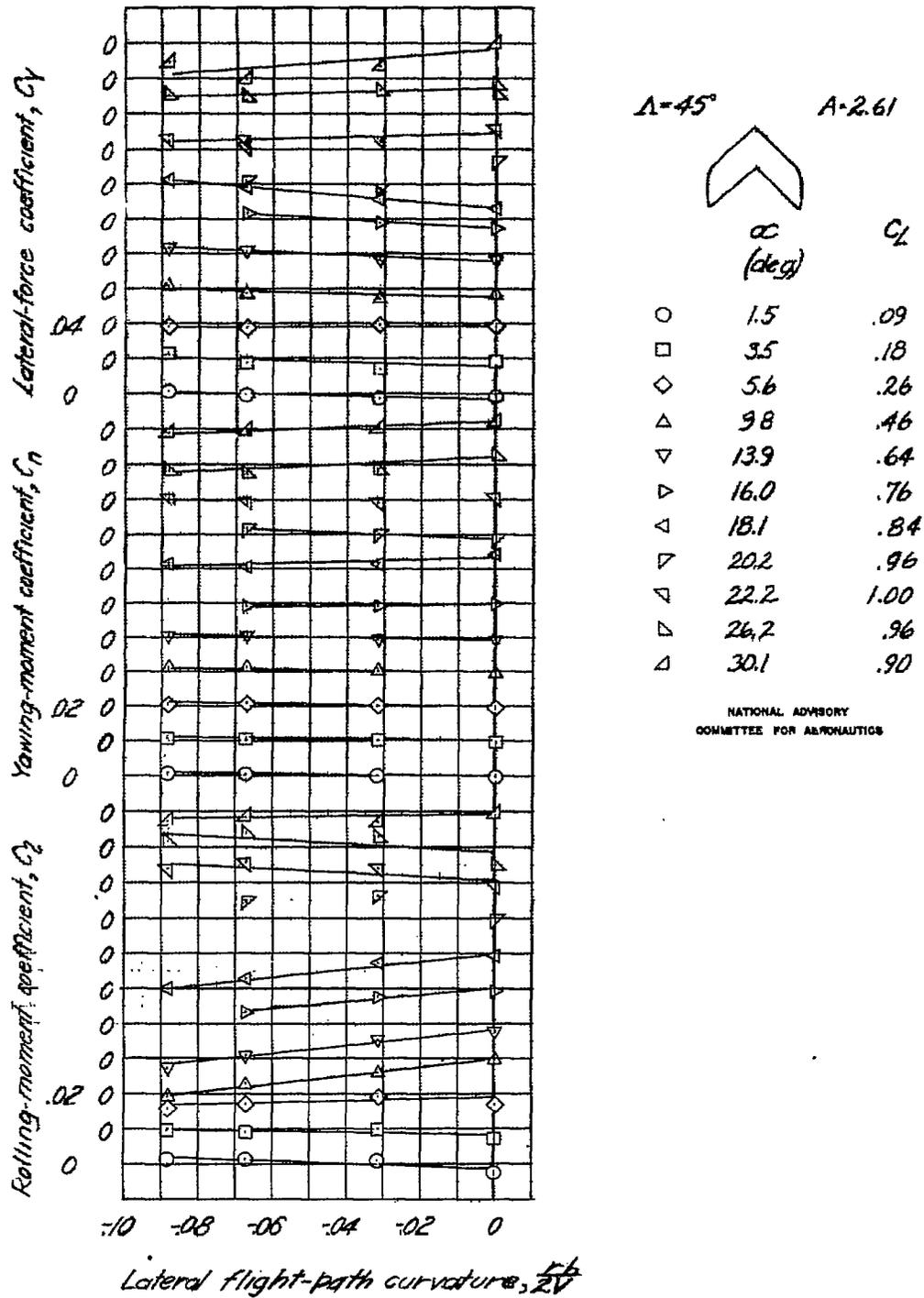


Figure 8.- Variation with lateral flight-path curvature of the lateral characteristics for a  $45^\circ$  sweptback wing.

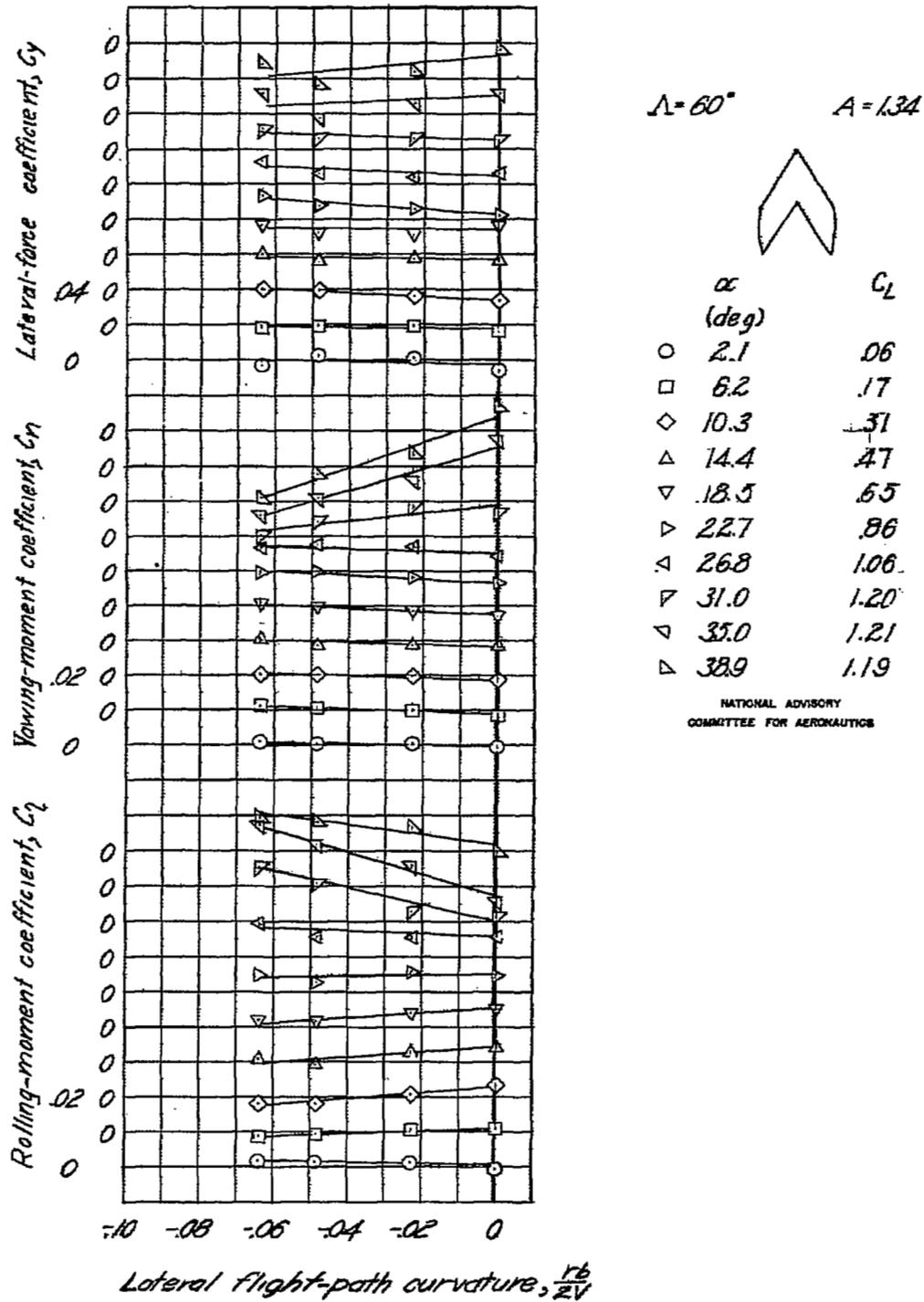


Figure 9.- Variation with lateral flight-path curvature of the lateral characteristics for a  $60^\circ$  sweptback wing.

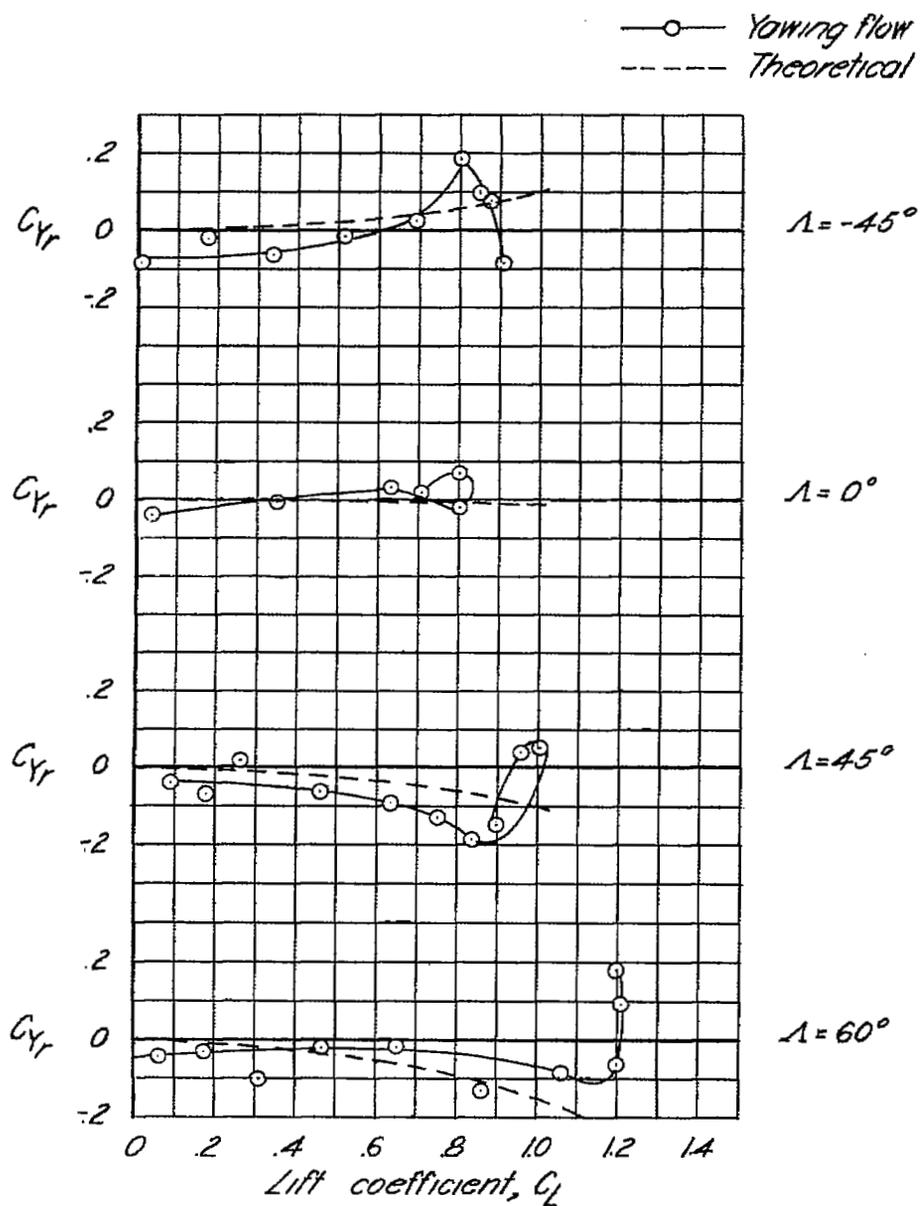


Figure 10.- Variation of experimental and theoretical values of  $C_{Y_r}$  with lift coefficient for several swept wings.

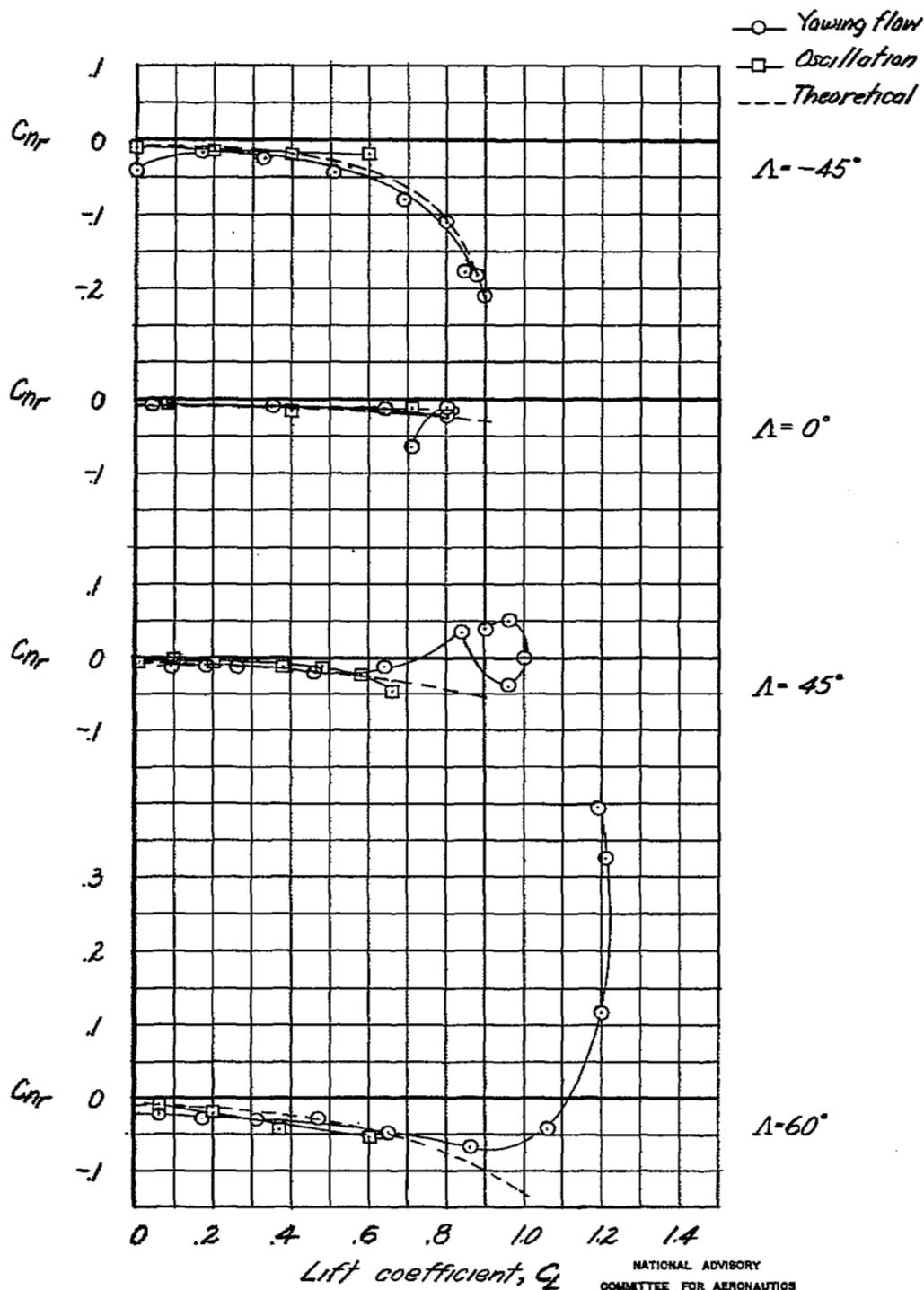


Figure 11.- Variation of experimental and theoretical values of  $C_{nr}$  with lift coefficient for several swept wings.

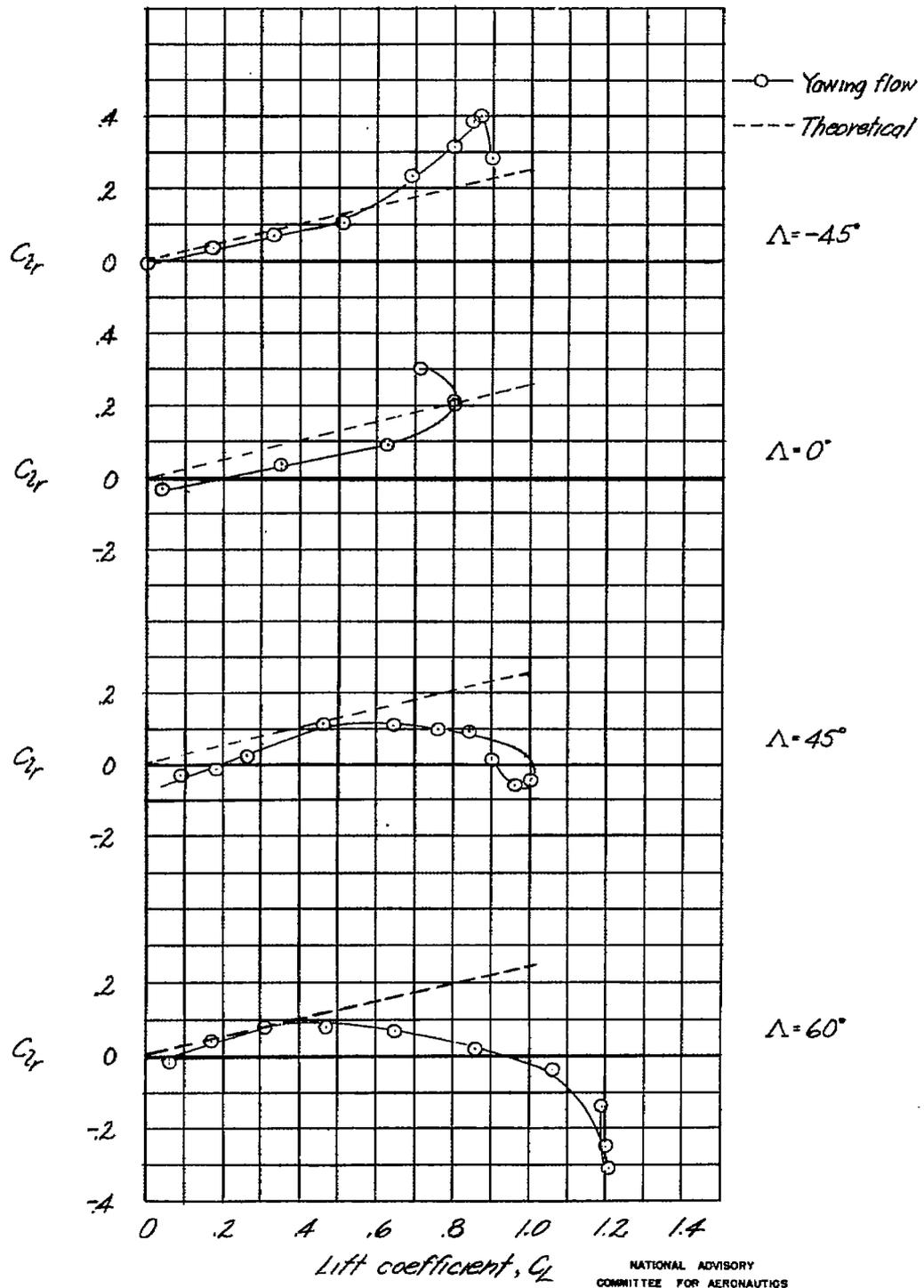


Figure 12.- Variation of experimental and theoretical values of  $C_{br}$  with lift coefficient for several swept wings.

TDIN FORM 89 A (13 MAR 47)

Goodman, Alex  
Feigenbaum, D.

**DIVISION:** Aerodynamics (2)  
**SECTION:** Wings and Airfoils (6)  
**CROSS REFERENCES:** Wings, Swept-back - Aerodynamics (99305.2); Wings - Aerodynamics - Yaw effect (99153); Wings, Yawed - Stability (99336)

**ATI-** 20762

**ORIG. AGENCY NUMBER**

NA-L7109

**REVISION**

**AUTHOR(S)**

**AMER. TITLE:** Preliminary investigation at low speeds of swept wings in yawing flow

**FORG'N. TITLE:**

**ORIGINATING AGENCY:** National Advisory Committee for Aeronautics, Washington, D. C.

**TRANSLATION:**

COUNTRY	LANGUAGE	FORG'N. CLASS	U. S. CLASS.	DATE	PAGES	ILLUS.	FEATURES
U.S.	Eng.				24		photo, tables, diagr, graphs

**ABSTRACT**

Tests were conducted at low speeds in yawing flow to determine the yawing derivatives at constant sideslip of a series of untapered wings with sweep angles from  $-45^\circ$  to  $+60^\circ$ . At low-lift and moderate-lift coefficients, the values of the damping in yaw became more negative with increasing lift coefficient and were in fair agreement with simple sweep theory. Near maximum lift coefficient, this derivative became positive for the swept-back wings and highly negative for the swept-forward wing.

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**EO 10501** dd 5 NOV 1953