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TECHNICAL NOTE

No. 1088

INFLUENCE OF LARGE AMOUNTS OF WING SWEEP ON STABILITY AND CONTROL PROBLEMS OF AIRCRAFT

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SUMMARY

The use of large amounts of sweep has been suggested in this country and in Germany as a means of avoiding some of the drag increase and stability and control difficulties encountered in high-speed flight with conventional straight-wing airplanes. Experience with sweep in tailless airplanes and studies made since this suggestion has been made have indicated that the use of a large amount of sweep will, in itself, introduce stability and control problems of sufficient magnitude and complexity to require considerable research, particularly for flight at high angles of attack. The paper discusses these problems and, although no proved solutions are given, in some cases promising lines for further investigation are presented.

INTRODUCTION

Early in World War II airplane speeds of the order of 0.75 to 0.85 of the speed of sound were attained. Because of a tendency of the airplanes to go into uncontrolled dives at these speeds, they have never been exceeded although some of the airplanes operating at the end of the war, so far as thrust and drag were concerned, were capable of higher speeds. The instability is a result of the radical changes in the flow over wings of the airplane configurations in general use, which occur at high speeds because the air is compressible. It has been evident for some time that, if airplane speeds are to be further increased, means will have to be developed for preventing the occurrence of these radical flow changes or, at least, for increasing the speed at which they occur. To date the use of large amounts of sweep in the wing plan form is the most promising means for dealing with these flow changes.

Whereas sweep offers promise of improving conditions at speeds above those reached at present, previous experience with swept plan forms has indicated that large amounts of sweep may adversely affect the stability and control in the low speed range. It is the primary purpose of the present paper to discuss the effect of large amounts of wing sweep on the problem of designing for stability and control at subcritical speeds.

SYMBOLS

C_L	lift coefficient
C_D	drag coefficient
$C_{L_{max}}$	maximum lift coefficient
C_m	pitching-moment coefficient
C_Y	lateral-force coefficient
C_n	yawing-moment coefficient
C_l	rolling-moment coefficient
C_{l_ψ}	variation of rolling-moment coefficient with angle of yaw in degrees $\left(\frac{\partial C_l}{\partial \psi}\right)$
C_{n_ψ}	variation of yawing-moment coefficient with angle of yaw in degrees $\left(\frac{\partial C_n}{\partial \psi}\right)$
$C_{l_{\delta_a}}$	variation of rolling-moment coefficient with aileron deflection in degrees $\left(\frac{\partial C_l}{\partial \delta_a}\right)$
C_{l_p}	variation of rolling-moment coefficient with angular velocity in terms of $pb/2V$

b	wing span, feet
c	wing chord, feet
c_a	aileron chord, feet
W	weight, pounds
S	wing area, square feet
V	velocity, feet per second
p	angular velocity, radians
α	angle of attack, degrees
ψ	angle of yaw or sideslip, degrees
ϵ	angle of downwash, degrees
Λ	angle of sweep, measured from quarter-chord line of wing (sweepback or sweepforward)
δ_a	aileron deflection, degrees

REASON FOR USING PLAN FORMS WITH LARGE AMOUNTS OF SWEEP

It is of some interest to review briefly the reason for the proposal for the use of sweep in the plan forms of high-speed airplanes before proceeding with the discussion of stability and control problems. For some time before high-speed stability problems were encountered with airplanes in flight, it was known that when the velocity of air over wing sections approached the velocity of sound, at a Mach number of from 0.75 to 0.85 depending on the particular section, a radical change of aerodynamic characteristics occurred. At this speed, now known as "force break" speed, the angle of attack for zero lift for cambered wings shifted to a more positive angle, the slope of the lift curve was reduced, and the drag was increased. As a result of the shift of zero-lift angle and the reduction of slope of the lift curve, an airplane when it passes force break speed must have its angle of attack suddenly increased in order to support the weight. Unfortunately the change of zero-lift angle and the reduction of lift-curve slope also cause a reduction of the downwash at the tail, which in turn produces an upload on the tail giving a nose-down pitching moment and tends to lower the angle of attack for trim. In addition, the reduction of lift-curve slope means a reduction of the variation of angle of downwash with angle of attack, which increases the longitudinal stability of the airplane about the new reduced trim angle of attack. The combination of these effects calls for a relatively large up-elevator deflection for maintenance of steady flight. The forces required for this deflection are generally beyond the capabilities of the pilot, hence the general report of a "frozen" elevator control and a "tucking under" tendency of airplanes at high speeds. These phenomena, it has been found since the end of the war, were encountered by pilots of all the warring nations.

The use of sweep is based on the concept that, for a wing with parallel leading and trailing edges, the lift - that is, the pressures that result in lift - is generated only by the velocity component perpendicular to the leading and trailing edges. Hence, when such a wing is yawed or swept, the velocity normal to the leading edge is reduced in proportion to the cosine of the yaw angle relative to the resultant velocity. This concept is utilized in most potential-flow theory. Early in the war, it has been recently discovered, Betz in Germany suggested the use of sweep for increasing the wing critical speed. In this country Jones in 1944 (reference 1) independently made a similar suggestion. The concept on which these suggestions are based is not strictly applicable to tapered and finite-span wings; however, experiments in both countries have been made which show that, while the full gain indicated by the simple theory is not attained, a swept wing does offer considerable advantage over an unswept wing.

On the basis of the same concept it can be shown that the pressure drag of a wing is also reduced by sweep. At supersonic speeds the pressure drag constitutes an important part of the total wing drag. Even if the instability of airplanes at high speeds was to be eliminated by other means, it is very probable that sweep still would be considered for supersonic-speed airplanes because of its effect on wing drag.

In order to give an idea of the amount of sweep necessary to obtain a reasonable increase of critical speed, figure 1 has been prepared presenting critical Mach number as a function of angle of sweep. The figure is based on the elementary assumption that the critical Mach number or speed at any angle of sweep equals the critical speed for zero sweep divided by the cosine of the angle of sweep. A value of $M = 0.8$ has been chosen to represent the critical speed for the zero sweep condition. Experiments with three-dimensional wings have shown that, because the original concept is not applicable at the wing root and tips, the actual gain in critical speed resulting from sweep is of the order of one-half that shown by figure 1. The figure shows that very little is to be gained in critical speed with angles of sweep of less than 30°. Angles of sweep of 40° to 45° appear necessary in order to obtain an appreciable gain in critical speeds, particularly since the actual gain may be only half that shown by the figure.

PROPORTIONS OF SWEPT WINGS

For wing plan forms there are three basic dimensional parameters: aspect ratio, taper, and sweep. If these are taken as independent parameters, it is possible to derive a systematic series of wing plan forms covering all possible combinations that might be considered for high-speed aircraft. Some of the swept-back wings of this series are illustrated in figure 2. In practice the three parameters are related by strength requirements. From simply an inspection of the figure it is immediately evident that high aspect ratios and large angles of sweep are probably not compatible structurally.

In order to avoid a waste of time on aerodynamic studies of structurally impracticable configurations, it appears desirable to determine structural limitations more closely than can be done by visual inspection. The ratio, wing length divided by wing root thickness, is a generally accepted criterion of structural efficiency. At the present time the average value for this ratio falls between 30 and 35. In at least one case a value of 50 has been obtained. A larger value may be obtained at some later date, but 50 probably can be taken as representative of practical structures in the near future.

On the basis of the ratio of wing length to root thickness of 50, the wing with aspect ratio 8 and taper ratio 0.5 would have to have a root section with a ratio of thickness to chord of 0.12. With sweep the root section would have to be relatively thicker because, for the same aspect ratio, the panel length is increased and the chord is decreased, as illustrated in figure 2. As an increase in the ratio of section thickness to chord decreases the critical Mach number, it is evident that, if the thickness is increased as the wing is swept, some of the advantages of sweep will be lost. Furthermore, theory indicates that at the root the alleviating effect of sweep on drag is not obtained, which is another reason for keeping the root thickness small. Because of these considerations, it is probable that for high-speed aircraft the ratio of section thickness to chord will be held to 0.10 or less. If 0.10 is taken as a limiting value for this ratio, no wings of aspect ratio 8 and taper ratio 0.5 are structurally practicable for high-speed aircraft. With an aspect ratio of 2 and a taper ratio of 0.5, structural considerations will limit the angle of sweep to about 55°. For the pointed wing plan forms the limiting sweep for aspect ratio 8 is 25° and for aspect ratio 2 is 65°. For the present, therefore, it is apparent that large amounts of sweep imply low aspect ratios and some of the stability problems referred to as relating to large angles of sweep actually result, at least in part, from the accompanying low aspect ratios.

REPRESENTATIVE DATA ON THE AERODYNAMIC CHARACTERISTICS OF SWEPT-BACK WINGS

When the use of sweep for high-speed airplanes was suggested in this country, German data on the subject were not available. For purposes of evaluation of the low-speed stability and control problems the NACA made tests at low Reynolds numbers of a series of swept wings of taper ratio 1. These tests are reported in detail in reference 2. As a later inspection of German test data showed that the information obtained is fairly representative and as the information of reference 2 has been used as a basis for some of the later discussion, a part of the data has been reproduced in the present paper so that some of the detail characteristics which could not be otherwise covered might be inspected.

Figure 3 gives the dimensional characteristics of the wings tested. The wing section was an NACA 23012. The span and the chord of the wing measured perpendicular to the leading edge were the same for all angles of sweepback. The dihedral was zero and the wing tips were cut off parallel to the air flow. Semispan split flaps and semispan ailerons and spoilers were tested on the wings. The Reynolds numbers for the tests varied from about 1,000,000 to 2,000,000, depending on the angle of sweep.

The lift, drag, and pitching-moment coefficients for the wings without flaps are shown in figure 4 as a function of angle of attack. With the unswept wing the pitching-moment-coefficient curve is straight up to the stall and then bends down, giving a diving moment. This type of curve is normal for straight wings. As was anticipated from past experience with tailless airplanes, for large angles of sweep the pitching-moment curve turns up at the stall, giving a stalling moment that tends to hold the wing above the stalling angle. What was not anticipated was the increase of the negative slope of the curve of pitching-moment coefficient which occurs below the stall with angles of sweep of 45° and 60°. Although the practical importance of this negative slope has not been established, it is a matter of some concern, particularly for wings with 60° sweep for which the change of slope occurs at angles of attack corresponding to high-speed flight. The reason for the concern is that a change of slope in the pitching-moment-coefficient curve represents an increase in longitudinal stability. As will be recalled, an increase of longitudinal stability is one of the factors contributing to the present high-speed stability troubles with straight-wing airplanes. With straight-wing airplanes, however, the change of slope is much greater than is illustrated in figure 4.

With regard to lift coefficient, the main effect of sweep is to reduce the variation of lift with angle of attack. Part of the reduction may be attributed directly to the reduction in aspect ratio. An additional point to be noted is that for the wings with 45° and 60° sweepback (fig. 4) the lift curves have a point of inflection where the slope is noticeably increased.

The change of slope of the lift and pitching-moment curves for a given amount of sweepback occurs at the same angle of attack indicating that, through some unknown mechanism of the flow, the variation of lift of the wing tips with angle of attack suddenly increases at a critical angle. Tuft studies show that this change is accompanied by a slight ruffling of the tufts near the leading edge about 40 percent of the semispan from the root. The shape of both the lift and pitching-moment curves may be affected by erecting a small barrier to spanwise flow in the boundary layer at this point. The effect of sweep on the maximum lift coefficient and on the angle of attack at which it occurs will be discussed later. The drag curves are of interest only as indicating the large magnitude of the drag for the swept wings at high lift coefficients.

Figure 5 shows the variation of lateral-force, yawing-moment, and rolling-moment coefficients with angle of sideslip for the same series of wings at an angle of attack of approximately 11°. It shows primarily that the functions, with the exception of those for the wing with 60° sweep for C_Y and C_n, vary in an orderly manner with yaw and sweep. The reversed slopes, for the 60° swept wing, of the lateral-force and yawing-moment curves are representative of the erratic conditions that exist with all the swept wings at some angles of attack. Apparently these conditions are associated with the flow change previously mentioned in connection with the lift and pitching-moment curves and with the stalling of the wing tips.

Figure 6 is representative of the effect of installing a half-span split flap with a 60° deflection on the lift, drag, and pitching-moment coefficients of a swept-back wing. The effects on lift are similar to those for a straight wing, although the increments of lift caused by the flap are less and the wing with flaps stalls at a lower angle of attack than the wing without flaps. The diving moment normally resulting from a flap deflection on a straight wing is reduced by virtue of the fact that the center of lift for the flap is ahead of the center of lift for the plain wing. The flap adds an almost constant increment of drag throughout the angle-of-attack range tested. It is of interest to note that the wing with flaps has a lower drag at the stall than the wing without flaps.

LONGITUDINAL STABILITY AND CONTROL

Practically all of the following discussion is based on the test data of reference 2 or of similar investigations made at relatively low Reynolds numbers. As a number of the characteristics treated, particularly those relating to conditions at high angles of attack, may be critically dependent on boundary-layer conditions and, hence, on the Reynolds number of the tests, it should be appreciated that the points made can in no way be considered final. They are advanced at this time simply as the best available and as an argument for the need for studies at large Reynolds numbers.

Minimum Speed and Landing

The effect of sweepback on airplane minimum speeds is indicated in figure 7, which gives the variation of the maximum lift coefficient and the variation of the angle of attack for maximum lift coefficient with angle of sweepback for the plain wings and for the wings with half-span split flaps. So far as the plain wings are concerned, a relatively small change of maximum lift with sweepback is shown. The values of maximum lift coefficient for the wings without flaps are actually greater at small angles of sweep than for the straight wings. With flaps, however, the greatest value of maximum lift is attained with the straight wing. The effect of the flaps on maximum lift decreases with sweep, and for an angle of sweep of 60° the gain in lift resulting from the flaps is negligible. At angles of attack below the stall, however, there is still an appreciable change of lift due to flap deflection at a given angle of attack.

The angle of attack for maximum lift is important because of its influence on landing-gear design and vision at landing. For the plain wing, the angle of attack for maximum lift is approximately doubled when the angle of sweep is increased from 0° to 60°. Flaps decrease the angle of attack for maximum lift by an amount increasing with angle of sweep. Even with flaps, however, the angle of attack for maximum lift is considered excessive for large angles of sweep because the stowage of even a landing gear of normal length in an airplane with thin wings is difficult. Fortunately airplanes designed for very high speeds will have so much available thrust that take-offs need not be made at angles of attack near maximum lift. It may be possible, therefore, to proportion the landing gear for take-off and to allow the airplane to touch tail first and rock over on the gear at landing.

The high drag at maximum lift for the swept wings has been previously mentioned. The significance of the high drag is indicated by figure 8 in which is plotted the variation of glide angle at maximum lift with angle of sweepback. In this particular case the low Reynolds number of the tests affects the quantitative values and some revision is expected when full-scale data become available. Some such variation of glide angle is to be expected, however, as the induced drag will normally increase with the decrease in aspect ratio accompanying sweep. The importance of the 30° glide angle for the 60° swept wing without flaps will be appreciated if it is recalled that the vertical velocity equals the velocity along the flight path times the sine of the glide angle. As the sine of 30° is 0.5, the vertical velocity will be about one-half the approach speed, or about 75 feet per second when the minimum speed is 100 miles per hour. The flight study reported in reference 3 has indicated that, when the vertical velocity exceeds about 25 feet per second, the piloting technique of judging the point to start the landing flare and of executing the flare so that the vertical velocity will be reduced to a reasonable value for contact becomes extremely difficult.

Rather surprisingly, flaps for the larger angles of sweep decrease the glide angle. This decrease appears to be associated with the lower angles of attack for maximum lift with flaps down. Figure 6 has shown that the drag increase resulting from the flap deflection is more or less constant as the angle of attack is varied.

It is appreciated that figure 8 does not give a complete picture of the landing problem. In actual landings, pilots make the landing approach at speeds in excess of the minimum speed so that they will have energy available to flatten out the flight path just prior to contact. The glide angle at maximum lift, however, is a rough measure of the margin of speed needed for the approach glide and the indications are that the landing-approach speed will have to be much higher for wings with large amounts of sweep than for straight wings, even if equal landing speeds are assumed.

Another means used for reducing vertical velocities at landings is the application of power in the approach. The problem of carrying enough fuel for reasonable duration and range of flight is admittedly difficult for high-speed airplanes, but the provision of reserve fuel for landing appears to be essential.

Longitudinal Stability

In figure 4 it was noted that, for the wing configurations illustrated, sweep caused an unstable variation of the wing pitching-moment-coefficient curve at stall. Inspection of other data has shown that this result should be attributed to the particular configurations tested. Other data on the pitching moment of swept wings are given in figure 9 where pitching-moment coefficient is plotted as a function of lift coefficient for other representative swept-wing configurations. It is shown that for certain combinations of taper and aspect ratio an unstable variation of pitching moment at the stall may be obtained with large amounts of sweepback. On the other hand, the lower right-hand curve shows the interesting fact that with some configurations there may be a continuously increasing stable variation of the pitching-moment coefficient with lift coefficient.

Some consideration of what is wanted in the way of a pitching-moment-coefficient curve is desirable at this point. Perhaps it is best to consider the curve for the complete airplane first. The most important point is that for plots of the type given in figure 9 there should be no large amounts of curvature of the pitching-moment curves. Curvature signifies an aerodynamic center or "neutral point" variation with speed which makes it difficult to obtain stability throughout the complete speed range without obtaining excessive stability in certain speed ranges. Extreme upward curvature at the stall is particularly dangerous because it tends to promote inadvertent stalling. For tailless airplanes the remarks for the complete airplane apply directly to the wing. For airplanes with tails the wing characteristics may be masked because of the influence of the tail on the pitching moments. Even for airplanes with tails, however, it is considered advisable as a first approximation to choose a wing configuration having relatively good pitching-moment characteristics.

Data of the type given in figure 9 have been inspected for more than 40 wing configurations with various amounts of sweepback. The results of this inspection have been summarized in figure 10. Although aspect ratio, sweep, and taper were considered as possible parameters, the figure shows only aspect ratio and sweepback as variables because taper turned out to be only of secondary importance. The curve shown is for the approximate variation of aspect ratio and angle of sweepback for which the pitching-moment curve against lift is a straight line. In the upper right-hand portion of the figure the moment curve turns up with increasing lift whereas in the lower left-hand portion it turns down. The greater the distance from the curve shown the greater is the curvature of the pitching-moment curves.

Apparently with different aspect ratios, it is possible to get a pitching-moment-coefficient curve with either upward or downward curvature with any angle of sweepback. If upward curvature, which may be dangerous, is to be avoided, the aspect ratios will have to be reduced when the angle of sweepback is increased. This conclusion is similar to the conclusions previously drawn from consideration of structural requirements.

Because the unstable pitching moments encountered with swept-back wings of high aspect ratios are the result of wing-tip stalling, considerable attention is being given to means for improving the lift characteristics of the tip portions. There is an additional interest in leading-edge lift-increasing devices because, for airplanes designed for very high speeds, sections with sharp leading edges, which have poor lift characteristics, may be required regardless of sweep. These devices take three general forms as illustrated in figure 11 - slots, nose flaps, and drooped leading edges. All these devices can be expected to give some increase in section lift characteristics, with slots having the greatest effect. Slots may be either fixed or movable. Just how effective the devices will be on a swept leading edge has not been definitely established. German information is confusing - proponents of leading-edge flaps think slots will not work and vice-versa. In tests made by the NACA with slots on a wing swept back 60°, no gain in lift was obtained. The tests, while not conclusive, at least indicated that slot proportions will be more critical on swept than on straight wings.

The effect of the horizontal tail on the longitudinal stability depends on the downwash at the tail location. Very little information exists on the downwash field behind swept wings. From the fact that the downwash behind a straight wing increases with a decrease in aspect ratio, it would be deduced that with large amounts of sweep the horizontal tail would contribute little to the longitudinal stability and hence the interest in the tailless configuration for airplanes designed for very high speeds.

A preliminary investigation has been made to determine the downwash field behind swept-back wings. Figure 12 shows the wing and tail arrangement which was tested, and figure 13 shows the variation of the angle of downwash with the angle of attack. In the investigation the average downwash over the tail was determined by finding the tail setting at which the contribution of the tail to the pitching moment was zero. Two tail heights and two tail lengths were studied. In figure 13, which gives the results, the lift curve for the wing is also presented. The figure shows that for the lower lift coefficients the downwash is approximately a linear function of lift coefficient. The slopes in this range, as a function of angle of attack, vary from 0.55 with the tail low and forward to 0.38 with the tail aft and high. Vertical movement of the tail has a greater effect on downwash than fore-and-aft movement. In no case is the rate of change of downwash much greater than the value of 0.5 generally considered representative of straight wings of normal aspect ratios.

At lift coefficients above that where flow changes occur on the wing, the tail location has a pronounced effect on the integrated downwash at the tail. Of particular interest is the curve for the short, high tail location. The increased slope shown for the high-lift-coefficient range signifies a decrease in the contribution of the tail to longitudinal stability. In this case the combination of wing and tail is actually less stable than the wing alone. The other curves indicate an increase in the contribution of the tail to stability at high lifts. It is concluded that tail location is as important as wing configuration for the attainment of uniform longitudinal-stability characteristics throughout the speed range and that the tail may, depending on its location, either increase or decrease the stability in the vicinity of stall.

LATERAL STABILITY AND CONTROL

Dihedral Effect

With regard to lateral stability and control, the influence of sweep on the rolling moment due to sideslip or the "effective dihedral" appears to be of primary importance. Figure 14 shows the variation of the rolling-moment coefficient with sideslip C_{l_ψ} as a function of lift coefficient for several angles of sweepback. The information was obtained from the tests for which representative data were illustrated in figure 5. The increasing slope of the curves with sweepback is apparent. Of particular interest is the fact that there is a maximum value obtained regardless of sweepback. This value is equivalent for the wings tested to over 20° of geometric dihedral on a straight wing. Higher-scale tests will be needed to establish the value more definitely. The reason for the limiting value is not known but it is probably connected with boundary-layer conditions and stalling of the wing tips. As the parameter C_{l_ψ} increases with lift coefficient, the stability problems of sweep are generally problems of flight at high angles of attack.

Figure 15 is a plot of the slopes of the straight portions of the curves of figure 14 as a function of angle of sweepback. The theoretical curve takes into account the velocity and angle-of-attack changes that occur over the wing section with yaw. (See reference 2.) It is of interest that the values can be predicted with reasonable accuracy.

Lateral Stability

The significance of the large variation of rolling-moment coefficient with angle of sideslip, insofar as lateral stability is concerned, is shown by figure 16. This chart shows the boundary between associated values of the variation of rolling-moment coefficient with sideslip C_{l_ψ} and the variation of yawing-moment coefficient with sideslip C_{n_ψ} that give so-called "dutch roll" instability and stability. The values are for representative airplanes with two values of wing loading and two values of angle of sweepback. For the basic airplane the sweep was zero. The 40°-sweep case was obtained by considering each half of the wing swept back 40° with no change of panel length, and hence the span and aspect ratio for the swept-wing case was lower than for the straight wing. The span is a parameter of the stability equations and the reduction with sweep was taken into account in the preparation of the figure. The figure shows that with 40° sweep more directional stability is required than for the straight wing. For the value of wing loading of 104 at the ground, conditions are particularly bad, the minimum value of C_{n_ψ} required for stability being at least twice that for a conventional airplane. As the coefficient C_{n_ψ} varies inversely with the wing span, it should be appreciated that a given vertical tail will give a value of the coefficient about 1.4 times greater for a 40° swept wing than for the comparable straight wing. Since the increase in the value of C_{n_ψ} due to the reduced wing span is less than that required for satisfactory stability, larger vertical tails are apparently indicated for swept-wing airplanes. For the airplane investigated an increase of fin area of about 40 percent appears indicated. An increase of tail length both for lateral and longitudinal stability would appear desirable if the weight-balance problems could be worked out. One unfortunate feature about increasing vertical-tail size is that with the tail on top of the fuselage the fin itself contributes to the rolling moment due to yaw. If care is not taken, the designer can get into a vicious circle where increasing fin size because of its effect on rolling moment demands a further increase and so on. The other means of avoiding lateral instability with swept-back wings is to use negative geometric dihedral by bending the wings down at the tips, either full or partial span. There is some concern as to the effect of the negative dihedral at low lift coefficients, although experience indicates that small values of negative dihedral have no detrimental effect except that the ailerons must be used to keep the wings laterally level.

The contribution of the fin to the rolling moment due to yaw decreases with angle of attack because of the lowered position of fin center of pressure. It has been suggested, therefore, that a combination of negative wing dihedral, large fin area, and a relatively long tail might result in the most satisfactory configuration. If the proportions are correctly chosen, it appears possible to obtain a small variation of the rolling-moment coefficient due to sideslip with angle of attack or lift coefficient. For practical reasons, such a combination will probably be impossible. The negative dihedral is limited by ground clearance and the tail length by weight-balance considerations. The method even with compromises, however, appears most promising at the present time.

Aileron Control

The aileron control for swept wings is a function of the direct rolling moment of the ailerons, the damping in roll given by the wings, and the rolling moment of the wings due to yaw coupled with the weathercock stability of the airplane. Some indication of the direct rolling moment of the ailerons was obtained from the systematic series of tests previously mentioned. The results are summarized in figure 17 where the rolling moment for a unit deflection of a semispan aileron is shown as a function of angle of sweepback. The theoretical curve is again based on the simple theory. The results show that the direct moment due to the aileron drops off with sweepback and that the aileron characteristics are satisfactorily predicted by the simple theory.

Figure 18 gives data for spoilers located on the upper surface at 0.8 chord behind the leading edge and extended 0.05 chord. Spoiler effectiveness is reduced with sweepback more rapidly than aileron effectiveness and spoilers are totally ineffective for large angles of sweepback. The reason for this ineffectiveness with large angles of sweepback appears to be related to boundary-layer conditions on the wing upper surface with large amounts of sweepback. The observations have shown that at the spoiler location the flow in the boundary layer is nearly parallel with the spoiler and that the boundary-layer thickness increases rapidly with angle of attack.

The effect of sweepback on the damping moments of a rolling wing is shown in figure 19. The same data have been plotted against angle of attack and lift coefficient. The figure shows that below the stall the damping moments of wings are reduced by sweepback. The decrease, however, is not so great as the decrease in aileron power. Another point of interest shown by the figure is the low damping moments for the swept-back wings at and above the stall. In contrast, the figure shows that for the straight wing for a range of angle of attack just above the stall large positive moments exist indicating autorotative tendencies.

Figure 20 shows data obtained by deflecting ailerons on the wings shown in figure 19 and recording the rolling velocities. The solid-line curves give the total aileron deflection required for a value of pb/2V of 0.1. A considerably greater aileron deflection is required for the wing with an angle of sweep of 60° than for the wing with an angle of sweep of 0°. The difference, however, is not too significant because the rolling parameter pb/2V does not take into account the change of rolling velocity that results from a change of span. The rolling velocity for the 60° swept wing, for example, will be approximately twice that of the wing with zero sweep for the same value of pb/2V. Apparently normal ailerons of the same proportions as those used on straight wings will be satisfactory for swept wings. The dashed curves of figure 20 represent the aileron deflections that were computed by procedures normally used for straight wings with a knowledge of aileron characteristics for zero rate of roll and damping moments for zero aileron deflection. The agreement with the measured values is satisfactory.

Rudder Control

Little attention has been paid up to the present time to the rudder control for high-speed airplanes. This condition is a result of the belief that because of the large rolling moments accompanying sideslip with swept wings the rudder will be an extremely powerful rolling control and its use will generally be avoided. It is not yet considered advisable to eliminate the rudder from high-speed airplanes because of possible use when taxying; rudder-locking devices may have to be provided to avoid its inadvertent use at high speeds.

Control Hinge Moments

Sweep has been proposed on the theory that the velocity component producing the normal force and consequently affecting the major aerodynamic parameters equals the velocity of the airplane times the cosine of the angle of sweep. This theory apparently is valid when applied to certain stability characteristics, as has been discussed. In regard to control hinge moments, therefore, it is expected that for a given size surface sweep reduces the hinge moments. Most balances used for straight wings can probably be satisfactorily applied to swept wings.

SWEEPBACK VERSUS SWEEPFORWARD

Most of the data that have been presented apply to swept-back configurations. As the arguments in favor of sweep for high-speed airplanes apply equally well to sweepforward, the question naturally arises as to the consideration given this alternate configuration. A study is being made of sweepforward but it has not proceeded as fast as that of sweepback because of the smaller amount of existing knowledge about it when sweep was proposed. The differences in characteristics are apparently as would be expected. Sweepforward tends to inhibit wing-tip stalling but promotes wing-root stalling. In both cases instability at high angles of attack may occur. With sweepforward the rolling moment due to yaw decreases with increasing lift; this condition may be advantageous from the standpoint of lateral stability.

POSSIBLE HIGH-SPEED EFFECTS

So far the discussion has been confined to subsonic characteristics. The data presented were obtained at low subsonic speeds. In the subsonic-speed range the characteristics may be expected to vary according to the Prandtl-Glauert rule in the same manner as they do for a straight-wing airplane. For characteristics dependent on the over-all flow the Mach number for the application of established corrections, as in the case of downwash, should be based on the general flow. For detail characteristics, as aileron hinge moments for example, the Mach number should be based on the normal component of the local flow. Except for such details as hinge moments, there is no proof that the corrections will apply beyond Mach number 1 where the fuselage flow becomes supersonic.

For the transonic regime - that is, where the normal flow is above the equivalent force break speed - practically no data exist. As a first approximation it is assumed that for moderate aspect ratios the problems encountered will be similar to those encountered with straight wings at lower speeds. For the very low aspect ratios that occur with short-span triangular plan forms some evidence exists that the center-of-pressure location will be independent of Mach number indicating that, as far as longitudinal stability is concerned, for this configuration no difficulty is expected through any speed range.

According to theory for straight wings, in subsonic flow the aerodynamic center will be at approximately 25 percent of the wing chord while in supersonic flow it will be at 50 percent; for narrow triangular plan forms the aerodynamic center should be at approximately the center of area at all speeds. Swept-back plan forms should fall between these extremes. Available test data indicate that such is the case. In the transonic regime the location of the aerodynamic center for straight wings is more or less unpredictable at present. The aerodynamic center for the transonic regime depends on the thickness distribution with its resultant effect on the pressure gradients behind the shock wave. Local flow separation may result from steep gradients with a consequent change in the load distribution. It is suspected that the center of pressure may vary with time at the same Mach number and angle of attack. Aileron buzz is thought to be a manifestation of this phenomenon. While no supporting evidence is available, it is thought that the transition processes will be more orderly with sweep because of the obliquity of the wave front when transition occurs and because the flow may be wholly supersonic.

Downwash changes, which are the worst features of the transonic regime, can be expected to be delayed with sweep. Whether they can be avoided is a debatable question. It is more probable that they cannot. Maybe the magnitude of the downwash changes will be reduced. At present, however, for airplanes with horizontal tails the possibilities are that an increase in the longitudinal stability will occur at some speed and this factor should be considered in design. An adjustable stabilizer appears to be a requisite feature of high-speed airplanes. The other alternative is the tailless configuration which the Germans have given a lot of attention.

The lateral-stability discussion concerning the relation between dihedral and directional stability applies at all speeds, as there is nothing to indicate that the effective dihedral will change with the speed. The directional stability, however, may increase at high speeds because of the relatively greater contribution of the drag.

Control hinge moments will increase with speed and control balancing is expected to be an important problem regardless of sweep.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., April 16, 1946

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1. Jones, Robert T.: Wing Plan Forms for High-Speed Flight. NACA TN No. 1033, 1946.

2. Letko, William, and Goodman, Alex: Preliminary Wind-Tunnel Investigation at Low Speed of Stability and Control Characteristics of Swept-Back Wings. NACA TN No. 1046, 1946.

3. Gustafson, F. B., and O'Sullivan, William J., Jr.: The Effect of High Wing Loading on Landing Technique and Distance, with Experimental Data for the B-26 Airplane. NACA ARR No. L4K07, 1945.

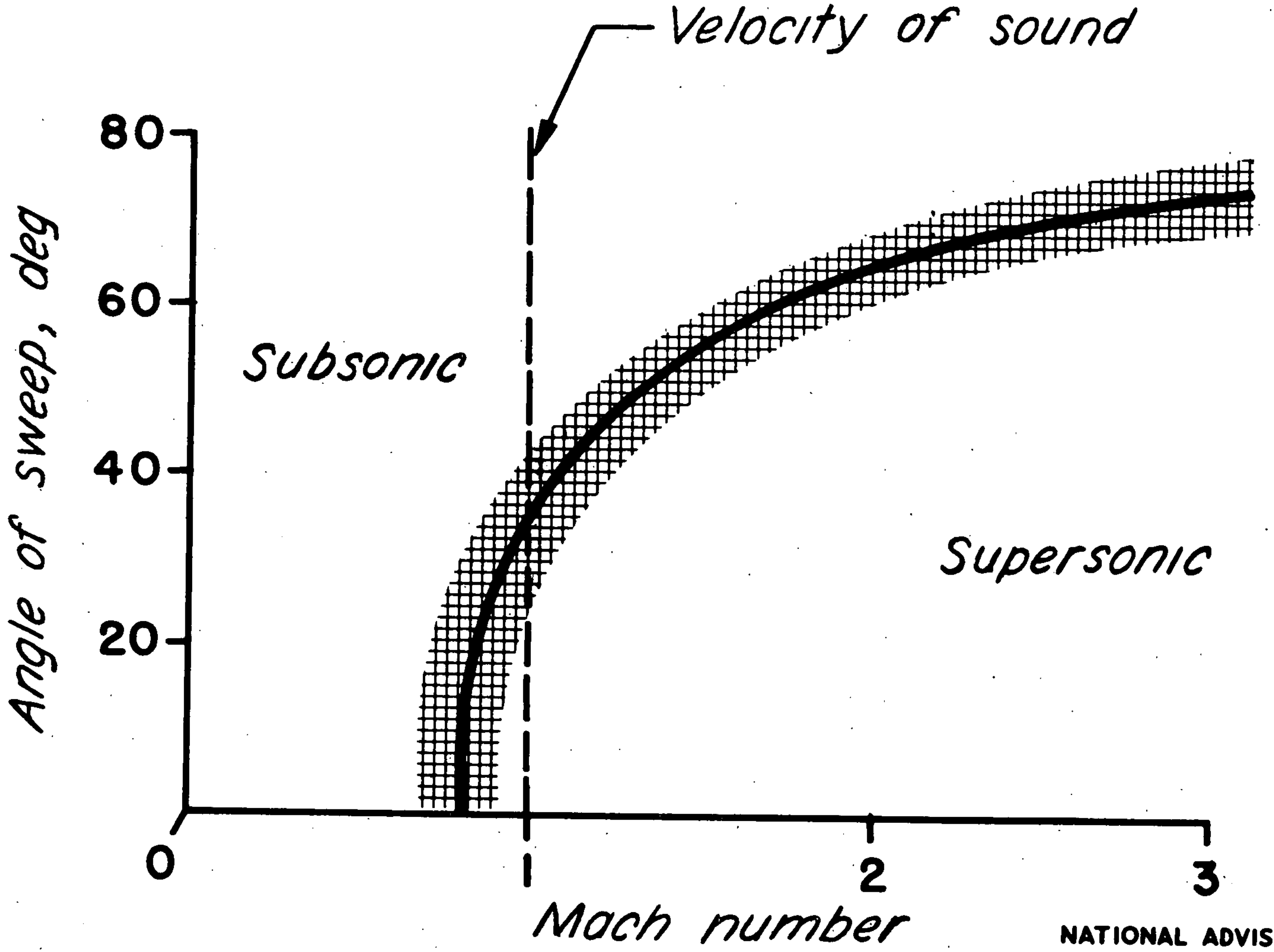

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Figure 1.- Effect of angle of sweep on critical Mach number as predicted by simplified theory.

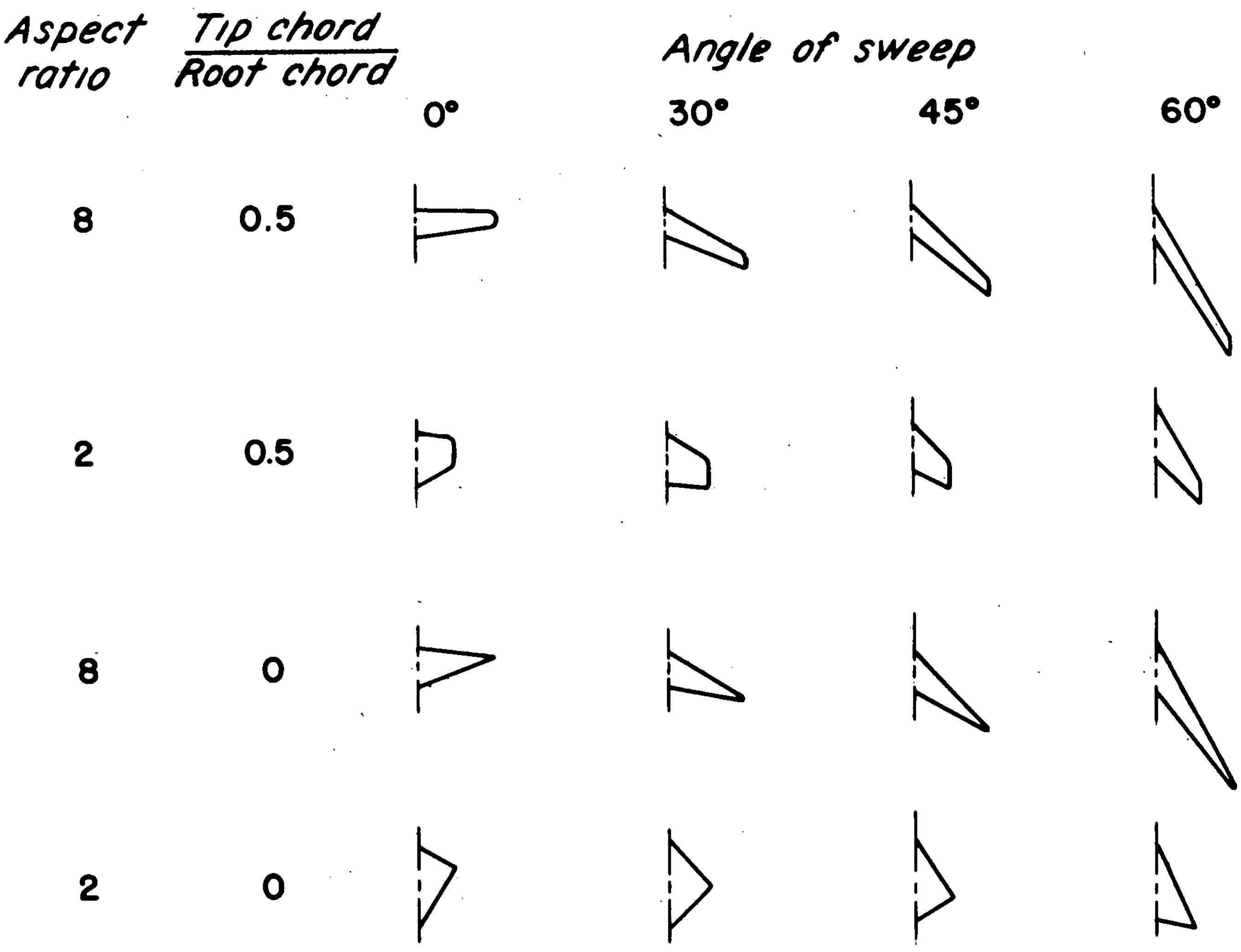

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Figure 2.- Dimensional characteristics of swept-back wings.

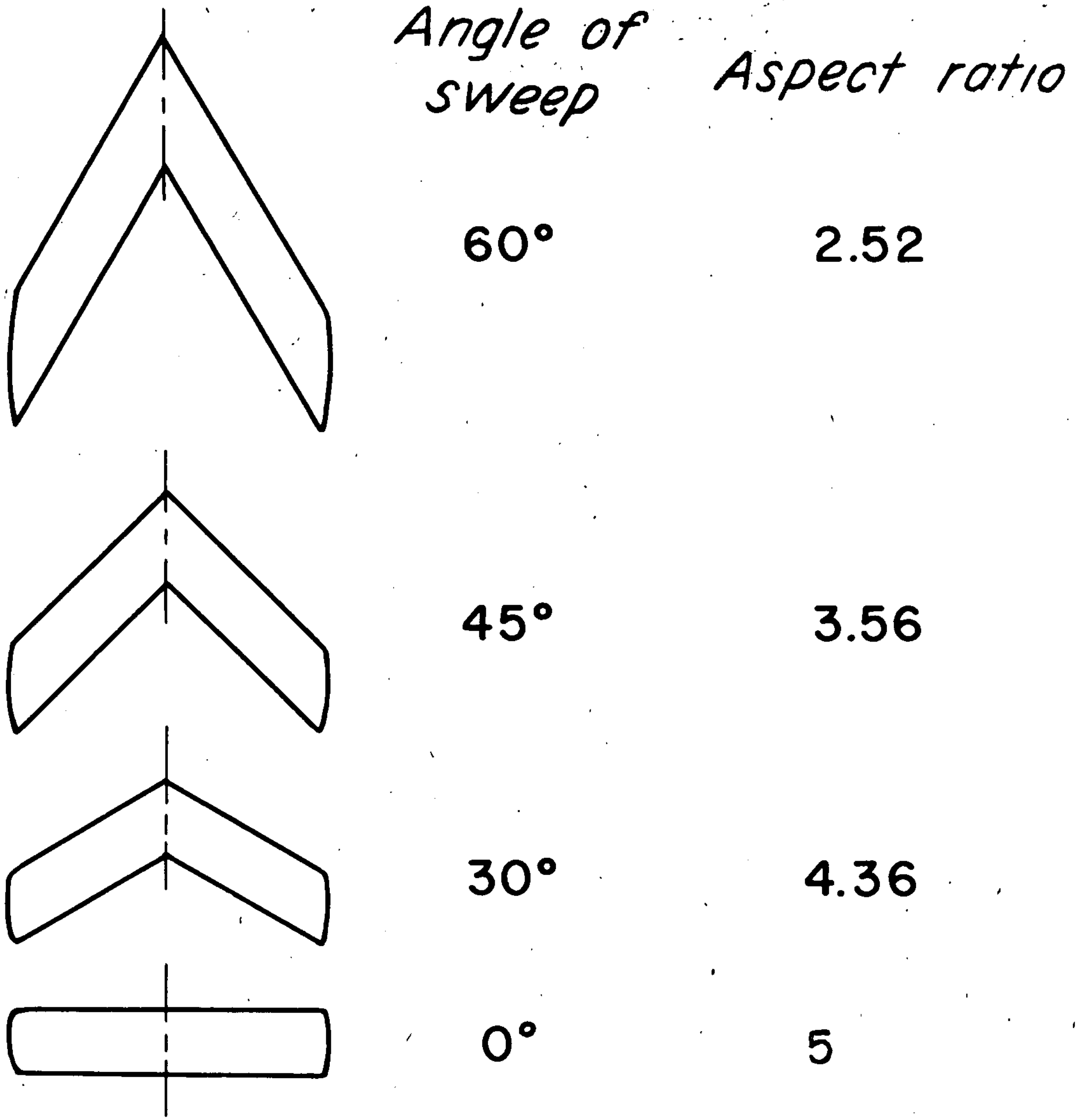

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Figure 3.- Series of swept-back wings used in tests reported in reference 2.

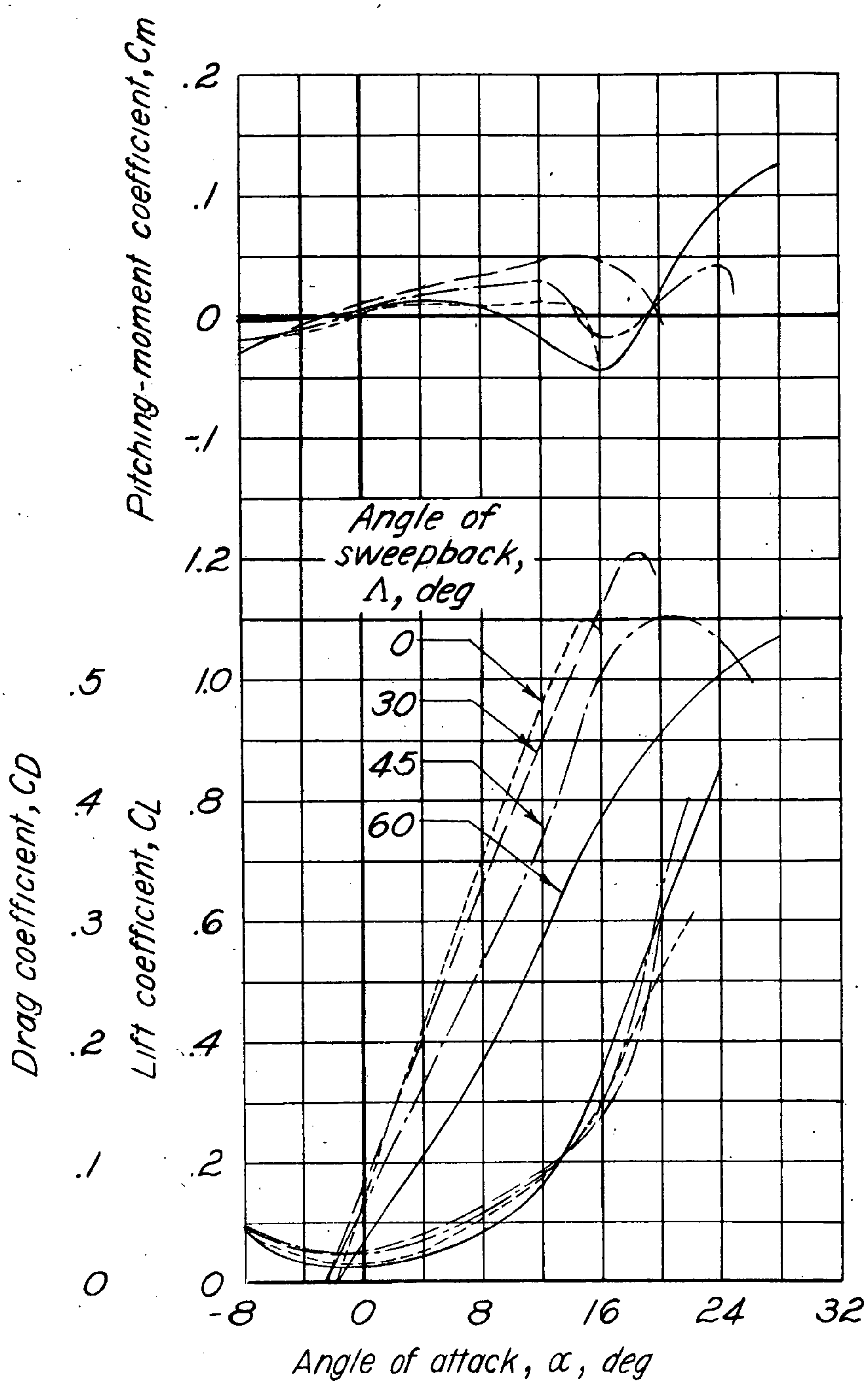

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Figure 4.- Representative data from reference 2 showing the effect of sweepback on lift, drag, and pitching-moment coefficients.

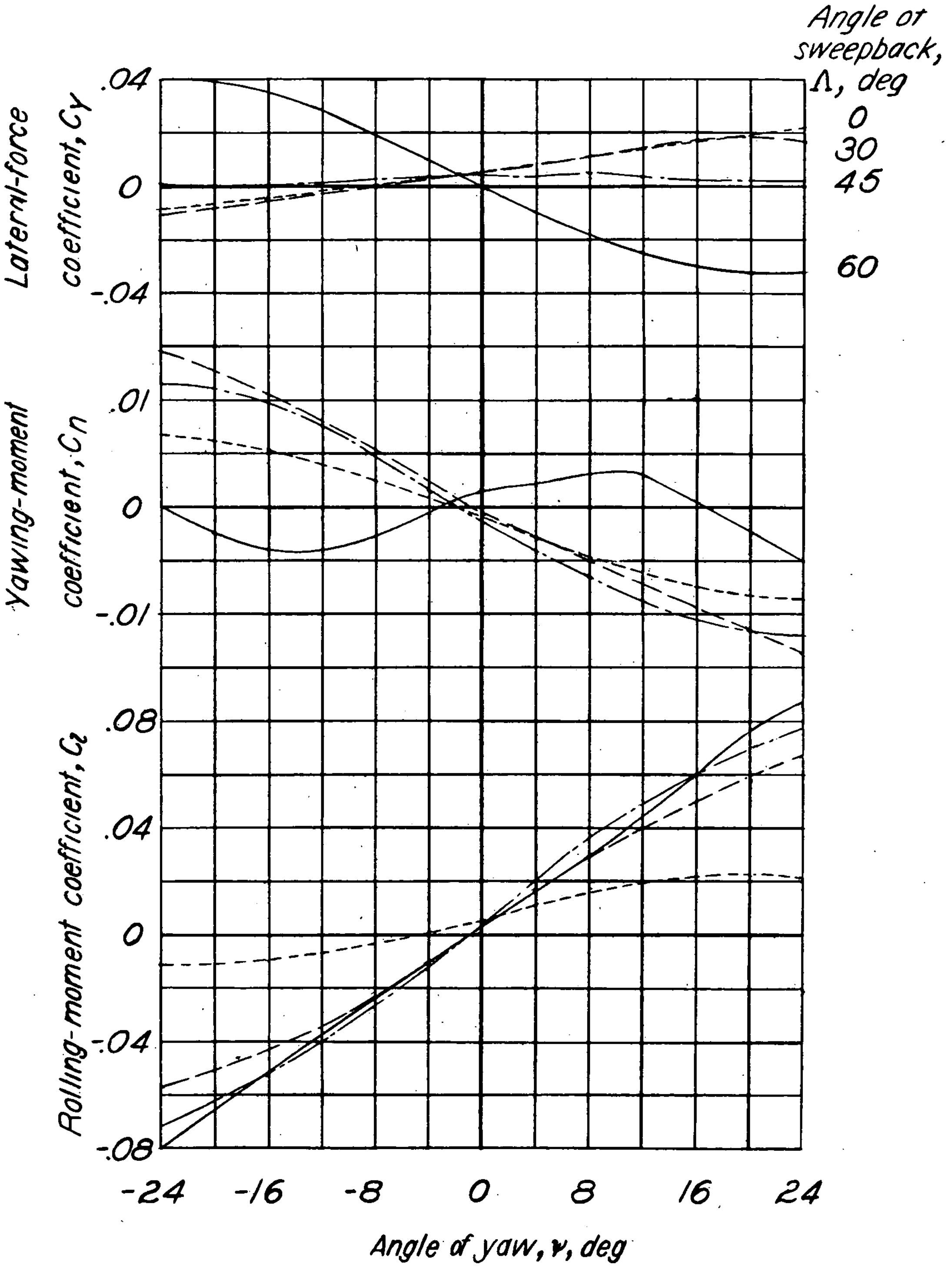

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Figure 5.- Representative data from reference 2 showing the effect of sweepback on lateral-force, yawing-moment, and rolling-moment coefficients. $\alpha = 11^\circ$.

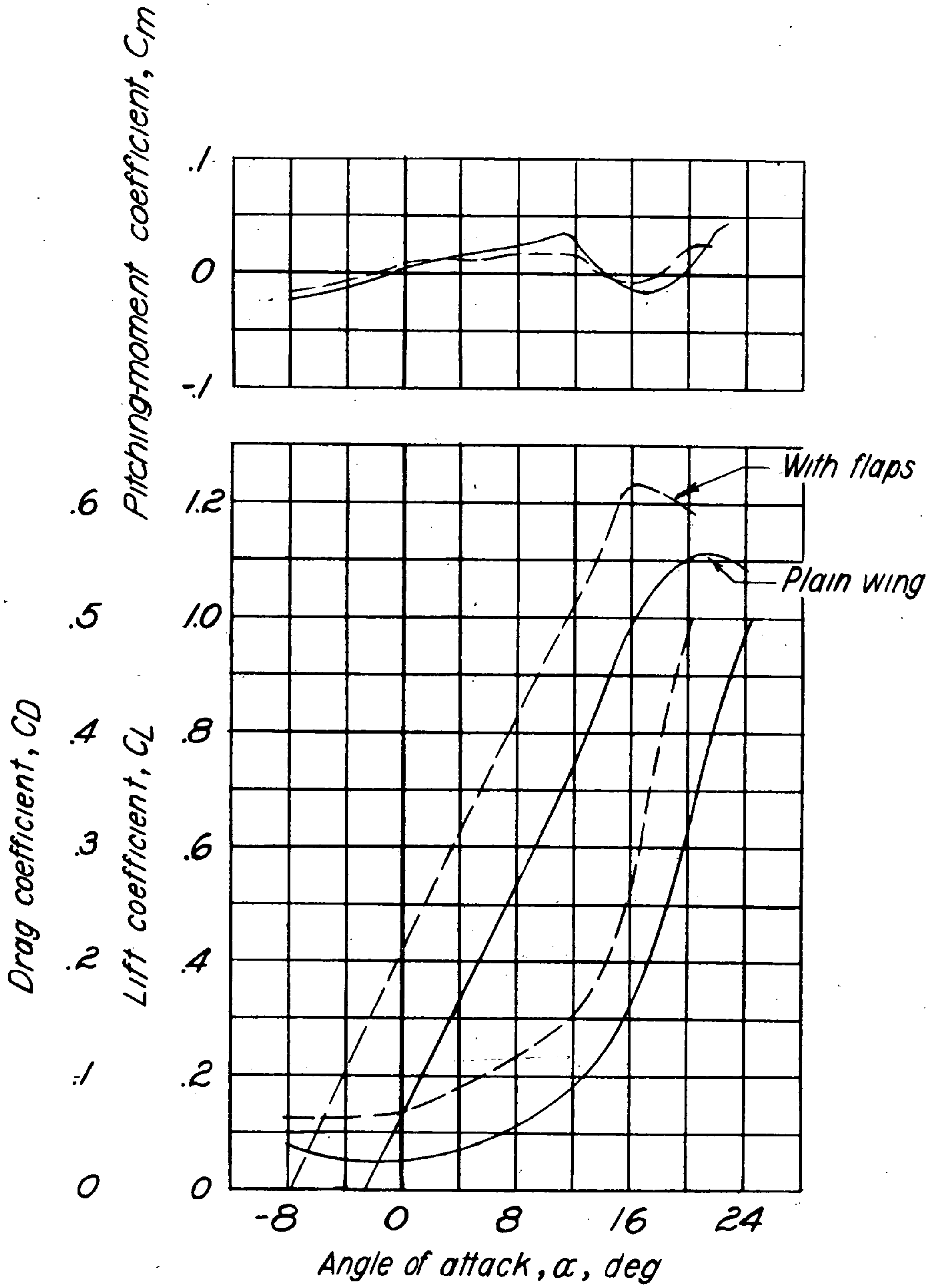

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Figure 6.- Representative data from reference 2 showing the effect of a half-span split flap deflected 60° on the characteristics of a wing with an angle of sweepback of 45°.

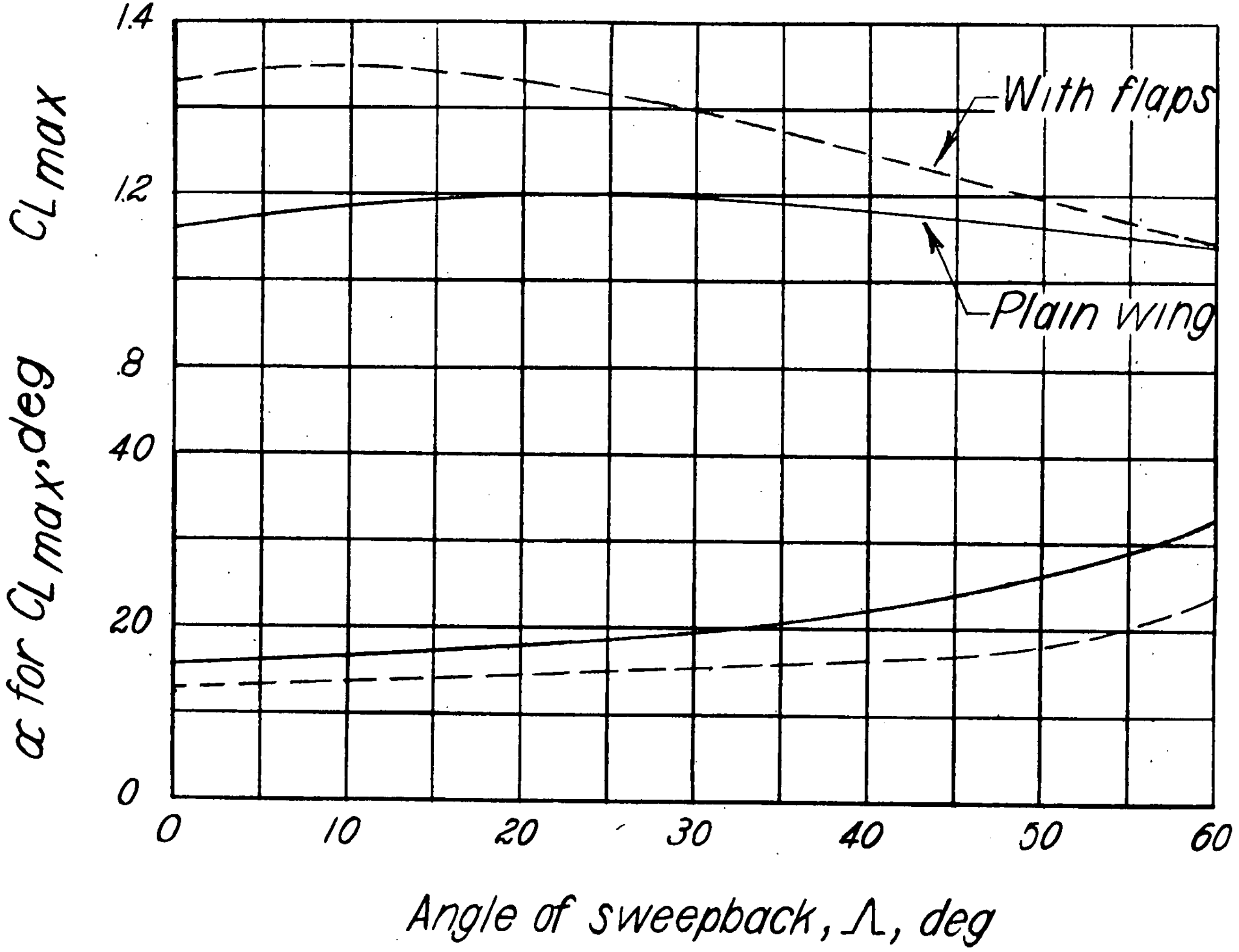

Figure 7.- Effect of sweepback on maximum lift characteristics. (Data from reference 2.)

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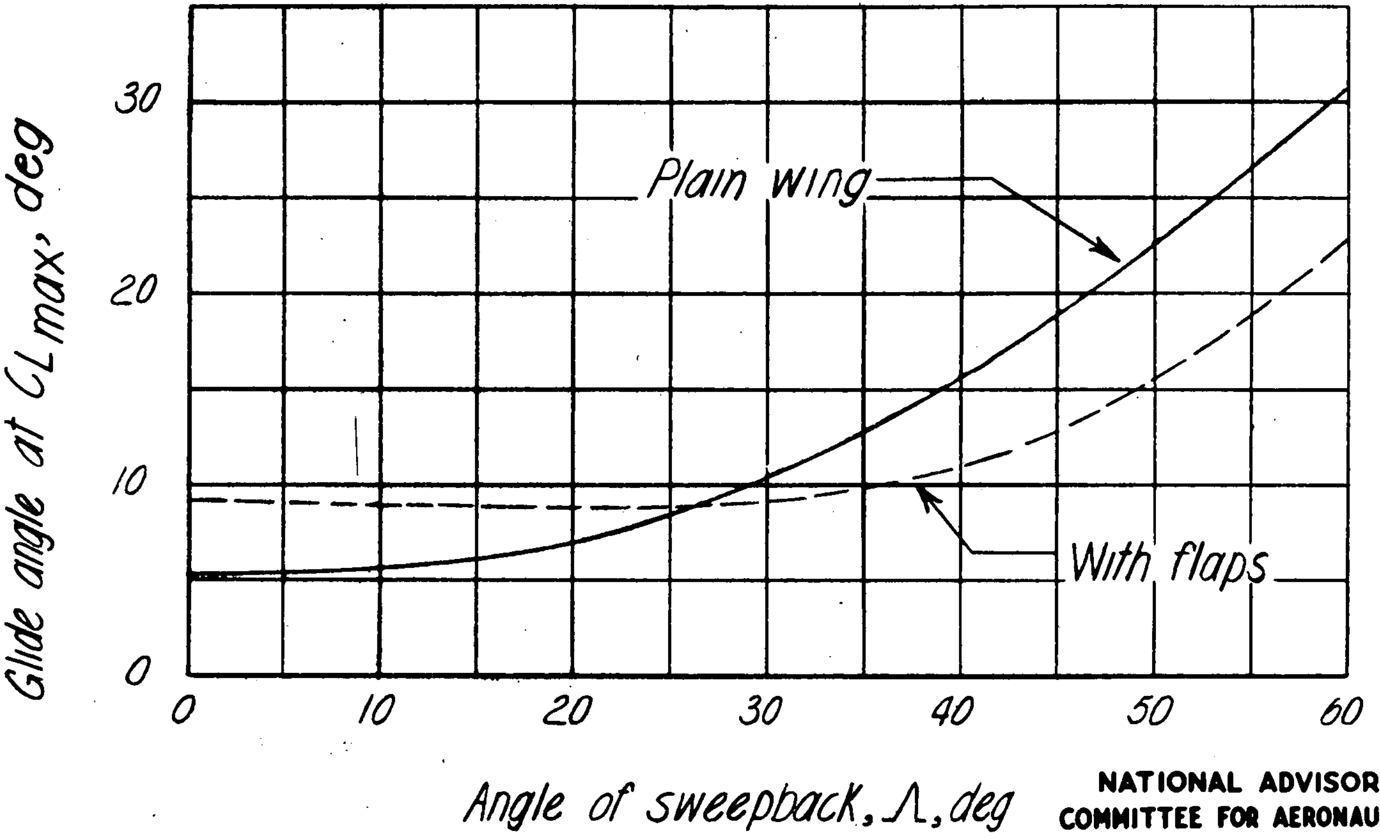

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Figure 8.- Effect of sweepback on glide angle at maximum lift coefficient. (Based on data from reference 2.)

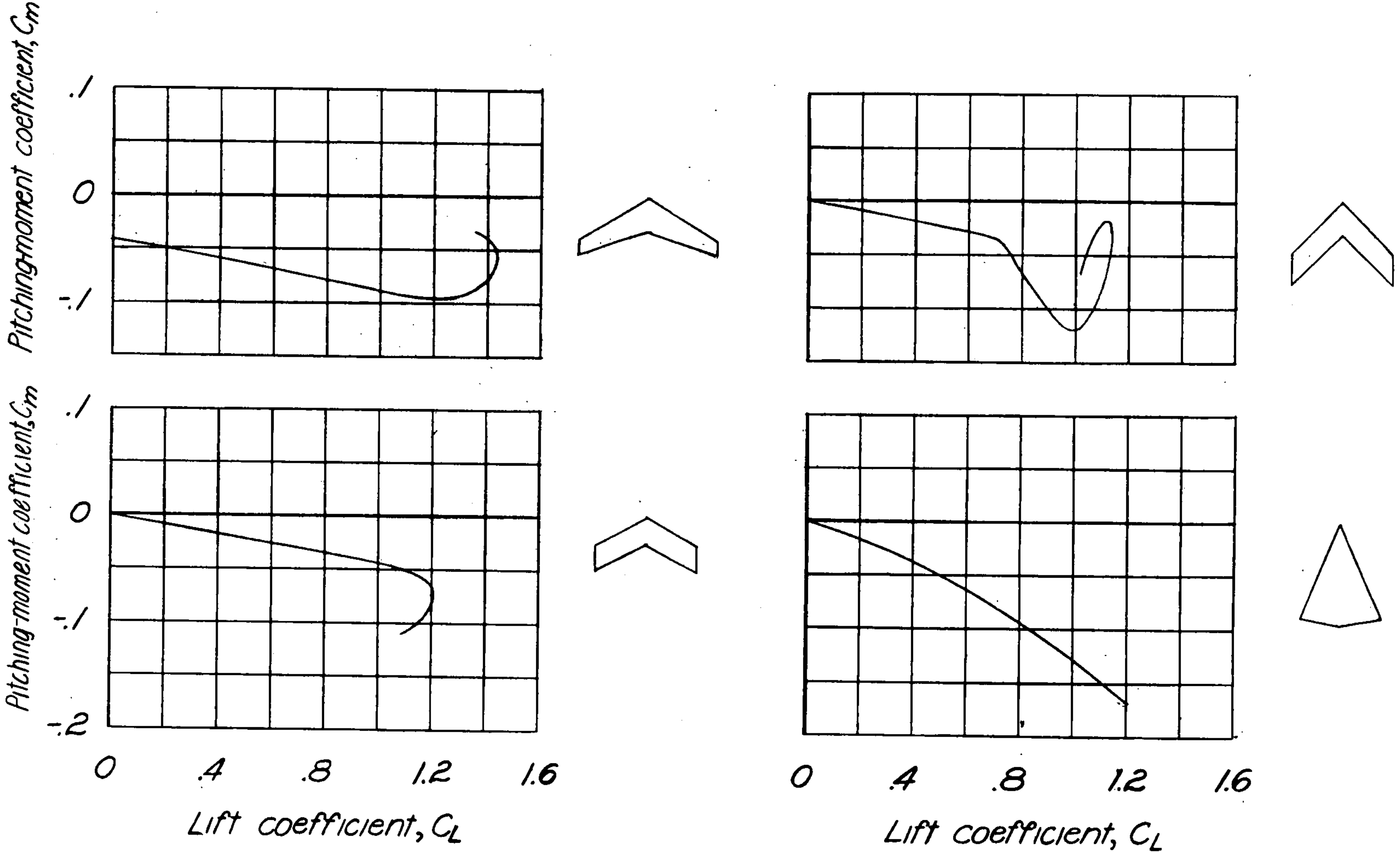

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Figure 9.- Representative pitching-moment-coefficient curves for swept-back wings.

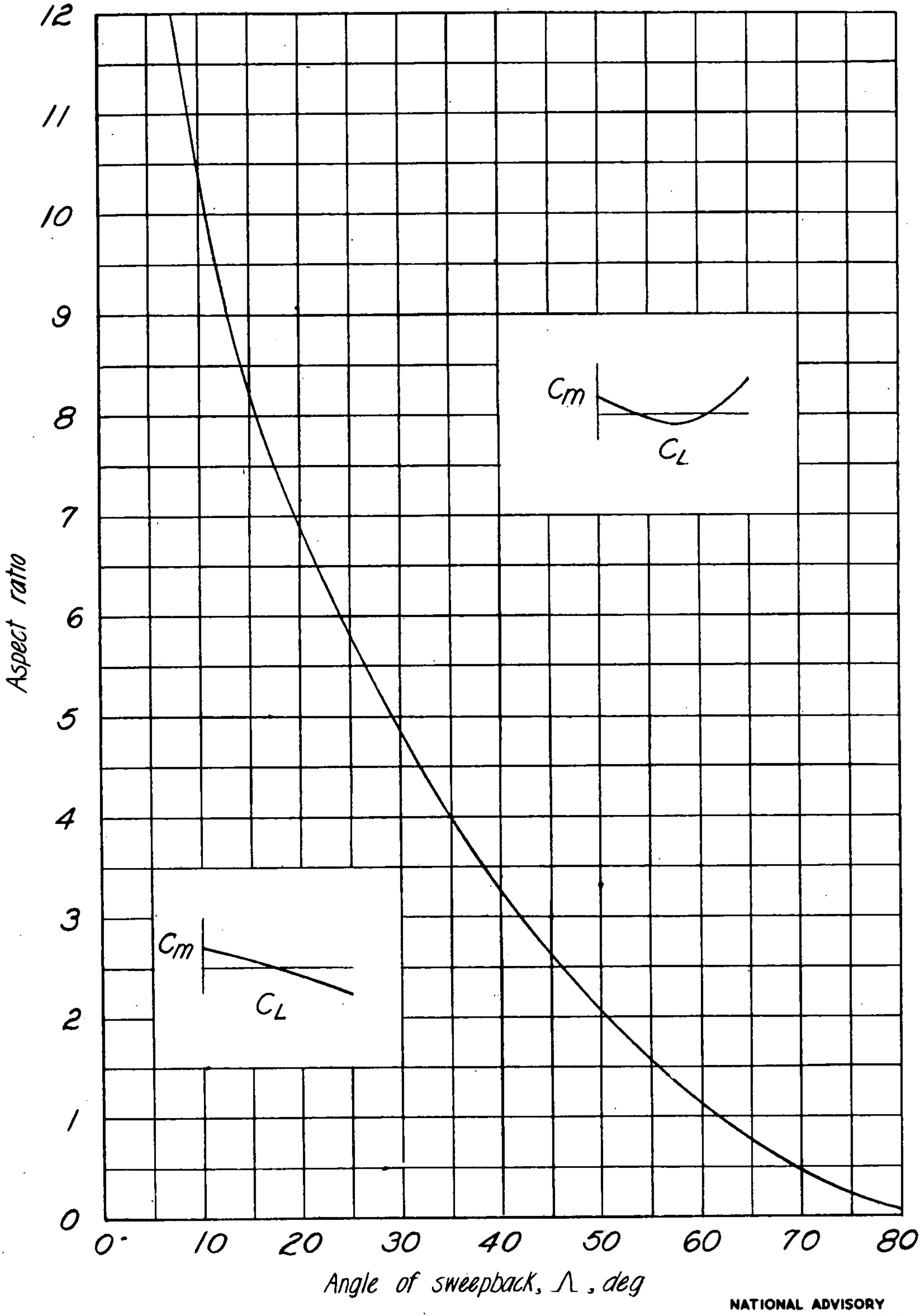

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Figure 10.- Effect of aspect ratio and sweepback on the shape of the pitching-moment-coefficient curve.

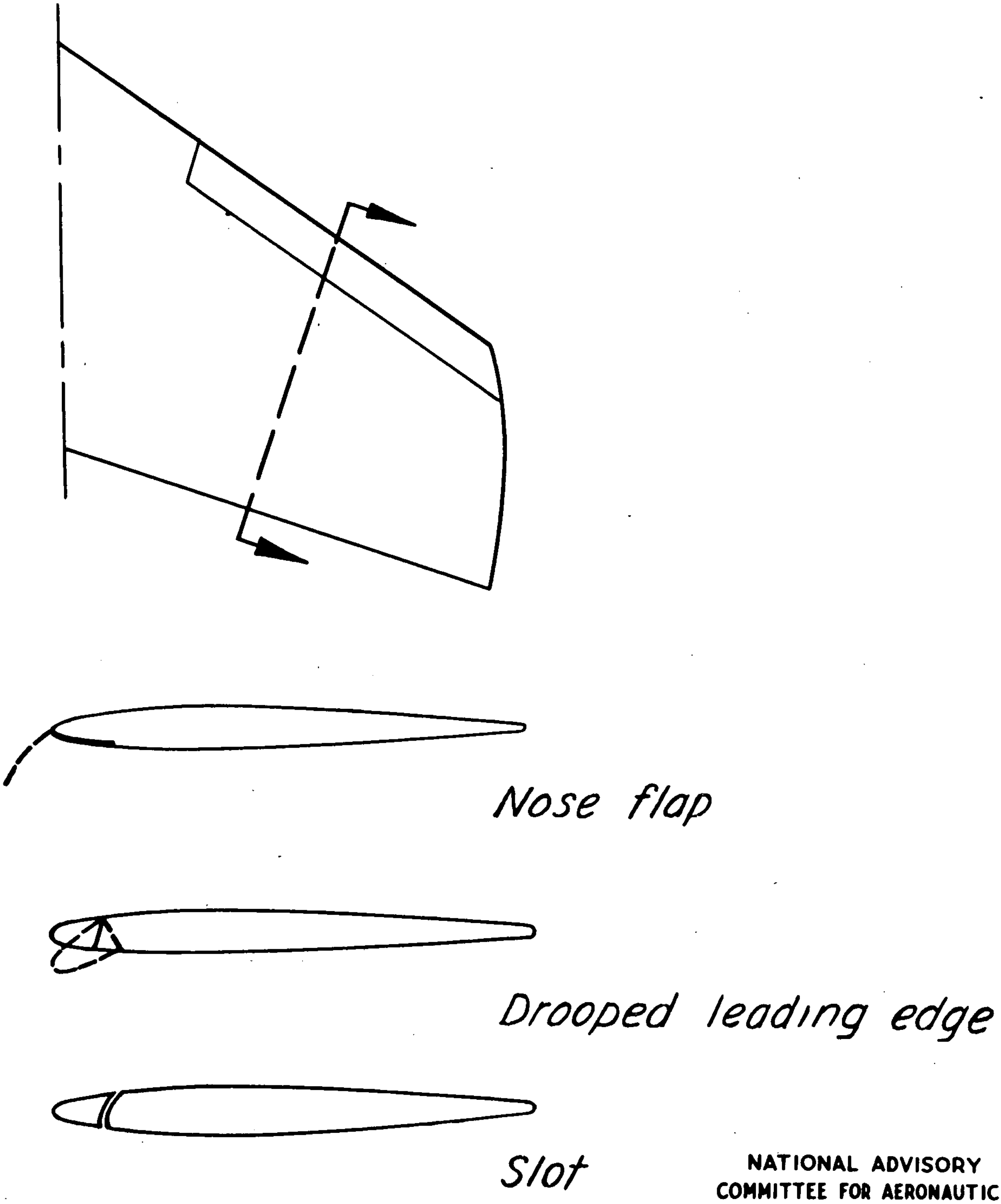

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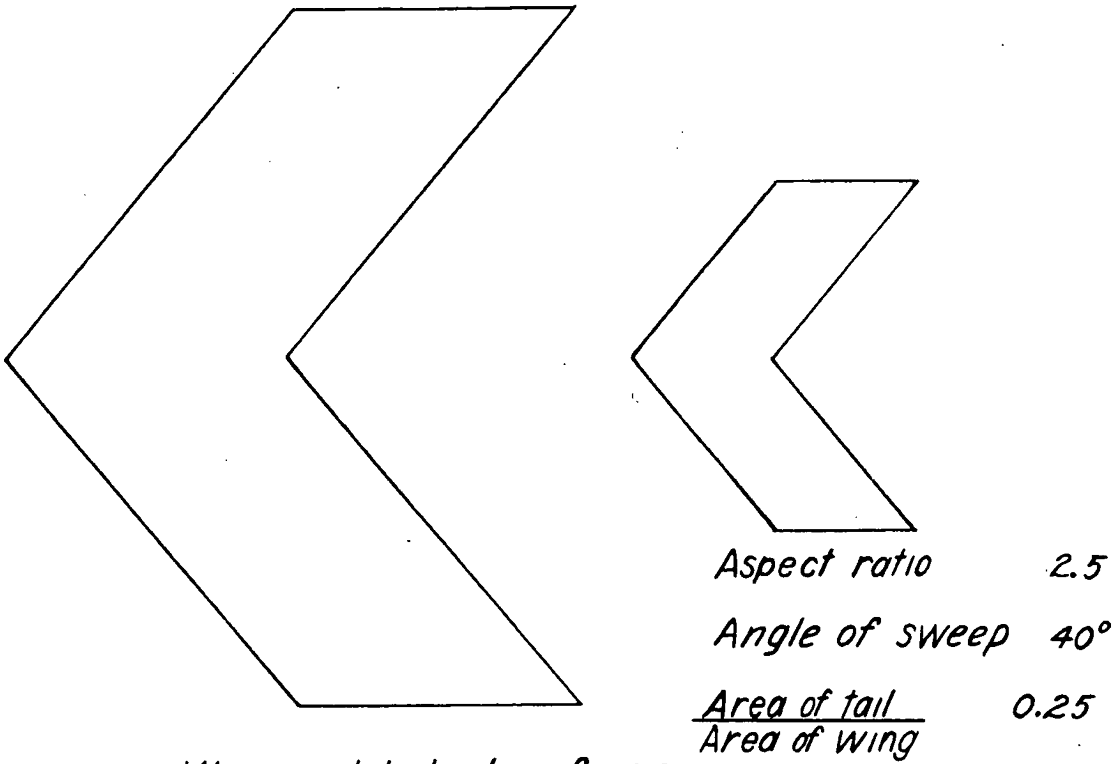
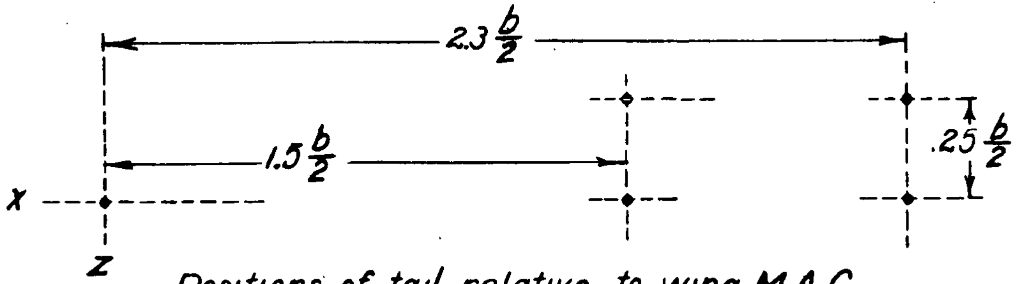
Figure 11.- Leading-edge devices proposed for swept-back wings.



Wing and tail plan forms



Positions of tail relative to wing M.A.C.

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Figure 12.- Configurations of model used in survey of downwash behind swept-back wing.

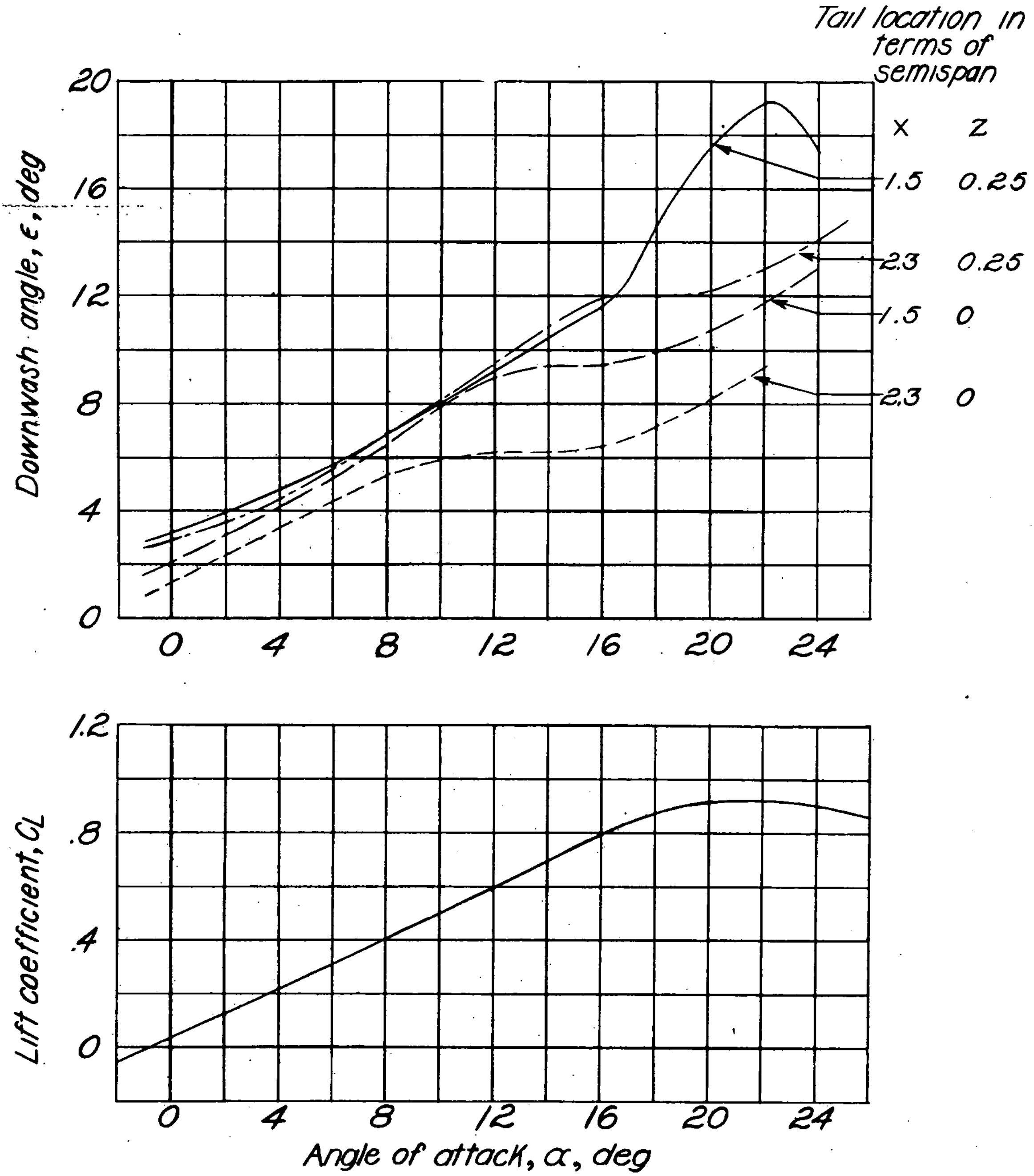

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Figure 13.- Downwash angles behind swept-back wing at horizontal-tail positions given in figure 12.

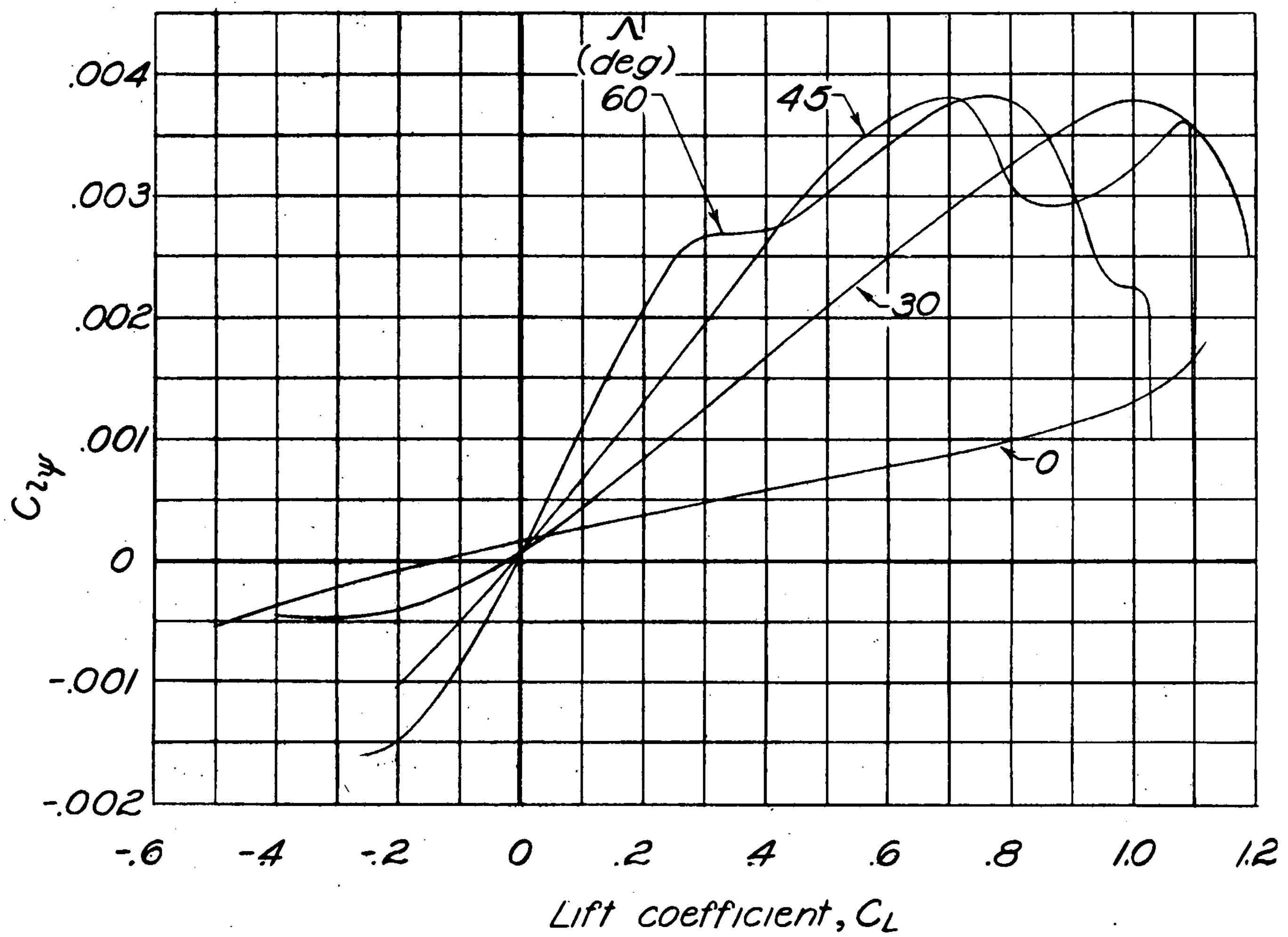

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Figure 14.- Effect of sweepback on the rolling-moment parameter C_{l_ψ}.
(Data from reference 2.)

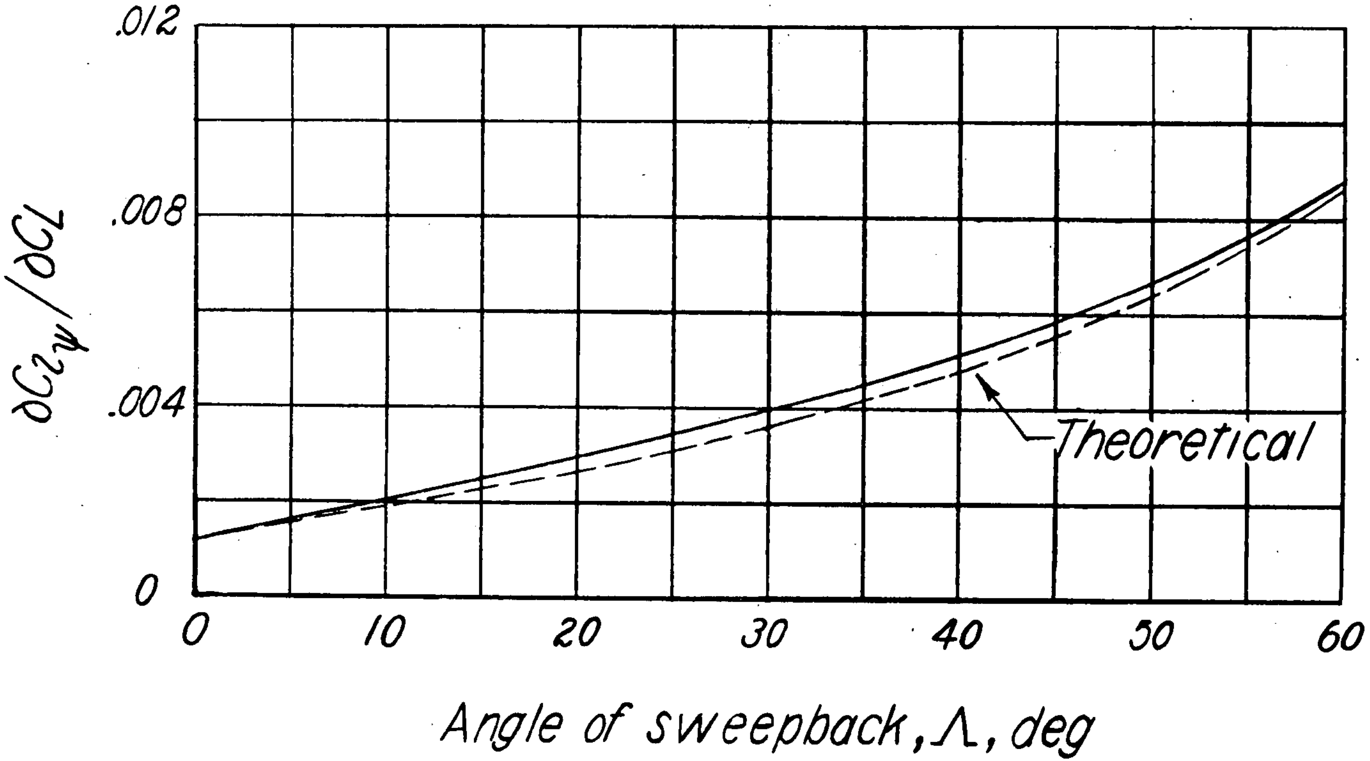

Figure 15.- Variation of the parameter $\partial C_{l_\psi}/\partial C_L$ with sweepback.

(Data from reference 2.)

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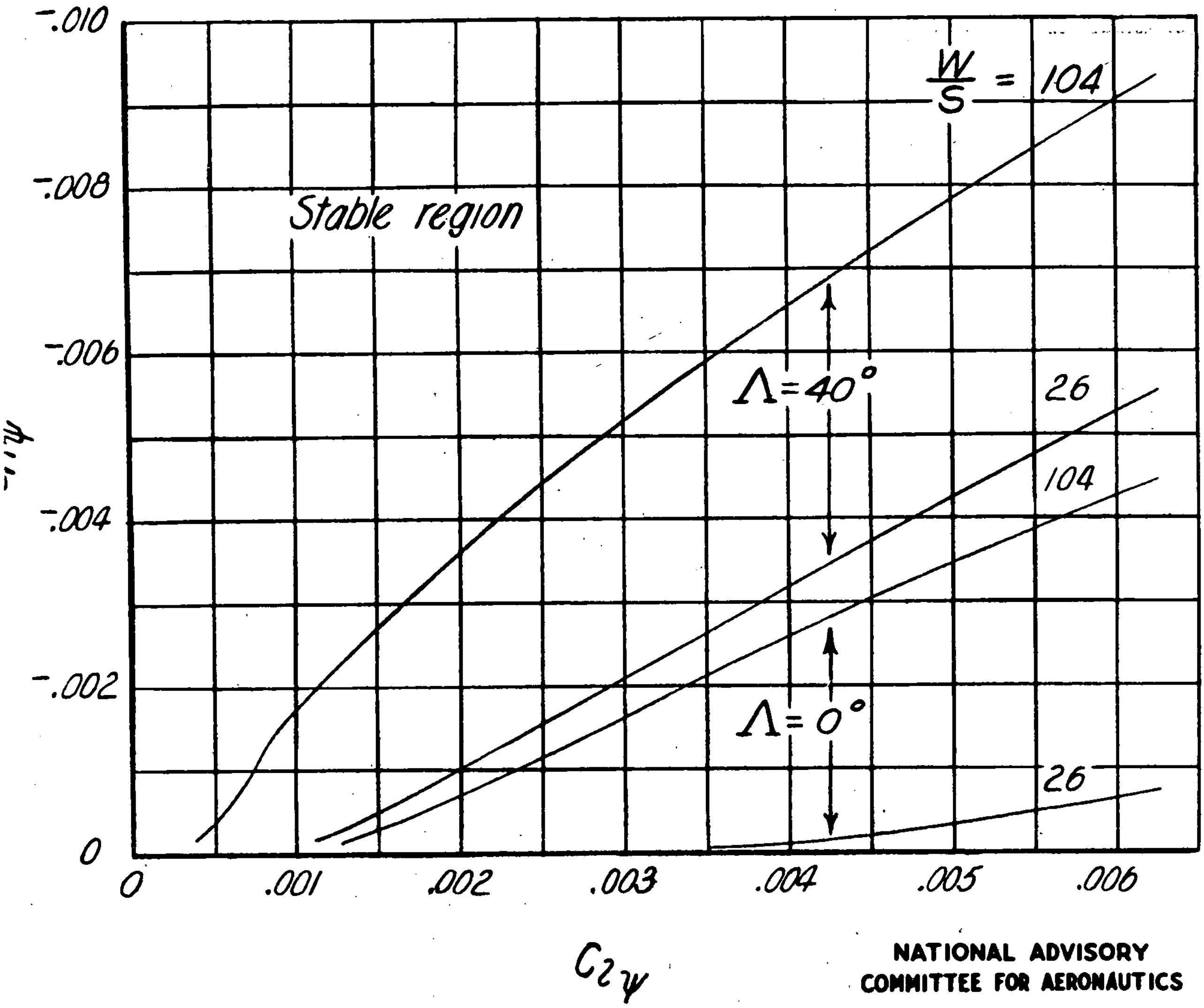

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Figure 16.- Effect of sweepback and wing loading on the boundary for lateral oscillations. $C_L = 1$.

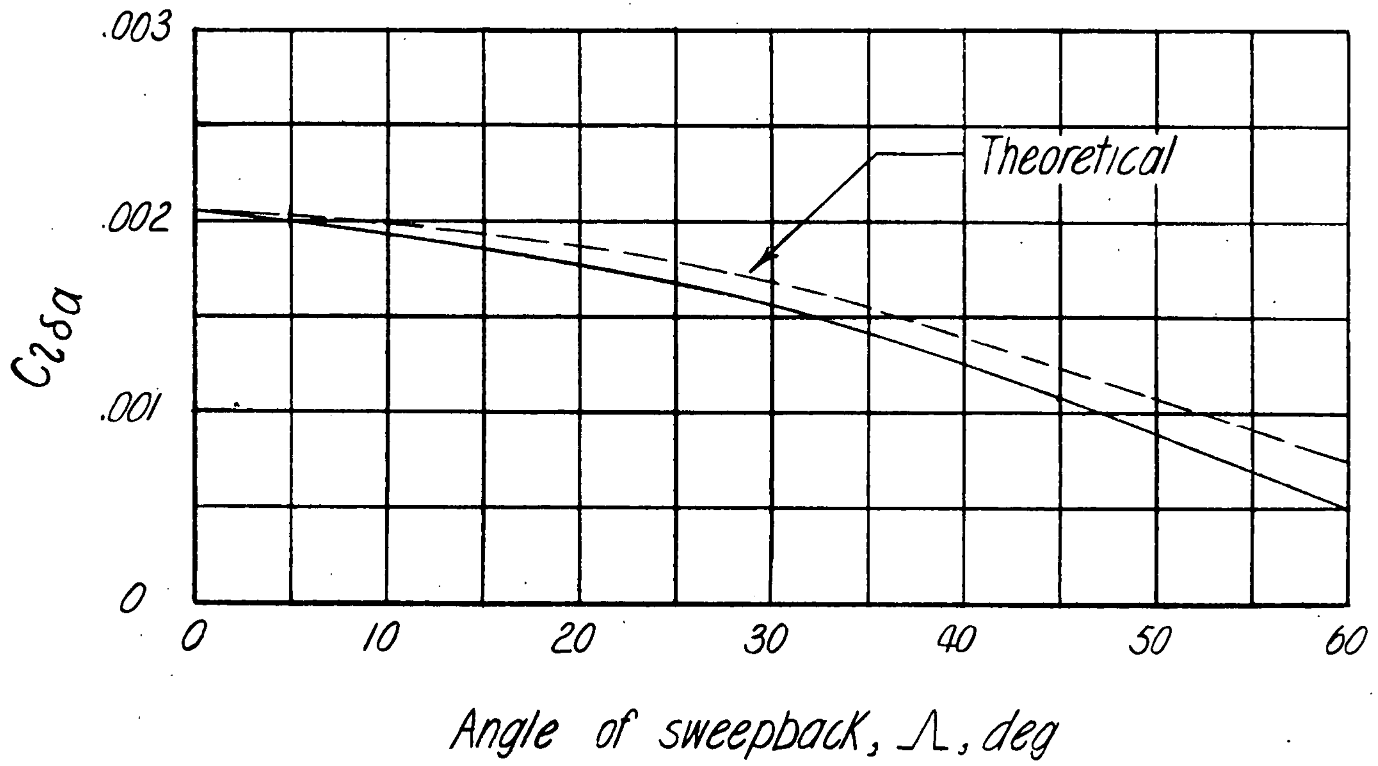

Figure 17.- Effect of sweepback on aileron power. $c_a = 0.2c$.
(Data from reference 2.)

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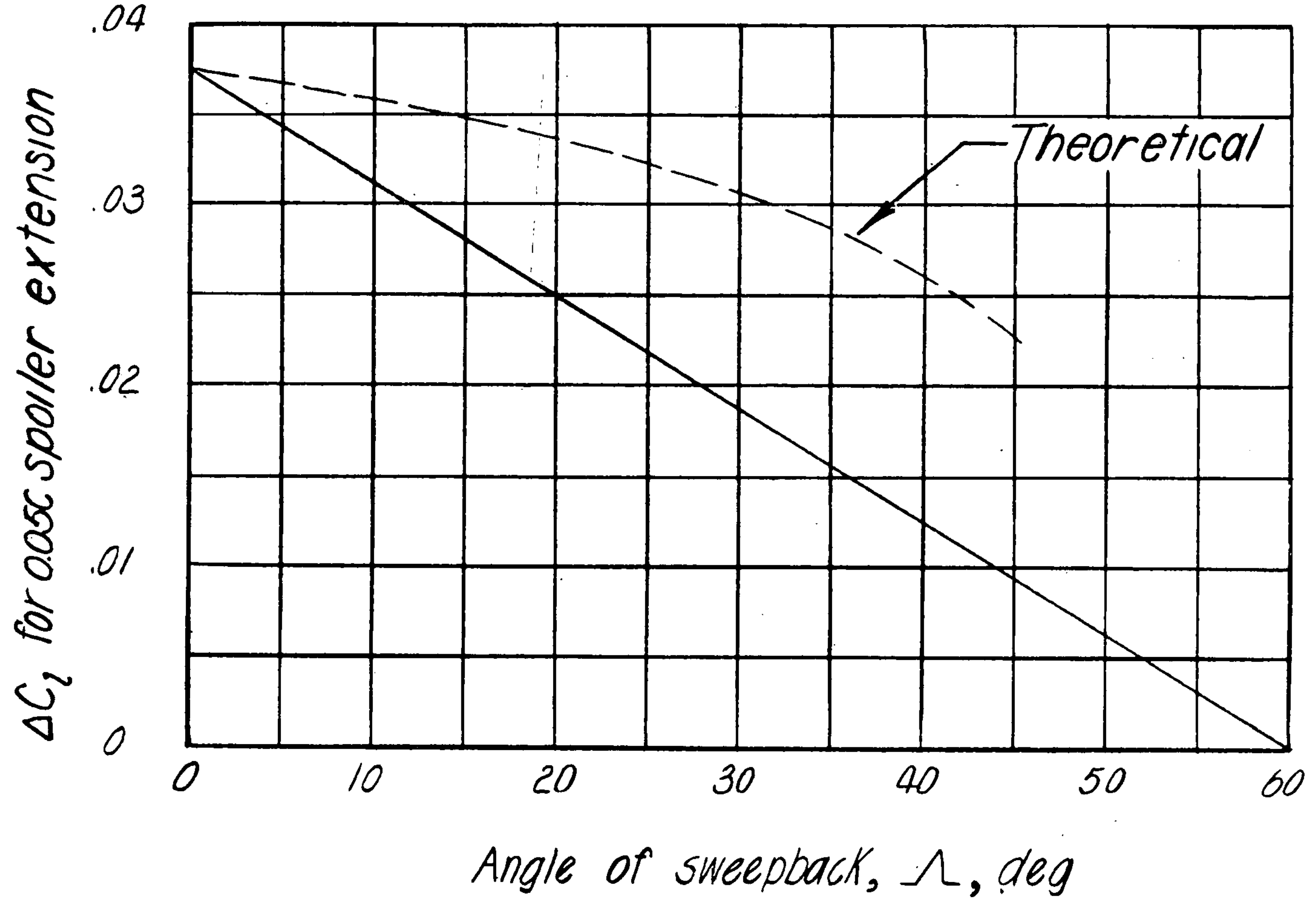

Figure 18.- Effect of sweepback on spoiler power. Spoiler located at 0.8 chord. (Data from reference 2.)

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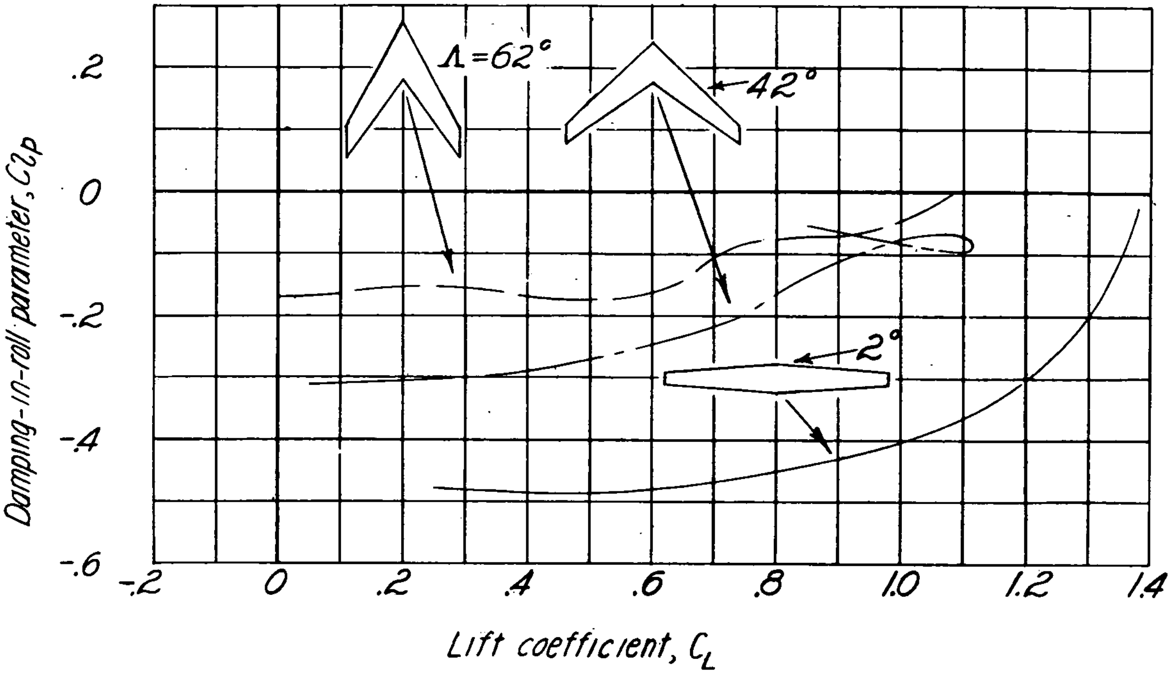

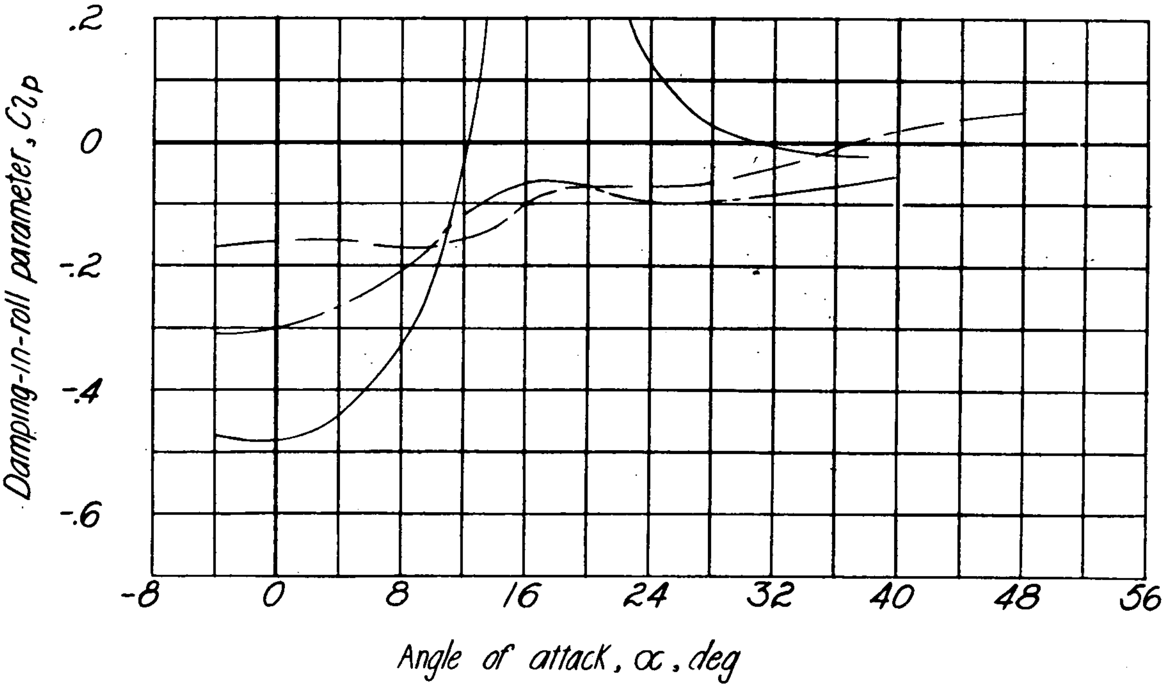

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Figure 19.- Effect of sweepback on damping in roll.

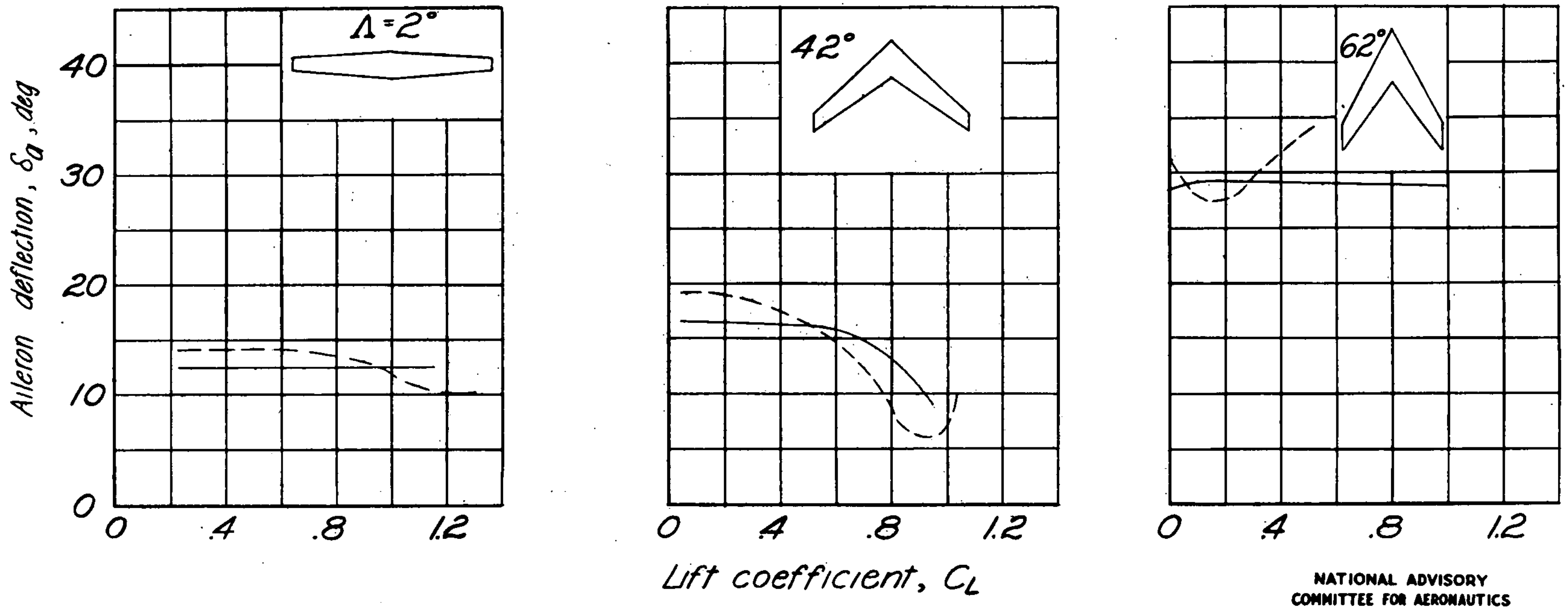

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Figure 20.- Effect of sweepback on the aileron deflection required for $\frac{pb}{2V} = 0.1$.