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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 468

A STUDY OF FACTORS AFFECTING THE STEADY SPIN OF AN AIRPLANE

By Nathan F. Scudder

Langley Memorial Aeronautical Laboratory

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By Nathan F. Scudder

SUMMARY

Data from wind-tunnel tests on a model of the NY-1 airplane were used in a study of the effect on the steady spin of a number of factors considered to be important. The factors were of two classes, mass distribution effects and aerodynamic effects.

The study indicated that mass extended along the longitudinal axis has no detrimental effect or is even slightly beneficial, mass extended along the lateral axis is detrimental if the airplane spins with the inner wing tip far down, and mass extended along the normal axis, if of considerable magnitude, has a strong favorable effect. The aerodynamic effects considered in terms of rolling, pitching, and yawing moments added to those for a conventional airplane showed that added stable rolling moment could contribute favorable effect on the spin only in decreasing the amount of inward sideslip required for equilibrium; negative pitching moment of moderate magnitude has unfavorable effect on a high-angle-of-attack spin, and stable yawing moment has pronounced beneficial effect on the spin. Experimental data from various sources were available to verify nearly all the deductions resulting from the study of the curves.

When these results were considered for the purpose of deciding upon the best means to be developed for controlling the spin, the yawing-moment equilibrium was found to offer the most promising field for research. The wing-cellule yawing moment, of which the shape of the chord-force curve is an approximate measure, should be made as small as possible in the unstable sense and the damping yawing moment of the tail should be made as large as possible. The most serious unfavorable effect on the damping yawing moment of the tail is the blanketing of the vertical surfaces by the other parts of the tail.

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INTRODUCTION

In a previous study of the steady spin (reference 1), it was found that wind-tunnel data obtained in simple force and moment tests with a stationary model could be utilized with fair success in an analysis of the conditions for equilibrium in a steady spin. The wind-tunnel data used in that case were obtained on a model of the NY-1 airplane tested at angles of attack up to 90°. The data were used to predict the angles of attack at which spinning equilibrium would occur in flight by utilizing the method of analysis outlined by Fuchs and Schmidt (reference 2). A comparison of these results with flight measurements for the NY-1 airplane showed the agreement to be reasonably satisfactory.

The curves derived from these wind-tunnel tests in connection with the previous analysis have subsequently been used in a general study of the effect of various factors affecting the steady spin. The results of this study are presented herein. The fact that the study is necessarily confined to consideration of the conditions of equilibrium for the steady spin does not prevent the results from being of considerable practical value. In any steady spin the opposing aerodynamic and inertia forces are in equilibrium. The dangerous or uncontrollable spin arises from the fact that this equilibrium cannot be upset by movement of the control surfaces. By studying the effect of variations in the factors that influence the equilibrium conditions, one learns what the relative importance of the factors is and what design factors tend to make equilibrium impossible. A knowledge of these factors is important for all airplanes, because there must be provision in the form of controls to upset equilibrium quickly and surely before the airplane may be considered safe for general use as long as there is possibility of equilibrium in a spin. It might be argued that the problem of spinning may be solved by adjusting the properties of the airplane so that entry into a spin would become extremely difficult, as has been accomplished with a few airplanes already, but this measure alone cannot be considered a complete solution of the problem.

The deductions are given in general terms as trends rather than in terms of specific numerical values, and consequently may be considered as more or less generally applicable to all airplanes of conventional form. The effects

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of all possible mass-distribution combinations were considered for an airplane having normal aerodynamic properties. Then, in order to decide what aerodynamic properties of an airplane could be most effectively improved with regard to spinning, the effects of a pure rolling moment, pitching moment, and yawing moment were considered separately. Some special devices that have been considered important with regard to spinning because of the aerodynamic moments they produce are also discussed very briefly.

METHOD OF ANALYSIS.

The study of the effects to be considered herein was facilitated by the existence of the curves already available from reference 1. These curves are reproduced in figures 1 to 6, inclusive. The force curves for the NY-1 model (fig. 1) and the normal- and chord-force curves (fig. 2) will be employed occasionally, but the rolling-moment equilibrium (fig. 3), pitching-moment equilibrium (fig. 4), and yawing-moment equilibrium curves (fig. 5) and the curves for equilibrium of three moments (fig. 6) will be used continually in the discussion. It will be noted that the shape of the rolling- and yawing-aerodynamic-moment curves is such that more than one intersection denoting equilibrium with the gyroscopic moment curves may occur for the same value of glide-path angle. For this reason there are three rolling-moment equilibrium curves and similarly two yawing-moment equilibrium curves on figure 6. The derivation of the curves was based on strip theory. The assumptions employed are given in detail in references 1 and 2. The axes employed for expressing components of moment and force were the body axes, as these coincide almost exactly with the principal axes.

The use of these curves in finding the effect of a particular factor will be described only briefly, since a complete discussion would require the repetition of equations given in several previous papers, such as reference 1. The main steps of the process are as follows: First, the effect of the factor on the aerodynamic and gyroscopic moment curves is noted. This effect may be a shift of the aerodynamic or the gyroscopic moment curves for one or more axes depending on whether the factor introduces aerodynamic moments or affects the mass distribution. Secondly, the effect on the moment equilibrium curves (fig. 6) is studied to determine where the new point of intersection will fall.

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The new values of angle of attack and glide-path angle are obtained in this way. If other quantities, such as linear velocity or angular velocity, were desired, they could be read from the appropriate curves at the angle of attack and glide-path angle found for equilibrium of the three moment curves. (See figs. 5 and 6, reference 1.)

This procedure may become slightly involved if the rolling-moment equilibrium curve does not pass through the intersection of the pitching- and yawing-moment equilibrium curves. The lack of rolling-moment equilibrium, however, may be readily compensated for by assuming a small amount of inward or outward sideslip, which in turn makes only negligible changes to the forces and pitching moment and completes the conditions for equilibrium. The damping yawing moment originating from the empennage may be affected seriously by large changes in sideslip, but for small changes in sideslip the change in total yawing moment is probably small enough so that, as a working approximation, it may be said that failure of the rolling-moment equilibrium curve to pass through the intersection of the yawing- and pitching-moment equilibrium curves may be entirely compensated for by assuming an appropriate amount and sense of sideslip. The question of the effect of large inward sideslip on the damping yawing moment will be discussed later.

As has been indicated, this method gives, for final results, shifts of or the elimination of curves denoting equilibrium. Obviously the most desirable result would be to find a combination of mass and aerodynamic properties for the airplane that would make equilibrium of all forces and moments impossible, or in other words, that an intersection of the three moment equilibrium curves could not exist nor be made to exist by moderate changes in the various parameters of the spin motion. If this ultimately desirable result cannot be obtained, combinations of aerodynamic and mass properties will be considered desirable when they require that equilibrium occur at relatively low values of angle of attack excepting, possibly, extremely low values (between stall and 35°). Ordinarily the difficulties of bringing about recovery are less acute for airplanes that spin at low values of angle of attack than for those that spin at high values of angle of attack. In addition, equilibrium with outward sideslip may be considered more favorable to recovery than equilibrium with inward sideslip, because the geometric orientation of the rudder to the incident air is less favorable with inward sideslip than with outward sideslip.

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EFFECT OF MASS DISTRIBUTION

The effect of mass distribution was studied by noting the effect on the equilibrium of the three moments for all the possible changes of mass distribution. The changes of mass distribution expressed as ballast added to or taken from the airplane in positions on each of the three axes, the effect of the mass distribution on the individual moment equilibria of each of the three axes, and the change in the equilibrium of all forces and moments are given in table I. These mass distribution changes are considered as being made without change of the mass centroid of the airplane. Since the assumed mass changes did not in any way affect aerodynamic properties, it was only necessary to determine how the gyroscopic moment curves were affected and what the corresponding changes in equilibrium were. The entries in the table include only the simple increases or decreases of ballast because all the other combinations may be derived from these. For example, the effect of adding ballast on two axes simultaneously is the same as removing ballast from the third axis for which the effect is already given in the table. This relation is true because the gyroscopic moments depend on the moment-of-inertia difference rather than upon their absolute magnitudes. For the same reason it follows that addition or subtraction of the same amount to or from all three of the axes would cause no change. Only one of the remaining combinations need be considered; namely, the case of the addition of ballast on one axis and removal of ballast from another. In this case there are changes for all three gyroscopic moments, one of them being changed by the sum of the two moment-of-inertia changes. For purposes of the discussion, however, it is just as satisfactory to note the effect given in the table for each of the separate changes and combine these effects.

A study of flight data has been made to determine the extent to which the statements of table I have been verified in flight. Authoritative reports from various sources in this country and abroad have been consulted. The extent of this verificiation for changes in mass distribution along each axis will now be considered briefly.

The effects of moderate extensions in the mass distribution along the longitudinal axis, which were small decreases in angle of attack and rate of rotation, have been

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confirmed in a number of instances. These confirmations are to be found in the mass-distribution tests on the NY-1 airplane (reference 1); mass-distribution tests on the XN2Y-1 airplane (to be published soon); mass-distribution tests on airplanes and flying models in England (references 3 and 4); and several authentic reports from aircraft builders in this country. The same effect as that given in the table for retracting the mass distribution along the longitudinal axis has been observed in at least one authentic case.

The effect of extension or retraction of mass along the lateral axis is somewhat complicated by the fact that the aerodynamic moment-equilibrium conditions have considerable influence on the manner in which this type of mass distribution will affect the spin. If the wing axes are practically horizontal, the angular velocity in pitch will be practically zero and mass-distribution changes along the lateral axis will have no influence on the spin. In cases where sideslip is such that the wing axes are not horizontal, there is an important effect on the spin when the lateral distribution of mass is changed. The results in the table are applicable to the usual case with inner wing tips down. Since no authentic observations of spins with outer wing tips down have been made at this laboratory or reported to us from other observers in this country (with the exception of spins with unusual control settings), such a case evidently need not be considered further than to note that the results would be opposite to those given in the table. The results in the table have been in complete agreement with the results of flight tests with the XN2Y-1 airplane in its normal condition (to be reported soon) and with a sharp-leading-edge strip installed on the wings (reference 5). In the latter tests the wing axis was horizontal and no effect was observed when ballast was put on the wing tips. The statements regarding the effect of ballast at the wing tips have also been substantiated by flight tests in England, and if not actually substantiated, at least not refuted by tests reported in reference 6. In the latter case, the attitude of the wings was not reported, but it is probably safe to assume that the inner tips were down for the O2E airplane, and that the wing axis was almost horizontal for the O1 airplane. This assumption makes the results reported in reference 6 agree with all other observations on this subject.

The effects of changes of mass distribution along the

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normal axis stated in the table cannot readily be verified because of lack of flight data. It is interesting to note, however, that the spinning of a small monoplane with overhead engine nacelle has been reported to us to be unusually satisfactory. This monoplane entered the spin in a normal manner, but would recover immediately if either of the controls were eased slightly toward neutral, and with one loading condition, it recovered against the controls after four to six turns. Another case of some interest in regard to this subject, which should be recalled from reference 1, relates to the effect of moving lead weights away from the center of gravity along a rod in the position of the normal axis of a flying model. In these tests, the continued extension of mass distribution along the normal axis caused the model to spin steeper and steeper until finally it would not spin at all.

The findings of this study and the other investigations of the effect of mass distribution from which data have been drawn may be summarized in terms applicable to design practice as follows:

(a) The moderate changes of mass distribution along the longitudinal axis likely to be encountered in various arrangements of the structure and loads of an airplane of conventional design are not important, and in this case arrangements that tend to make the extension of mass along the longitudinal axis great are slightly preferable. On the other hand, if the design of an airplane is such that the difference (C-A)* may be diminished to less than half the value of that characteristic of present conventional airplane designs, then such retraction of mass along the longitudinal axis is very desirable. A decrease in (C-A) of sufficient magnitude to be beneficial is not possible if an airplane is to have even the same general appearance as the conventional landplane of today.

(b) It is good practice to have the extension of mass along the lateral axis as small as possible, although it often does not make any difference.

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*A, B, and C are moments of inertia in slug-ft.^{2} about the three airplane axes X, Y, and Z, respectively.

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(c) Little can be done with mass distribution along the normal axis that is of sufficient magnitude to be important in common airplane arrangements. If, however, the engine is mounted in a nacelle over the wing, favorable effects may be expected because removing the motor from the nose and placing it some distance above the center of gravity produces a combined effect large enough to give favorable results. The addition of floats to an airplane otherwise similar to conventional landplanes may be expected to affect the spin unfavorably, partly because the moment-of-inertia contribution of the floats is not great enough to extend the effect of mass distribution along the vertical axis into the favorable range and partly because the presence of the float or floats may unfavorably affect the aerodynamic pitching and yawing moments. The importance of the yawing-moment effect will be discussed later. In one case at least, that of the NY-2 seaplane (single float), the difference in moments of inertia (reference 7) between the landplane and seaplane is largely a difference that might be obtained by adding ballast at the wing tips.

EFFECT OF AERODYNAMIC MOMENTS

The effect of added aerodynamic moments on spinning equilibrium may be found by the method employed for the study of the effect of mass distribution. In this case the primary effect is some arbitrary change of a set of aerodynamic-moment curves. This change may in turn produce secondary changes in other aerodynamic moments if a change in sideslip should be introduced, and if many secondary effects occur, the conditions become too complex to lead to clear conclusions. Fortunately, this complexity does not always develop.

Rolling moment.- The effect of added rolling moments is complicated by the effect of rolling moment due to sideslip. Moderate magnitudes of added rolling moment of either sense will evidently produce a new spin equilibrium at a slightly different attitude and rate of rotation as shown by tracing through the effect of sideslip changes. Owing to the large effect on the rolling moment of practical magnitudes of sideslip, fairly large rolling moments are effectively compensated for by small changes in angle of side-

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slip. The magnitude of this difference in attitude is not easily determined from the subject curves. Some computations based on comparatively extensive model measurements made in England (reference 8) indicate that for the airplane studied in those tests a stable rolling moment (opposing the spin) would produce equilibrium at a higher angle of attack and higher rate of rotation. It is evident, however, that extraordinarily large stable rolling moments would bring about recovery. Such large rolling moments could not be produced by any practical alteration to conventional airplanes, which leads to the conclusion that little direct benefit could be derived from added rolling moments.

There are indirect effects of stable and unstable rolling moments, however, which should be metioned. The outward sideslip characteristic of equilibrium with stable rolling moment is associated with an attitude in which the wing axis is nearly horizontal. This effect is desirable, as mentioned before, unless the outward sideslip is so great that the outer tip is forced far below the horizon, in which case equilibrium might occur at high angles of attack if (A-B) were negative. Spins with outer wing tips down, however, seldom occur. Unstable rolling moments will induce inward sideslip which causes the inner wing tip to go down. This is an adverse effect as regard the angle of the vertical surfaces relative to the incident wind. If, in addition, (A-B) is positive, equilibrium can only occur at high values of α and Ω. If (A-B) is negative, the effect of decreased damping moment in yaw due to change in angle of the incident air on the vertical surfaces is partly compensated for by the change of gyroscopic moment, with the consequence that the angle of attack and rate of rotation for equilibrium are not greatly changed.

Since the magnitudes of the rolling moments considered in this part of the discussion are not extremely large, it is evident that where unfavorable spinning conditions are aggravated by the particular magnitude and sense of cellule rolling moment prevailing, some desirable effects may be obtained by appropriate changes in the cellule rolling-moment characteristics. Such changes should be introduced by changes in the cellule arrangement (chiefly stagger in biplanes) or section characteristics, since control surfaces are not well suited to this function at the high-angle-of-attack conditions prevailing in the spin. An example of such a change that actually has been accomplished is the case of the experiment with a sharp leading edge installed on the wings of the XN2Y-1 airplane (reference 5).

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The measurements of sideslip angle showed that the sideslip was changed from a moderate value inward to a strong value outward by the addition of the strips. The decrease in angle of attack is to be attributed to other causes to be discussed later under yawing moments.

Sideslip, as indicated above, plays an important and unique role in the equilibrium conditions of the spin. It has predominating influence on rolling-moment equilibrium without having effects of importance on the equilibrium of forces along any of the axes or of the moments about the lateral and normal axes. The study of the curves indicates that if rolling moment were not generated by sideslip, ability to reach spinning equilibrium would be a rare, rather than an almost universal property of airplanes. From this conclusion, it follows that if a means of controlling the sideslip could be found, mass distribution might be adjusted so that spinning equilibrium for many typical combinations of aerodynamic properties would not be possible, which would be a very desirable result. Practically no information is available at present to indicate whether an appreciable effect on the rolling moment due to sideslip could be obtained by devices or wing-tip shapes developed for the purpose. A preliminary study of the question is, therefore, in progress.

Pitching moment.- Pitching-moment equilibrium, compared to the equilibria of moments about the other axes, is an equilibrium between moments of very large magnitude. A study of the curves shows that in the high-angle-of-attack range, a moderate increase in aerodynamic pitching moment (diving) should cause an increase in angle of attack and rate of rotation for equilibrium. This effect has been demonstrated by the flight measurements with elevator down on the NY-1 and XN2Y-1 airplanes and observed for other airplanes. If the change in aerodynamic pitching moment is an extremely large diving moment but with no important change in the slope of the pitching-moment curve plotted against angle of attack, then the equilibrium state may be shifted to a low value of angle of attack. If it were possible to make the slope of the curve of aerodynamic pitching moment for the subject airplane steep in the angle-of-attack range of 25° to 45° (of a slope equivalent to the slope between $\alpha = 0^\circ$ and $\alpha = 25^\circ$), then the pitch equilibrium curve would be approximately parallel to the two yaw equilibrium curves and about midway between them. Such an arrangement would be ideal for eliminating the possibility of equilibrium in the spin, but the measures necessary for this

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result would probably not be considered practical. Some method of delaying the stall of the tail surfaces until very high values of angle of attack had been reached combined with unusually large stagger might be effective.

Stagger and center-of-gravity position may be considered in the light of the effect of moderate pitching moments. An examination shows that positive stagger alone, because it increases the aerodynamic diving moment (references 9 and 10), leads to equilibrium at a slightly higher angle of attack than would occur for zero stagger when pitching moment only is considered. Similarly it is seen that a rearward position of center of gravity is slightly better than a forward one. It must be remembered that positive stagger affects the rolling moment in a manner that might be much more important than the effect here cited, and that a rearward position of center of gravity usually has an unfavorable effect on the first stages of the entry into a spin. The effect of a forward position of the center of gravity has especially conspicuous favorable effects on the entry into a spin if the positive pitching moment producible by the elevator is inadequate to cause complete stalling. Instances of this effect of center-of-gravity position are to be found described in references 11 and 12. The effects of both stagger and center-of-gravity position as related to pitching moments are small and not worthy of very serious consideration for the steady spin.

<u>Yawing moments</u>.- The moments that make up the yawing-moment equilibrium are all very small compared with the moments about the other axes, and, for other reasons discussed later, constitute the most promising field for research directed toward control of the spin. The effects of a pure stable yawing moment (opposing or damping the spin yawing motion) and a pure unstable moment are given in the following table.

Added moment	Shift of yawing-moment equilibrium curves		Change in angle of attack of steady spin	
	Low-angle-of-attack curve	High-angle-of-attack curve	Low-angle-of-attack curve	High angle-of-attack curve
Stable	Toward higher α	Toward lower α	Increase	Decrease
Unstable	Toward lower α	Toward higher α	Increase	Decrease

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It will be noticed that the yawing-moment equilibrium curve situated in the low-angle-of-attack range (20° to 30°) on figure 6 gives opposite results to those of the corresponding curve at higher angles of attack. The possibility of spinning in the low-angle-of-attack range depends on somewhat special conditions as shown by the nature of the curves. Such a condition might be expected also because spins in this range are seldom observed. The curves indicate that rolling-moment equilibrium could be expected only for the smaller values of $-\gamma$ (glide-path angle) provided that equilibrium could be obtained for the moments about the other two axes. Equilibrium of these latter moments does not appear to be readily possible for the NY-1 airplane, but might be possible with other airplanes. The large stable rolling moment at large values of $-\gamma$ is, however, characteristic of practically all airplanes. During the spin tests with the NY-1 airplane, a maneuver, which the pilots called a "tight spiral", occasionally resulted from attempts to enter the spin. This maneuver was characterized as a rotating rapid descent with nose almost straight down and with very large control forces being required to hold the airplane in the maneuver. It was never continued long enough to determine whether an equilibrium state existed. This maneuver may have involved the low-angle-of-attack yawing-moment equilibrium curve.

The curves show, as stated above, that a damping yawing moment would lead to a new state of equilibrium at a higher angle of attack and rate of rotation when the angle of attack of the spin is within the range of the low-angle-of-attack curve. It is evident, however, that if the damping yawing moment becomes large enough, equilibrium would not be possible. Because the magnitudes of these moments would be comparatively large, the moment resulting from setting the rudder against the spin might, in many cases, be insufficient to eliminate equilibrium, and then the spin would continue against the controls. The likelihood of spin equilibrium against the controls is clearly indicated by curves for elevator down assuming the addition of damping yawing moment by reversed rudder setting. (See fig. 15, reference 1.) It appears, therefore, to be necessary to apply a very large damping yawing moment to eliminate spinning equilibrium in the angle-of-attack range of the low-angle-of-attack yawing-moment equilibrium curve. Of course this requirement might not always be evident because recovery might be obtained by setting up an oscillation by means of properly timed application of moments not neces-

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sarily as large as those required to eliminate equilibrium conditions.

The effect of a damping yawing moment on the equilibrium of a spin in the angle-of-attack range to which the high-angle-of-attack yawing-moment equilibrium curve applies is shown by the curves to be a decrease in angle of attack and rate of rotation, which are of greater magnitude as the damping yawing moment is increased until equilibrium is no longer possible. As damping yawing moment is added, the two equilibrium curves come closer together until they meet, and, finally, this point of intersection moves to a region on the chart above the pitching-moment equilibrium curve. Evidently no spinning equilibrium can exist with such a disposition of the curves. The indications are that a damping yawing moment sufficient to produce as extensive a change in the position of the curves as just described would be greater than the suddenly applied rudder moment ordinarily required for recovery. The mechanism suggested in reference 8 indicates that a properly timed application of moment might start a series of events resulting in recovery, while an equal moment applied in some other manner would merely set up a new condition of spinning. Theory suggests, therefore, that the conservative design practice would consist in providing sufficient damping yawing moment by means of fixed parts of the airplane so that the undesirable spin characteristics would be eliminated, or so that, if possible, spinning equilibrium would be eliminated.

Definite experimental verifications for many of the preceeding statements regarding the effect of damping yawing moments are already available for a few clear cases and for a number of other cases if certain reasonable assumptions are made. A case that may be considered definite is that of some British tests (references 3 and 13) on an airplane which was reported to be almost entirely uncontrollable in the spin and which was made easily controllable by the addition of vertical fin area. The effect of added fin area was, as demonstrated by wind-tunnel tests on a model of the airplane, to increase strongly the damping yawing moment. The same improvement in spin characteristics was demonstrated with a flying scale model of the same airplane. If now it is assumed that addition of fin area aft of the center of gravity will never produce other than damping yawing moment (except when no moment whatever is produced), all the effects of increasing fin area may be taken as further evidence of the effect of damping yawing

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moment. A number of such cases observed during the course of investigations made by the National Advisory Committee for Aeronautics or reported from reliable outside sources have invariably shown that addition of vertical fin area has produced either a decrease in angle of attack and rate of rotation or has had no effect. The failure of added fin area to develop any appreciable damping moment, and correspondingly to affect the spin, is a question of the design of the entire tail of the airplane and of the geometry of the spin.

One further topic related to the magnitude of yawing moments of the wings and of the rudder should be mentioned at this point. Recent tests on a fighter-type airplane have shown that it is possible to attain a condition of equilibrium with the rudder reversed. This state of spinning was obtained by operating the controls in such a manner that as little impulse as possible tending to start recovery would be produced. It was done usually by a slow process of reversing the rudder over a period of several turns, but it was possible to make the transition also by a very abrupt complete reversal of the rudder. The equilibrium is quite unstable and is characterized by low angle of attack and extreme inward sideslip. The existence of this state of equilibrium at a low angle of attack might be expected from the form of the yawing-moment curves of figure 5. The curves on this figure are probably representative of the curves for conventional biplanes. An airplane having comparatively ineffective fin and rudder, as was true for the fighter-type airplane, probably would not generate sufficient damping yawing moment from the fuselage, fin, and reversed rudder to exceed the maximum value of unstable wing moment in the low-angle-of-attack range similar to the value computed for the NY-1 airplane.

Summary of effect of aerodynamic moments.- The effects of the addition of aerodynamic moments about each of the airplane axes when considered with a view to deciding upon the most satisfactory method of favorably altering or completely upsetting spinning equilibrium may be very briefly outlined from the results of this study as follows: (a) Added rolling moment, when of practical magnitudes, would usually bring about a new state of spinning equilibrium to be distinguished from the original equilibrium state mainly by a change in sideslip angle; (b) added pitching moment, in order to have beneficial effect, must be very large in the negative sense; and (c) added damping yawing moment

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will usually have beneficial effect when of small magnitude and always when of large magnitude, but even these large moments are much smaller than the moments considered for the other two axes.

DISCUSSION

It is evident, of course, that certain measures could be employed to produce favorable effects by altering the moments about the rolling and pitching axes, but there are no measures which seem as promising as those of developing the best relationships between the components of the yawing moment. This problem may be divided into two phases: one the study of means of avoiding large unstable yawing moments arising from the wing cellule throughout the complete range of angle of attack, and, the other, the design of the tail of the airplane to give a large damping moment throughout the complete angle-of-attack range. The main consideration in the first case is that of the nature of the chord component of the composite cellule force curves throughout the complete range of angle of attack; the second is mainly a consideration of means of overcoming the blanketing of the vertical surfaces that usually occurs.

With regard to the cellule yawing moments it is evident that when a portion of the chord-force curve has a positive slope the wing yawing moment will be unstable in the range of angle of attack in which this portion of the curve governs the wing moments. If the chord-force-curve slope is zero the wing yawing moments will be zero, or if the slope of the chord-force curve is negative the wing yawing moment will be stable (damp the spin motion). It may readily be realized that such moments arising from the wings have the potentiality of being large because the forces on the wings are large and the moment arms may be very large. The mechanism of the disposition of forces which leads to these conclusions is easily understood when it is noted that the outer wing tip (fig. 7) is usually at an angle of attack somewhere between a few degrees below stall and a few degrees above stall, whereas the angle of attack of the inner wing tip is in the range between 50° and 70° when the angle of attack of the center section is between 40° and 50°. If the chord-force curve is similar to the one used in this study (fig. 2), the chord-force components along the span could be replaced by a single force at the outer tip directed forward along the chord of the wing for

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a considerable portion of the spinning-angle-of-attack range. Such a force system is associated with the unstable yawing moments of the wing cellule shown for the angle of attack range (of the center section) between 20° and 50° angle of attack in figure 5. If the slope of the chord-force curve is zero throughout, the yawing moment will be zero, and if the slope is negative, then the force system could be simulated by a single force at the outer wing tip directed backward, which would give a stable or damping yawing moment.

An analysis of chord forces of various sections and cellules was therefore made with such wind-tunnel data as exist for high angles of attack. The tests of reference 9 extending through a 90° angle-of-attack range were well suited for this use, but tests extending to about 30° angle of attack also give some idea of the yawing moments. The results of the study indicate that (a) thick airfoils have considerable variation of chord force with unfavorable slope, (b) thin symmetrical airfoils have practically no chord force, (c) an unstaggered biplane cellule is essentially the same as a monoplane of the same airfoil, (d) stagger without decalage and decalage without stagger do not materially alter the curve from that for the airfoils alone, and (e) gap-chord ratios in the usual range have little effect.

The tests by Fuchs and Schmidt (reference 14) show particularly interesting results for one combination of wing and auxiliary airfoil. Figure 8 reproduces their test results for that combination and includes a sketch of the arrangement. It is seen from the chord-force curve that no appreciable unstable yawing moment could be produced by this combination. Referring to the discussion already given with regard to yawing-moment equilibrium, it is seen that if (A-B) is negative (the usual case), then the spin would only be possible if the rudder (or aileron) could give a yawing moment in the direction of the spin (unstable). With controls neutral, recovery would be imperative. Thus, the effect of the auxiliary airfoil, by favorably affecting the cellule yawing moment, would eliminate the possibility of a spin with controls neutral, while the "continually rising" normal-force curve sought in the Fuchs and Schmidt investigation could alone only be expected to insure that the spin would be characterized by a moderate outward sideslip with the wing axis practically horizontal.

One further group of tests should be cited here be-

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cause it gives experimental verification of the effect of the shape of the chord-force curve. These were wind-tunnel and flight tests of the effect of adding a sharp leading edge to the wings of an airplane and to Clark Y and Göttingen 398 airfoils (reference 5). Figure 9 shows the normal and chord-force curves for a Göttingen 398 airfoil. The flight tests were made with a Clark Y - M 15 airfoil, but wind-tunnel data show that the sharp leading edge had the same effect as on the Göttingen 398 airfoil. The reduced variation and positive slope of the chord-force curve would indicate reduced unstable yawing moments. Reduced unstable yawing moments, according to the above-presented discussion of the effect of yawing moments on the spin, would cause a decrease in angle of attack and rate of rotation in the spin. This precisely was the effect on the spin found in the flight tests. (See reference 5, part II.)

In the question of tail design, two serious difficulties are encountered which complicate the problem of producing damping yawing moments in the spin. First, under conditions involving large inward sideslip, the geometry hinders the production of damping moment even to the point of making zero angle of sideslip at the tail; and secondly, blanketing of the vertical surfaces by the other parts of the tail greatly decreases, in most common designs, what moment might be produced. The problem of the unfavorable geometrical relations is not inherent in the tail design, but may be solved by so adjusting the wing aerodynamic rolling moments that outward sideslip will be required for rolling-moment equilibrium. The seriousness of the blanketing effect is clearly shown by the smoke-flow tests (reference 15), by the lack of change in the spin resulting from removal of the fin of the NY-1 airplane (reference 1), and by numerous other instances, which also could be cited. This inefficiency of the vertical surfaces caused by blanketing may, in a measure, be compensated for by making the vertical surfaces very large, but there is urgent need of a satisfactory and effective solution of the problem in order that wing cellules now in common use may be employed without the danger of poor airplane spinning properties. The effect of blanketing is of importance to recovery as well as to the steady spin, because the efficiency of the rudder in producing damping moments is as badly impaired as that of the vertical fin.

Some experiments have already been made that show the result of eliminating a large fraction of the blanketing

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(references 3, 4, and 13). The blanketing was diminished by moving the horizontal surfaces up to a new position at the top of the fin and rudder. The change greatly improved both the steady spin and the recovery. Other and possibly better methods for diminishing the effect of blanketing could undoubtedly be found.

CONCLUSIONS

1. The effects of mass distribution on the equilibrium of the spin were found to be:

   (a) Mass extended along the longitudinal axis has no detrimental effect or is slightly beneficial for variations of this factor likely to be encountered in conventional designs. If a mass arrangement corresponding to a very great retraction of the mass along the longitudinal axis is possible, beneficial results may be expected.

   (b) Extension of mass along the lateral axis is detrimental if the aerodynamic properties require that the airplane spin with the inner wing tip down. If this axis is nearly horizontal in the spin, distribution of mass along it has no effect.

   (c) Extension of mass along the normal axis may be detrimental if of small magnitude, or very beneficial if of large magnitude.

2. Aerodynamic moments affect the equilibrium of the spin as follows:

   (a) Rolling moment merely alters the equilibrium condition, the most important difference being a change in angle of sideslip.

   (b) Pitching moment, when of practical magnitudes, has very little effect on the spin equilibrium.

   (c) Damping yawing moment when of small magnitude causes decrease in angle of attack and rate of rotation for ordinary spins, and when of large magnitude prevents equilibrium.

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3. Airfoils and wing cellules should be chosen on the basis of the nature of the chord-force curve as well as on the basis of performance characteristics. Absence of positive slope, or, better, the existence of negative slope throughout the complete angle-of-attack range gives zero or stable yawing moments.

4. The damping yawing moment of the tail of the airplane during a spin should be made as large as possible.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., August 3, 1933.

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TABLE I. EFFECT OF MASS DISTRIBUTION ON SPIN EQUILIBRIUM

Axis	Mass distribution	Value of rolling moment	Value of pitching moment	Value of yawing moment	Displacement of rolling moment equilibrium curve	Displacement of pitching moment equilibrium curve	Displacement of yawing moment equilibrium curve	Change in angle of attack
Longitudinal (X)	Extended	Unaltered	Increased	Increased	None	Toward right	1st[1] curve toward right 2d curve toward left	Decreased
	Retracted	"	Decreased	Decreased	"	Toward left	1st curve toward left 2d curve toward right	Increased
Lateral (Y)	Extended	Increased	Unaltered	Decreased or may change sign and increase	1st & 3d curves right 2d curve toward left	None	1st curve toward left 2d curve toward right	Increased
	Retracted	Decreased	"	Increased	1st & 3d curves left 2d curve toward right	"	1st curve toward right 2d curve toward left	Decreased
Normal (Z)	Extended	Decreased	Decreased	Unaltered	1st & 3d curves left 2d curve toward right	Toward left	None	Increased or decreased or no spin
	Retracted	Increased	Increased	"	1st & 3d curves right 2d curve toward left	Toward right	"	Decreased

[1] Numbers of rolling or yawing moment equilibrium curves are assigned in order from left to right on figure 6.

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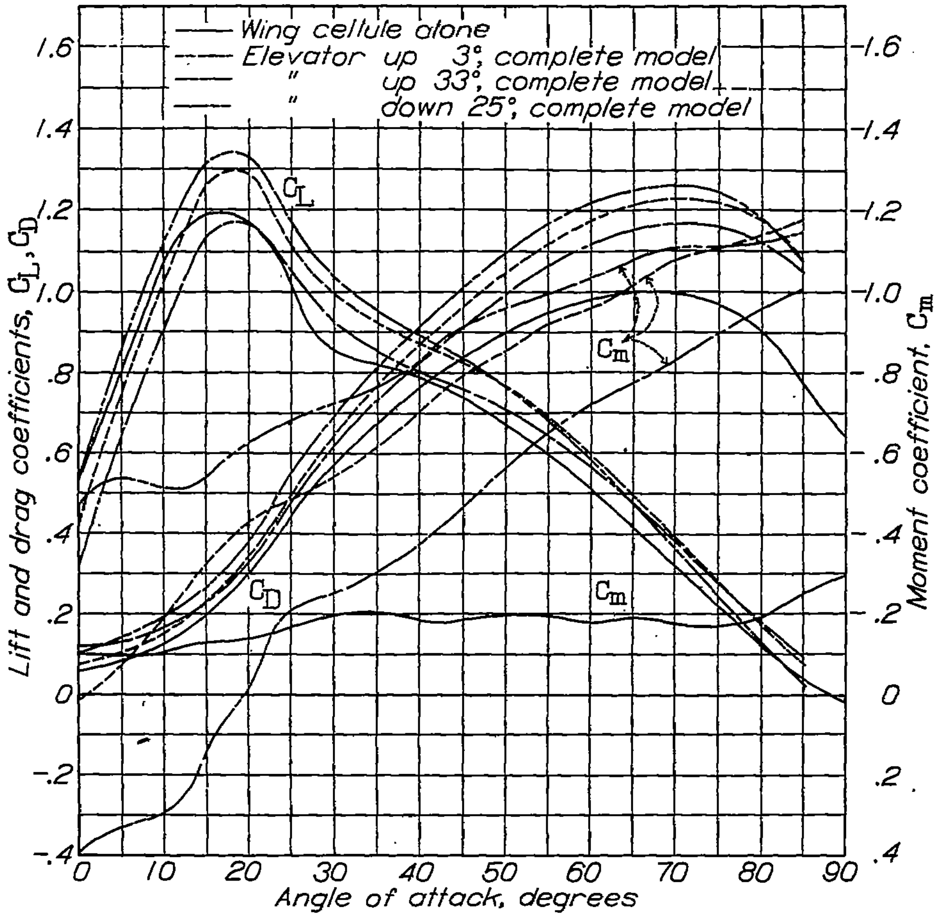

Figure 1.- Force and moment coefficients of model of NY-1 airplane and wing cellule alone.

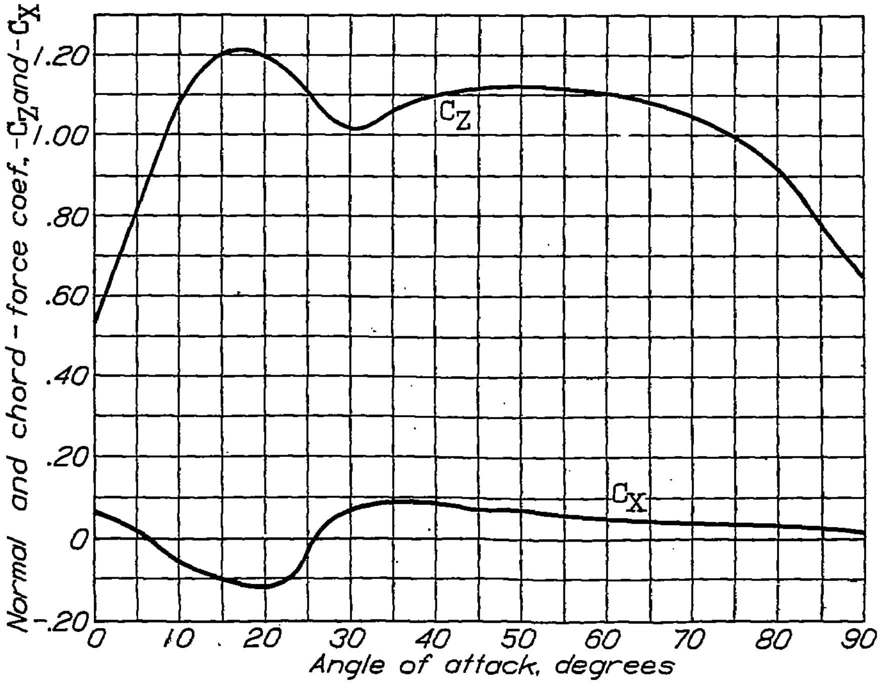

Figure 2.- Normal and chord-force coefficients of model NY-1 wing cellule.

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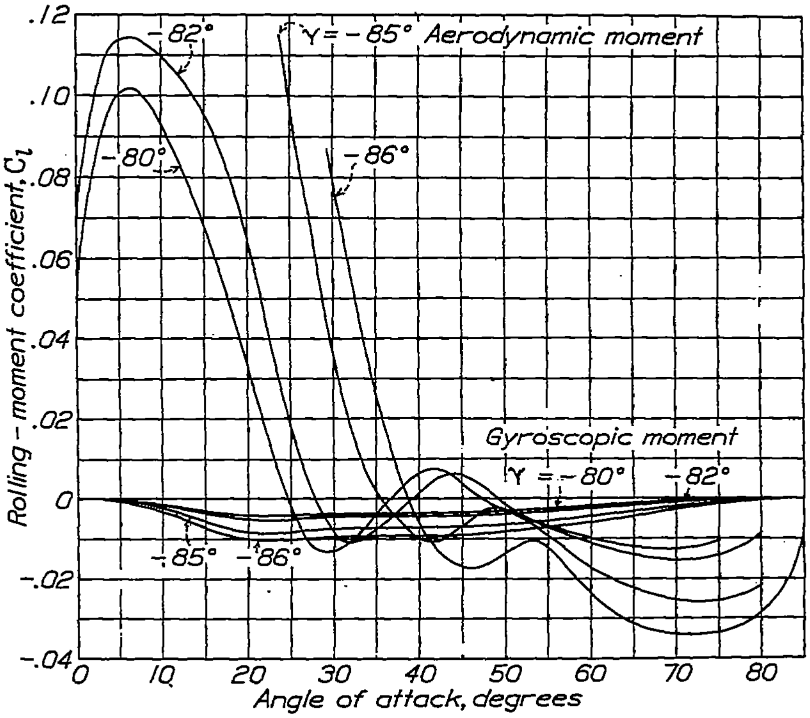

Figure 3.-Computed aerodynamic and gyroscopic rolling moment coefficients, elevator up 33°.

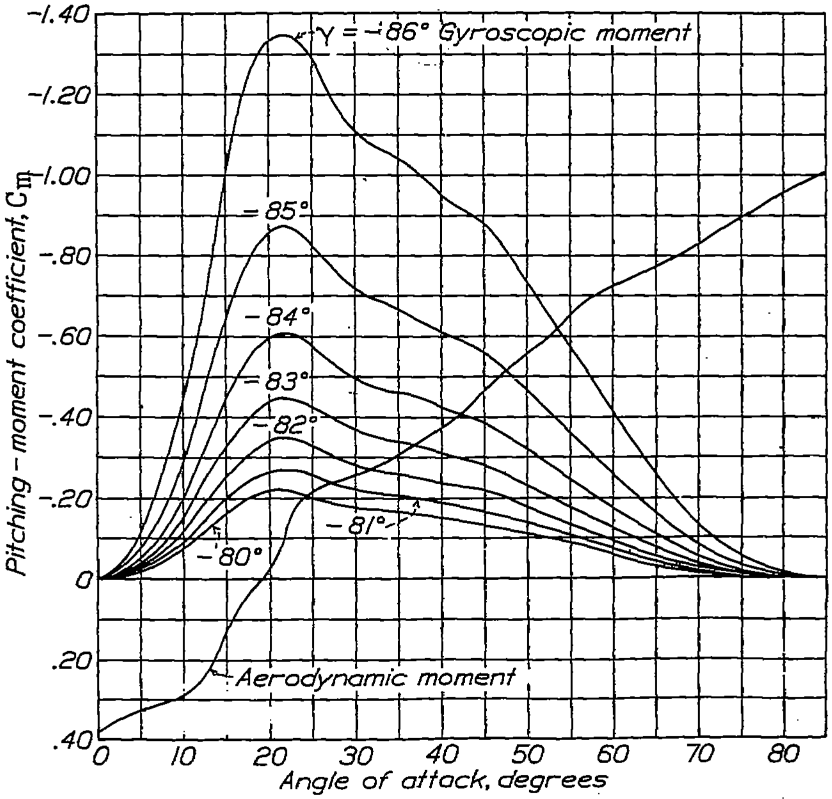

Figure 4.-Computed aerodynamic and gyroscopic pitching-moment coefficients, elevator up 33°.

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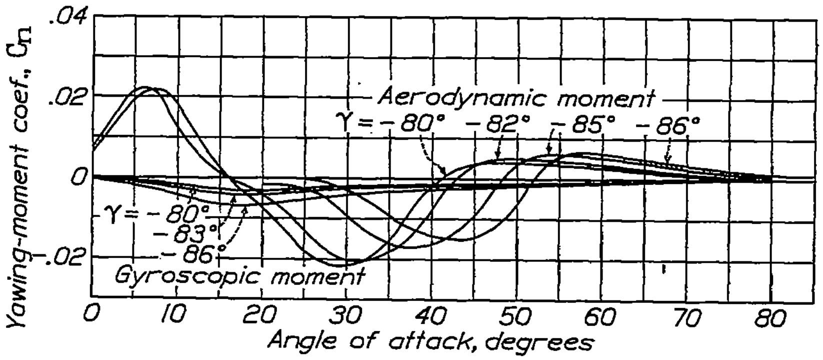

Figure 5.-Computed aerodynamic and gyroscopic yawing-moment coefficients, elevator up 33°.

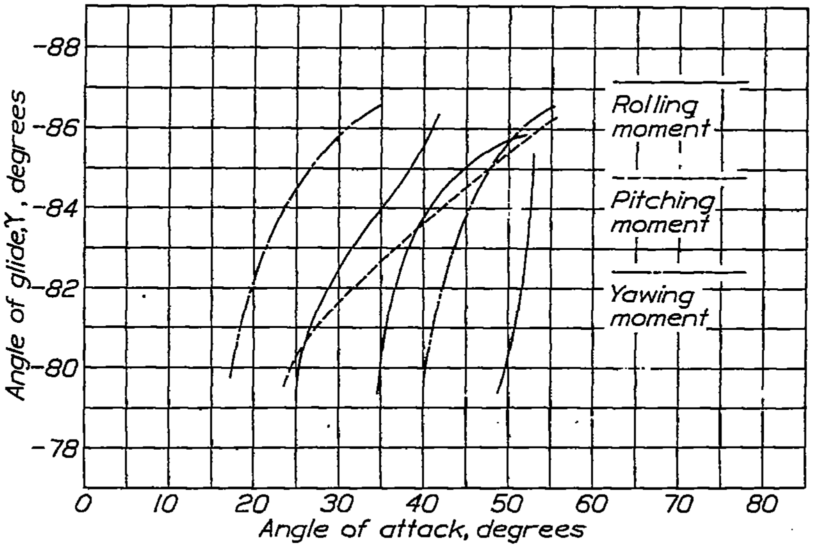

Figure 6.-Equilibrium of three moments, elevator up 33°.

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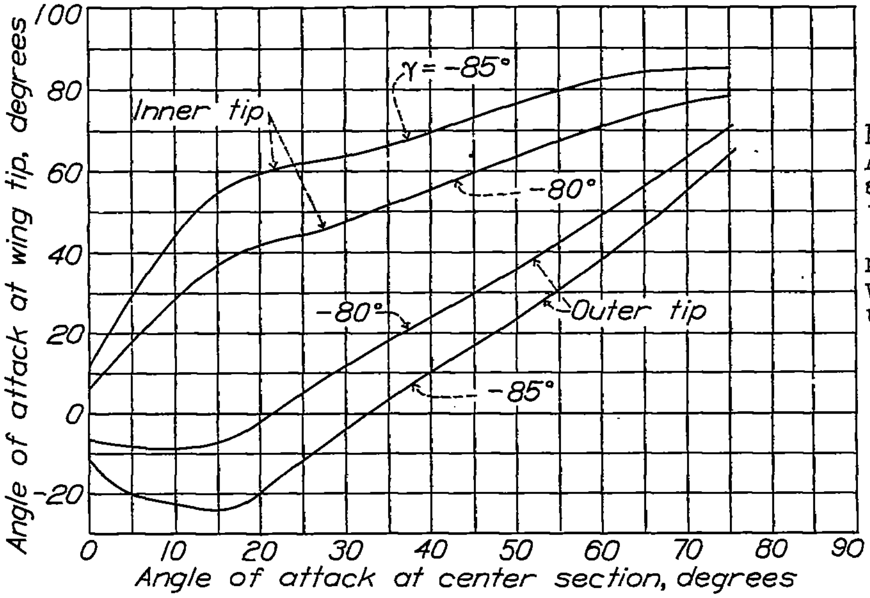

Figure 7.- Angle of attack at wing tips computed for NY-1 spinning conditions with elevator up 33°

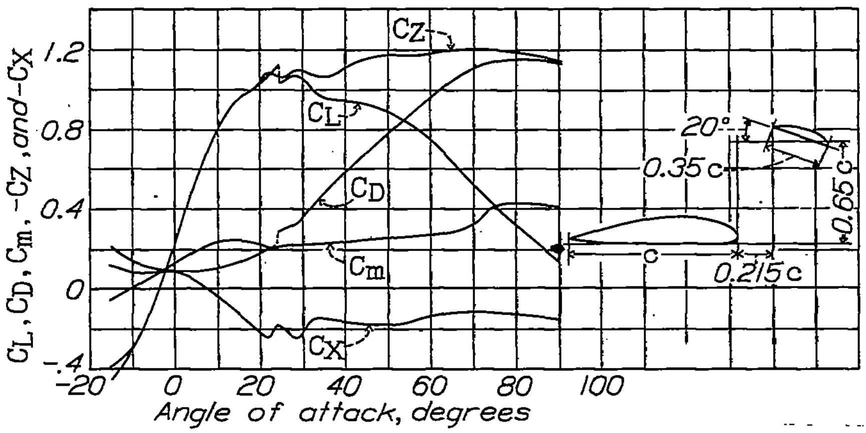

Figure 8.- Characteristics of wing and auxiliary airfoil combination. (From reference 14.)

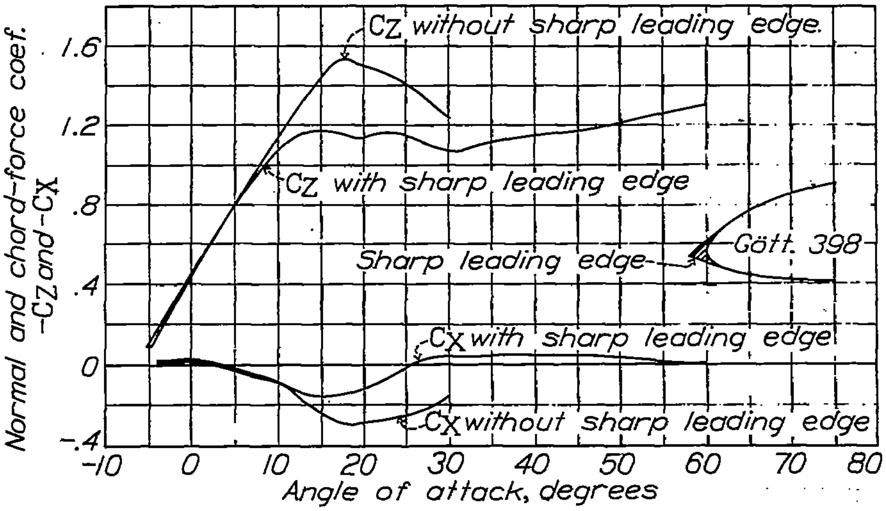

Figure 9.- Normal and chord-force coefficients for Göttingen 398 airfoil without and with sharp leading edge. (From reference 5.)