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Authority naca Release form #576 H. L. Dryden Date June 27, 1951
Dir., Aeron. Research
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7-10-51

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RESEARCH MEMORANDUM

LONGITUDINAL STABILITY AND CONTROL OF HIGH-SPEED AIRPLANES WITH PARTICULAR REFERENCE TO DIVE RECOVERY

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
September 4, 1947

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SUMMARY

An analysis of the effects of compressibility on the longitudinal stability, control, and trim of airplanes flying at high subsonic speeds and a discussion of the causes of and the means for lessening or preventing the diving tendency are presented. Wind-tunnel results for Mach numbers up to 0.90 are included for purposes of illustration and cover several investigations of longitudinal stability and control, airfoil characteristics, dive-recovery aids, and elevator characteristics. Methods are indicated for compensating for the undesirable control tendencies resulting from the characteristics of the wing at supercritical speeds by the appropriate choice of elevator contour.

INTRODUCTION

The marked increase in the speed of airplanes during the past few years has introduced many new problems concerning longitudinal stability and control. Perhaps the most significant problems have been those relative to dive recovery because the highest speeds have been reached in dives. The adverse effects of compressibility on the air flow over the lifting surfaces of the airplane were first evidenced when the diving speed sufficiently exceeded the critical speed of the airplane wing (the speed at which local sonic velocity first occurs on the wing). In many instances, airplanes developed strong diving tendencies and the pilots experienced great difficulty in effecting recovery from dives. Because of the hazardous nature of the problem, extensive high-speed wind-tunnel investigations were conducted, which resulted in the development of corrective devices and the establishment of high-speed design criteria.

A discussion of some of the problems of longitudinal stability and control arising in high-speed flight appears in reference 1. Several investigations conducted since the publication of reference 1 have added considerable new information. The present report summarizes the current knowledge of high-speed longitudinal stability and control for the range of subsonic Mach numbers thus far covered by wind-tunnel investigations. The remarks and design criteria included in this report should find use in the design of high-speed airplanes or for correcting the diving tendency of existing airplanes. It should be noted, however, that at Mach numbers above the limits of the tests summarized in this report additional drastic changes in stability and control may be encountered.

This discussion is divided into five main sections. The first section summarizes the causes and prevention of the diving tendency. The second section contains explanations of the effects of compressibility on longitudinal stability and trim. The third section contains a discussion of airfoil characteristics. The fourth section refers to three high-speed wind-tunnel investigations of various methods for improving diving characteristics of airplanes. The fifth section contains a discussion of the influence of elevator contour on longitudinal stability and control.

The wind-tunnel results included in this report are from tests conducted in the Ames 16-foot and 1- by $3\frac{1}{2}$-foot high-speed wind tunnels and have been corrected for tare, tunnel-wall, and constriction effects. For all calculations, unless otherwise noted, the center of gravity is assumed to be at the quarter-chord point of the mean aerodynamic chord.

SYMBOLS

The symbols used in this report are defined as follows:

C_L	lift coefficient $\left(\frac{\text{Lift}}{qS}\right)$
C_D	drag coefficient $\left(\frac{\text{Drag}}{qS}\right)$
C_m	pitching-moment coefficient about the quarter-chord point of the M.A.C. $\left(\frac{\text{pitching moment}}{qS\ C_w}\right)$

C_{m_o}	wing pitching-moment coefficient at zero lift
C_{h_e}	elevator hinge-moment coefficient $\left(\frac{\text{hinge moment}}{q\ b_e\ \overline{c_e^2}}\right)$
q	free-stream dynamic pressure $(\frac{1}{2}\rho V^2)$, pounds per square foot
ρ	free-stream mass density, slugs per cubic foot
V	free-stream velocity, feet per second
S	surface area, square feet
C	mean aerodynamic chord, feet
c	local chord, feet
α	angle of attack, degrees
δ_e	elevator angle, degrees
b_e	elevator span, feet
$\overline{c_e^2}$	mean square chord of elevator aft of the hinge line, square feet
δ	deflection of movable surface, degrees
n	load factor
M	free-stream Mach number
M_{cr}	critical Mach number
β	$\sqrt{1-M^2}$
a	lift-curve slope
a_{1_o}	two-dimensional lift-curve slope for incompressible flow
ϵ	downwash angle at tail plane, degrees
l_t	distance between the quarter-chord points of the mean aerodynamic chords of the wing and of the horizontal tail plane, feet

A	aspect ratio (b^2/S)
b	span, feet

Subscripts

w	wing
t	horizontal tail
f	flap
e	elevator

THE CAUSE AND PREVENTION OF THE DIVING TENDENCY

The primary cause of the high-speed diving tendency is the reduction in lift of the wing at supercritical Mach numbers. The loss in lift causes a reduction in wing lift-curve slope and is generally accompanied by an increase in the zero-lift angle, both of which lead to stability and trim changes and to an objectionable increase in the angle of attack of the horizontal tail. The longitudinal control may be aggravated further by the characteristics of the horizontal tail and elevators.

The ideal way of obtaining good high-speed dive-recovery characteristics for an airplane would be to provide a wing and horizontal tail with critical Mach numbers high enough so that the Mach number of lift divergence would exceed the maximum Mach number expected in dives. In cases where the Mach number of lift divergence of the wing must be exceeded in flight, the diving tendency may often be controlled or prevented by the proper choice of airfoil sections and airplane configuration. The main design factors affecting the critical Mach number of the airplane and the diving tendency are the spanwise variations of the thickness-to-chord ratio, camber, airfoil section, taper, and sweep of the wing and horizontal tail.

For existing airplanes where changes in the foregoing items are not feasible or are insufficient to achieve satisfactory control, changes in elevator contour or an auxiliary device, such as a dive brake, dive-recovery flap, or stabilizer flap may be employed, or the stabilizer may be made movable.

Detailed explanations of the effects of compressibility and of configuration changes on the longitudinal stability and control are presented in the following sections.

EFFECTS OF COMPRESSIBILITY ON LONGITUDINAL STABILITY AND TRIM

Longitudinal Stability

A necessary condition for an airplane to possess static longitudinal stability is that the pitching-moment coefficient decreases with increasing lift coefficient. If the pitching-moment components of only the wing and horizontal tail are considered, neglecting the contribution of the tail plane to the total airplane lift, the static longitudinal stability may be expressed as

$$-\frac{dC_m}{dC_L} = -\frac{dC_{m_w}}{dC_L} - \left(\frac{S_t}{S_w}\right)\left(\frac{C_t}{C_w}\right)\left(\frac{dC_{m_t}}{dC_L}\right) + \left(\frac{S_t}{S_w}\right)\left(\frac{l_t}{C_w}\right)\left(\frac{a_t}{a_w}\right)\left(1 - \frac{d\epsilon}{d\alpha}\right) \tag{1}$$

where the pitching moments are measured about the respective quarter-chord points.

In general, as pointed out in reference 1, the changes in the longitudinal stability of the wing $\frac{dC_{m_w}}{dC_L}$ and of the tail $\frac{dC_{m_t}}{dC_L}$ due to compressibility are relatively small compared to the changes in the stability of the complete airplane.

The predominant effect of compressibility on the static longitudinal stability of the airplane is its effect on the stabilizing contribution of the tail plane, expressed by the third term of equation (1). Below the Mach numbers of lift divergence of the wing and tail plane, the ratio of the lift-curve slope of the tail plane to that of the wing $\frac{a_t}{a_w}$ remains approximately constant. Above the Mach number of lift divergence of the wing but below that of the horizontal tail, the ratio $\frac{a_t}{a_w}$

increases because the wing lift-curve slope is materially decreased. The reduction in a_w and the accompanying reduction in $\frac{d\epsilon}{d\alpha}$ produce a serious increase in the static longitudinal stability. In cases where the critical Mach number is lower for the inboard portion of the wing than for the outboard portions, the loss of lift over the inboard portion results in a greater reduction of the downwash on the tail plane and a further increase in the longitudinal stability.

In the usual case, where the Mach number of lift divergence of the tail is higher than that of the wing, a decrease in the static longitudinal stability would be expected upon exceeding the lift divergence Mach number of the tail. Furthermore, the loss in elevator effectiveness above this Mach number would lead to control difficulties.

Longitudinal Trim

The changes in longitudinal trim due to compressibility effects may be analyzed by considering the pitching-moment coefficient of an airplane under the same assumptions as those used for establishing equation (1):

$$C_m = C_m \text{ due to wing} + C_m \text{ due to tail}$$

$$= C_{m_o} + C_L\left(\frac{dC_{m_w}}{dC_L}\right) + \alpha_t\left(\frac{dC_m}{d\alpha_t}\right)$$

but

$$\alpha_t = \alpha_{C_L=0} + C_L\left(\frac{d\alpha}{dC_L}\right) - \epsilon = \alpha_{C_L=0} + C_L\left(\frac{d\alpha}{dC_L}\right) - C_L\left(\frac{d\epsilon}{dC_L}\right)$$

therefore

$$C_m = C_{m_0} + C_L\left(\frac{dC_{m_w}}{dC_L}\right) + \left[\alpha_{C_L=0} + C_L\left(\frac{d\alpha}{dC_L}\right) - C_L\left(\frac{d\epsilon}{dC_L}\right)\right]\frac{dC_m}{d\alpha_t} \qquad (2)$$

No important trim change is to be expected in the subcritical range of Mach numbers, but above the Mach number of lift divergence of the wing, unfavorable trim changes occur which increase the angle of attack of the tail and lead to a diving tendency. The principal causes of the adverse changes in trim at Mach numbers above that for lift divergence for all airplanes are the reduction in lift-curve slope and outboard shifts in the span loading of the wing. Existing data indicate little change in the other factors entering equation (2) for airplanes with wings having symmetrical or conventional airfoil sections. However, for airplanes having wings with NACA 6-series airfoil sections, a significant increase in the angle of attack for zero lift occurs above the Mach number of lift divergence when camber and thickness-to-chord ratios greater than 12 percent are used. Accompanying the increased zero-lift angle for such airfoils, there is a favorable increase in the wing pitching moment which partially balances the adverse effect of the increased zero lift angle. Secondary trim changes may be caused by fuselages, nacelles, or power-plant installations, depending on the configuration of the airplane.

AIRFOIL CHARACTERISTICS

The preceding discussions have stressed that the wing should have a critical Mach number high enough that the Mach number of lift divergence approaches as closely as possible or exceeds the maximum Mach number expected in flight. The most effective means for accomplishing this are the use of sweep, low aspect ratio, or low thickness-to-chord ratio in conjunction with high-speed airfoil sections. High-speed wind-tunnel results suitable for comparative purposes are presented in figure 1 to show the effect of thickness on the drag coefficient, angle of attack for zero lift, lift-curve slope, and pitching-moment coefficient of NACA 6-series airfoils. Three-dimensional data are presented for 8-, 10-, and 12-percent-thick NACA 65-series airfoils, while two dimensional data are given for 6-, 8-, 10-, and 12-percent-thick NACA 64-, 65-, and 66-series airfoils.

The data in figure 1 indicate that reducing the thickness greatly decreases the drag coefficient at high Mach numbers; increases the Mach number of drag divergence; reduces the shift in the zero-lift angle; increases the Mach number of lift divergence; increases the lift-curve slope at high Mach numbers; and decreases the wing pitching-moment coefficient at high Mach numbers.

Figure 2 presents a summary of the effects of compressibility on the lift characteristics of several models of wings and airplanes. Above the Mach numbers of lift divergence, the lift coefficients at constant angles of attack for the cambered wings tend to converge at negative values. In order to sustain level flight at very high Mach numbers, the required positive lift, if obtainable, requires increasingly larger angles of attack, which in turn tends to develop an increasingly powerful diving tendency. Symmetrical airfoils tend to converge at zero lift above the Mach number of lift divergence. The use of sweep appears to be the most promising method for retaining lift somewhat farther into the transonic speed range, and has the advantage of significant reductions in drag at high Mach numbers. Longitudinal and lateral stability difficulties may arise with swept wings, however, as a result of changes in spanwise load distribution occurring at high Mach numbers.

Some favorable results have been obtained by the use of negatively deflected, trailing-edge flaps for reducing the variation of lift coefficient with Mach number for unswept wings. Two-dimensional and three-dimensional wind-tunnel results for negative flap deflections on the NACA 65-210 airfoil are shown in figure 3. Above the Mach number of lift divergence, the loss in flap effectiveness (negative) tends to balance the loss in wing lift. Because the lift does not drop off so abruptly as in the case of the basic wing, there results a somewhat smaller variation with Mach number of the angle of attack required to maintain a constant lift coefficient. The pitching-moment coefficients appear to converge toward those for the basic airfoil at the highest Mach numbers.

The use of negatively deflected flaps, however, involves some limitations. For each flap setting there is a relatively small range of lift coefficients where the variation of lift with Mach number is appreciably reduced. Also, increasingly larger deflections or larger flaps would probably be required for higher lift coefficient. Further, as shown in figure 3 at Mach numbers well above the Mach number of lift divergence, the flaps lose their effectiveness due to the separation on the lower surface of the flaps. After the flaps become ineffective, the lift may possibly diminish with further increase in Mach number in the same manner as that for the basic wing at or near the same angle of attack.

Negatively cambered airfoils have not been used in high-speed flight, but the results in figure 2 indicate that there would be a convergence at small positive lift coefficients if the wings were merely inverted. The maximum lift coefficient for such a wing, however, would be appreciably less than that for the wing in its normally upright attitude.

TYPICAL HIGH-SPEED WIND-TUNNEL INVESTIGATIONS

Three high-speed wind-tunnel investigations of airplane models exhibiting the diving tendency to varying degrees will now be presented.

Case 1

One of the first high-speed airplanes to encounter compressibility effects in flight developed a strong diving tendency which often could not be overcome by the pilot until considerable altitude had been lost. High-speed wind-tunnel tests of a model of this airplane, which are reported in references 2 and 3, showed that the inboard portion of the wing between the twin booms had a relatively low critical Mach number which was being exceeded considerably in dives at high altitude. At the supercritical speeds investigated there was little change in the angle of attack for zero lift, but there was a significant reduction in lift-curve slope accompanying the loss in lift of the center section of the wing and a shift of load to the outboard portions of the wing. The reduced lift-curve slope, the shift in span loading and the reduced downwash on the tail greatly increased the static longitudinal stability, resulting in a strong diving tendency. Figure 4 presents the variation of the pitching-moment coefficient with Mach number. The large decrease in the pitching-moment coefficient starting between 0.6 and 0.7 Mach numbers clearly illustrates the diving tendency of the standard model.

In order to develop cures for the diving tendency, several changes were made to the model as indicated in figure 4. Removal of the fuselage materially increased the Mach number at which the pitching-moment coefficient diverged. The large detrimental effect of the standard fuselage in reducing the critical Mach number of the wing may be attributed to the close proximity of the region of lowest pressure over the canopy to that over the upper surface of the wing and to the rapid convergence of the aft portion of the fuselage, which was conducive to separation. The installation of the revised fuselage remedied those two conditions and materially increased the Mach number at which the diving tendency developed. In terms of equation (2), the improvement was due to the delaying of the divergence in the lift-curve slope $\frac{dC_L}{d\alpha}$ and the downwash on the tail $\frac{d\epsilon}{dC_L}$ to a higher Mach number than that for the original configuration.

Other changes to the wing inboard of the booms included the separate additions of a wing bump and of a wing glove which extended the wing chord. The purpose of the wing bump was to restore lift to the inboard section of the wing. The wing glove was intended to increase the critical speed of the center portion of the wing by decreasing the thickness-to-chord ratio and the incidence. Neither alteration was satisfactory because of the powerful adverse effect of the standard fuselage, although each had some favorable effect.

Changes to the wing outboard of the booms included drooping the ailerons 15° and the addition of dive-recovery flaps. The drooped ailerons improved the pitching-moment characteristics and raised the Mach number at which the diving tendency developed because the large camber existing over the outboard portion of the wing relieved the lift on the center wing panel and reduced the angle of attack for zero lift by almost 3°. The result was that the tail angle of attack was considerably reduced. Such a configuration was not applicable to the airplane, however, for several reasons, among them being that the drag was doubled. The outboard dive-recovery flaps produced a favorable shift in trim by decreasing the angle of attack for zero lift and increasing the downwash on the tail, but did not alter the Mach number at which the diving tendency developed. The increase in trim lift coefficient due to the changes in pressure distribution produced by the flaps are explained in reference 4 which presents a summary of dive-recovery flap installations on several models including those discussed in this report.

Case 2

Another wind-tunnel investigation involved a model of configuration somewhat similar to the model just discussed, except that it had two fuselages instead of two booms and had no central fuselage, as shown in figure 5. The wind-tunnel tests were conducted to correct the diving tendency and buffeting which developed in flight above 0.70 Mach number.

High-speed wind-tunnel tests of the model with wool tufts glued to the surfaces revealed extensive separation from the center section of the wing and from the fuselages. Pressure data disclosed that the slope of the section normal-force curve was considerably higher for the inboard portion of the wing than for the outboard portion at high subcritical Mach numbers because the end-plate effect of the fuselages effectively increased the aspect ratio over the center section of the wing. The correspondingly reduced pressures over this portion of the wing appreciably lowered the local critical Mach number. In addition to these influences on the spanwise variation of critical Mach number, outboard of the fuselages there was 2° washout and a reduction in thickness-to-chord ratio from 15 percent at the fuselage to 12 percent at the tip.

The effect of adding dive-recovery flaps was to increase the trim lift coefficient; but, as in case 1, no change in the Mach number at which the diving tendency developed or in the stick-fixed stability was produced. Revisions to the cooling ducts under the fuselages and to the lower surface fuselage-wing fillets reduced the separation from the fuselages. Reflexing the aft portion of the wing between the fuselages effectively decreased the lift of the center section and appreciably increased the Mach number at which separation developed. The diving tendency was eliminated at low lift coefficients up to the limits of the test (0.80 Mach number), as indicated by the variation of pitching-moment coefficient with Mach number. The drag of the airplane at high speed was slightly reduced by the reduced separation. Subsequent flight tests of a revised airplane substantiated the wind-tunnel results and revealed that the buffeting and diving tendency had been eliminated.

The aerodynamic reasons for the improvement may be explained by referring to equation (2), term by term.

The modification to the wing increased the wing pitching-moment coefficient at zero lift C_{m_0} below 0.77 Mach number, but decreased it above this Mach number, relative to the values for the original configuration.

The effect of the wing modification on the wing stability $\frac{dC_{m_w}}{dC_L}$ was very small except for a slight decrease above 0.75 Mach number at low lift coefficients.

The angle of attack for zero lift $\alpha_{C_L = 0}$ was increased by the model revisions, but the variation of the zero lift angle throughout the Mach number range of the tests was appreciably reduced, thereby reducing the trim changes characteristic of the original configuration. The more constant zero-lift angle may be attributed to the reflexed portion of the inboard wing section, which produced effects similar to those of a negatively deflected 45-percent-chord flap. At the higher Mach numbers, the reduction of negative lift accompanying the loss in lift effectiveness of the reflexed trailing edge balanced the loss in positive lift of the wing.

The effect of the revisions on the wing lift-curve slope, the reciprocal of which appears in equation (2), was negligible. The rate of change of downwash at the tail with changing lift coefficient $\frac{d\epsilon}{dC_L}$ was affected favorably by the revisions to the model. Because of the reduction in effectiveness of the reflexed trailing edge at high Mach numbers, there was an inboard shift of the loading on the wing, increasing the downwash angle at the tail.

In summation of the effects, it appears that the improvement in the longitudinal stability and trim may be attributed in the most part to the reflexed trailing edge which relieved the lift on the inboard wing, increased the critical Mach number, delayed separation, and maintained a more nearly constant zero-lift angle for the model.

Case 3

The results of another wind-tunnel investigation are summarized in figure 6. The wing of the model was of rather unusual shape because of the location of the jet engines in its roots. The wing section at the center line of the jets closely resembled the NACA 66(218)-220 section with a leading-edge air inlet. The line of maximum thickness was swept back over the thickened root portion of the wing, reaching a maximum sweep angle of about 60° at the side of the fuselage.

The wind-tunnel results showed a large increase in the angle of attack for zero lift and a material reduction in the lift-curve slope, with increasing Mach number both of which usually lead to a diving tendency as outlined in the discussion of equations (1) and (2). The variation of pitching-moment coefficient with Mach number for the complete model, however, revealed only a slight diving tendency and indicated no difficulty in recovering from dives up to 0.80 Mach number. The pitching moments for the model with the tail removed increased markedly above 0.70 Mach number. This sizeable increase in wing pitching moment, denoted as C_{m_0} in equation (2), was due to a forward movement of the center of pressure caused by separation over the upper surface near the trailing edge and was large enough to balance the diving moment from the tail, so that in spite of the large increase in the angle of attack for zero lift and the reduction in wing lift-curve slope there was no strong diving tendency.

Chordwise pressure data for several stations along the span of the wing showed that the changes in the angle of attack for zero lift and the pitching moment occurred at all wing stations. The same changes have been observed in pressure data from other high-speed wind-tunnel investigations of thick, cambered, NACA 66-series airfoils. Further, a significant decrease in wing stability at the lower lift coefficients, as evident from the spacing of the pitching-moment curves in figure 6, helped to prevent a large increase in the static longitudinal stability of the complete model when the Mach number of lift divergence was exceeded. The pressure data indicate that there was an inboard shift in the spanwise loading at higher Mach numbers. Tufts and pressure data revealed that the flow over the inboard part of the wing was very good in spite of the large thickness-to-chord ratio. Closing the ducts produced no appreciable change. The spanwise variation of critical Mach number computed from the pressure data is shown in figure 6. The relatively high critical Mach number of the inboard portion of the wing may be attributed to the three-dimensional effects produced by the marked change in thickness, taper, and sweep of this part of the wing. The critical Mach numbers based on the peak negative pressures over the duct lips are indicated by the dashed lines in the figure. Actually, no appreciable shock or separation developed as a result of these local pressure peaks because of the strong favorable pressure gradient extending back to the midchord.

EFFECT OF ELEVATOR CONTOUR ON LONGITUDINAL CONTROL AND STABILITY

The effect of elevator contour on the hinge-moment coefficients and longitudinal-control characteristics of two models is summarized in figures 7 and 8. The results in figure 7 were obtained with the model shown in figure 6; whereas those in figure 8 were taken from the tests of a model of a conventional low-wing, single-fuselage, Army pursuit airplane reported in reference 5.

Because of the large number of factors involved, prediction of elevator characteristics at high speed is often more difficult than the prediction of the characteristics of a wing. Experimental data have been the best guide and some of the more general results are presented in the present report.

The effect of compressibility on the beveled trailing-edge balance is clearly shown in figure 7(a). The hinge-moment coefficients for the elevator having both the overhang-nose balance and the beveled trailing edge indicate a high degree of balance at 0.397 Mach number and a significant increase in hinge-moment coefficient with increasing angle of attack. At the higher Mach numbers the combined effectiveness of the two aerodynamic balances becomes excessive, and the elevators become unstable with respect to the variation of hinge-moment coefficient with elevator deflection. Removal of the bevels greatly reduced the aerodynamic balance and eliminated the instability at higher Mach numbers. The bevel causes a slight reduction in elevator effectiveness $\frac{dC_m}{d\delta_e}$. The marked increase in balance effectiveness at higher Mach numbers renders the bevel not generally suitable for high-speed use. The balance effectiveness of the overhang increases with Mach number but not as much as that for the bevel. The effectiveness of the sealed, internal nose balance varies with the area of the overhang, and is affected only slightly by compressibility. The horizontal tail on which the sealed, internally balanced elevator was tested had the NACA 65_2-015 section with a slightly increased span and an incidence of 0°, while the two blunt-nose elevators were tested on a horizontal tail having NACA 0012 and 0009 sections, respectively, at the root and tip, and an incidence of 1°. Both horizontal tails were set at 0° incidence. Because of the large thickness-to-chord ratio of the tail having the sealed, internally balanced elevators, the critical Mach number was below 0.75. At 0.80 Mach number, the balance effectiveness was reduced due to separation caused by a shock wave forward of the vent slots to the seal chamber.

The longitudinal-control characteristics of the model with each of the three elevators are shown in figures 7(b) through 7(f). The elevator hinge-moment coefficients for balance, shown in figure 7(b), are those corresponding to zero pitching moment and represent the conditions encountered in flight. An unstable variation of elevator hinge-moment coefficient for balance with elevator deflection generally results in an unstable variation of stick force with elevator angle and with normal acceleration. The overbalancing effect of the bevels is clearly evident. The balance curves for the model having the flat-sided elevator remain relatively steep because of the large variation of hinge-moment coefficient with angle of attack. The balance curves for the sealed, internally balanced elevator display little change in slope throughout the Mach number range. This is desirable for the maintenance of a constant stick-force gradient in accelerated flight throughout the Mach number range.

The variations of elevator effectiveness with Mach number for the three elevators are shown in figure 7(c). The reduction in effectiveness above 0.75 Mach number for the sealed, internally balanced elevator indicates the desirability of reducing the thickness-to-chord ratio below 15 percent.

The variation of neutral-point location with Mach number for the model with each of the three elevators is presented in figure 7(d). The destabilizing effect of the bevels on the elevator results in a large forward movement of the stick-free neutral point at the higher Mach numbers. The stick-free neutral points for the model with the flat-sided elevators and with the sealed, internally balanced elevators move aft at the higher Mach numbers due to the variation in hinge-moment coefficient with angle of attack. Above the critical Mach number of the tail having the sealed, internally balanced elevator, a forward movement of the stick-free neutral point accompanies the reduction in elevator effectiveness. The stick-fixed neutral point changes only slightly with changes in the elevator contour.

Figures 7(e) and 7(f) present the elevator deflections and stick forces calculated from the wind-tunnel results for the airplane at an altitude of 10,000 feet with a wing loading of 27.8 pounds per square foot. A mild diving tendency is indicated by figures 6 and 7(e) for the model in the stick-fixed condition. There is little difference in the variation of elevator angle with Mach number between the three cases, but there are large differences in the stick forces.

With the beveled elevators, the stick-force gradient becomes completely reversed at the higher Mach numbers. Above 0.75 Mach number, increasingly larger pull is required to maintain level flight. Removing the bevels eliminated the reversed stick-force gradient, but did not eliminate the unstable variation of stick force with speed above 0.75 Mach number. For the model with the revised horizontal tail incorporating the sealed, internally balanced elevators increasingly larger push is required above 0.75 Mach number. Thus, if the airplane were trimmed in level flight above 0.75 Mach number, any increase in speed would be accompanied by a climbing tendency.

The hinge-moment characteristics of three round-nose elevators are presented in figure 8(a). The bulged elevator was tested on a horizontal tail having the NACA 65-010 airfoil section, while the flat-sided and partially bulged elevators were tested on a horizontal tail having an airfoil section approximating the NACA 0010 airfoil section. Bulging the contour aft of the hinge line provides aerodynamic balance by moving the minimum pressure aft on the upper surface of the upwardly deflected elevator and forward on the lower surface. Near the trailing edge the pressure on the upper surface of the bulged elevator is less than that at a corresponding location on the lower surface for up-elevator settings less than about 5°. In addition to reducing the hinge moments, the bulge causes the hinge-moment coefficients to increase with angle of attack and appreciably reduces the elevator effectiveness, as shown in figure 8(c). Figure 8(d) indicates that the stick-fixed neutral point was affected little by change in elevator contour. The stick-free neutral point moved considerably aft for the model with the bulged elevators but changed very little from the stick-fixed location for the model with either the flat-sided or partially bulged elevators. A comparison of the stick-force characteristics, shown in figure 8(f), reveals that the model having the bulged elevators possesses a more favorable stick-force gradient and retains a stable variation of stick force with speed to a higher Mach number than when equipped with the flat-sided or partially bulged elevators. The reduced stick-force gradient is due to the balancing action of the bulge in reducing the hinge-moment coefficients. The increased push required at high speed may be attributed to the large decrease in balance hinge-moment coefficient with increasing Mach number, evident in the hinge-moment curve of figure 8(b).

The results shown in figures 7 and 8 serve to emphasize the importance of the elevator design in determining the high-speed dive-recovery characteristics of an airplane. The diving tendency exhibited by an airplane in the stick-fixed condition may be controlled to a considerable extent in the stick-free condition through the characteristics of the elevator. As was pointed out in the discussion of equations (1) and (2), the diving tendency is caused primarily by the increase in the angle of attack of the tail accompanying the increase in the zero lift angle, changes in span loading, and a reduction in the lift-curve slope of the wing. If the elevator hinge-moment coefficient or the elevator floating angle decreases with increasing Mach number and increasing tail angle of attack, an inherent pull-out tendency may be obtained. Thus, the effects of deficiencies in the characteristics of the wing of an airplane on the high-speed control may be lessened by the proper selection of elevator.

Some additional items relative to the design of the horizontal tail should be mentioned. The use of spoilers on the stabilizer to change the floating angle of the elevator is discussed in reference 6. Such a device serves as an effective dive-recovery aid, but is not suitable as a trimming device because of its abrupt action. Fabric covering is generally not suitable for control surfaces to be used in high-speed flight, because the deflection of the fabric has a considerable effect on the hinge-moment characteristics. Power-boost and spring-tab systems are useful for reducing stick forces at high speed and reduce or eliminate the need for aerodynamic balance on the elevator. A controllable stabilizer has many possibilities as a trimming device and dive-recovery aid, but it involves structural problems, especially for larger airplanes. Another possibility is the all-movable tail replacing the stabilizer-elevator combination. Besides the structural and flutter problems associated with such a tail, the hinge-moment characteristics would offer a control problem unless the elevators were power driven. There is an unstable variation of hinge-moment coefficient with tail deflection over a limited deflection range for an all-movable tail of low aspect ratio similar to the unstable variation of pitching-moment coefficient with lift coefficient characteristic of low-aspect-ratio wings operating at small angles of attack. The instability is produced by the rapid forward movement of the center of pressure as the angle is increased and is discussed in reference 7.

During dives, there may be rapid changes in the Mach number due to the reduction in altitude and variations in the speed of the airplane. Consequently, all longitudinal control and trim devices should be within immediate control of the pilot in order that excessive accelerations do not accompany changes in the airplane stability and trim and in the effectiveness of the control surfaces or trim devices. Finally, due consideration must be given to the effects of the deformation of the entire airplane structure in all stability and control investigations.

CONCLUSIONS

Results of several high-speed wind-tunnel investigations indicate the following to be conducive to favorable high-speed dive-recovery characteristics:

1. Because loss in lift at supercritical speed is the primary cause of the diving tendency, the Mach numbers of lift divergence of the wing and tail should approach as nearly as possible or exceed the maximum Mach number expected in flight. High Mach numbers of lift divergence may be obtained through the careful choice of airfoil sections and the use of reduced thickness ratios, low-aspect ratios, or sweep.

2. In establishing the spanwise variation of critical Mach number, and the span load distribution, consideration must be given to the interference and end-plate effects of nacelles, fuselages, or booms on the section lift-curve slope.

3. In order to insure a constant stick-force gradient there should be a minimum variation in the balance effectiveness of the elevators over the operating range of Mach numbers.

4. In cases of existing airplanes or those where modifications to the wing are not feasible and where the Mach number of lift divergence must be exceeded in flight, control difficulties can generally be lessened or prevented by the proper choice of elevators. In such cases, the elevator hinge-moment characteristics may be obtained such that favorable control tendencies result from the effects of the changes in the zero-lift angle and the span load distribution of the wing.

Ames Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Moffett Field, Calif.

REFERENCES

1. Hood, Manley J. and Allen, H. Julian: The Problem of Longitudinal Stability and Control at High Speeds. NACA Rep. No. 767, 1943.

2. Erickson, Albert L.: Investigation of Diving Elements of the Lockheed P-38 Airplane in the Ames 16-foot High-Speed Wind Tunnel. NACA CMR, Oct. 1942.

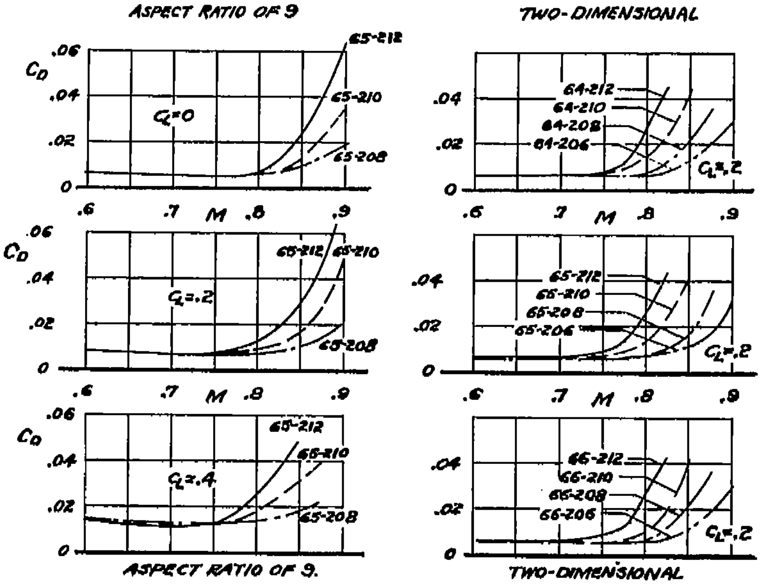
3. Erickson, Albert L.: Wind Tunnel Investigation of Devices for Improving the Diving Characteristics of P-38 Airplanes. NACA CMR No. 3F12, 1943.

4. Boddy, Lee E. and Williams, Walter C.: A Summary and Analysis of Data on Dive-Recovery Flaps. NACA RM No. A7F09.

5. Hall, Charles F.: The Effect of Modifications to the Horizontal-Tail Profile on the High-Speed Longitudinal Control of a Pursuit Airplane. NACA TN No. 1302, 1947.

6. Boddy, Lee E.: The High-Speed Characteristics of Several Flaps and Spoilers on the Upper Surface of the Horizontal Stabilizer of a 0.3-Scale Model of the Republic P-47D Airplane. NACA CMR No. A5L07, 1946.

7. Zimmerman, C.H.: Characteristics of Clark Y Airfoils of Small Aspect Ratios. NACA Rep. No. 431, 1932.



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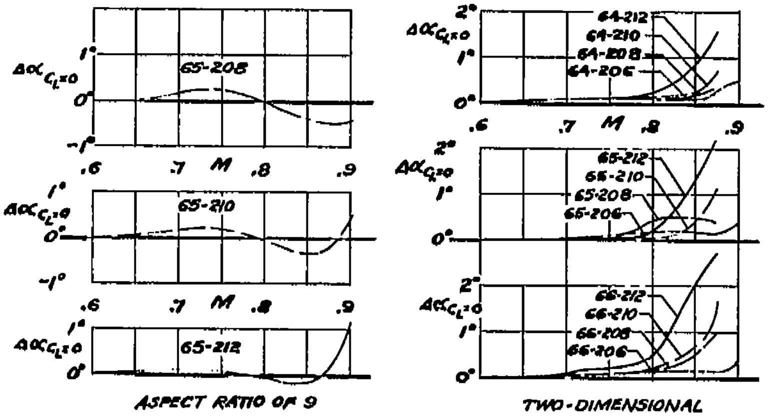
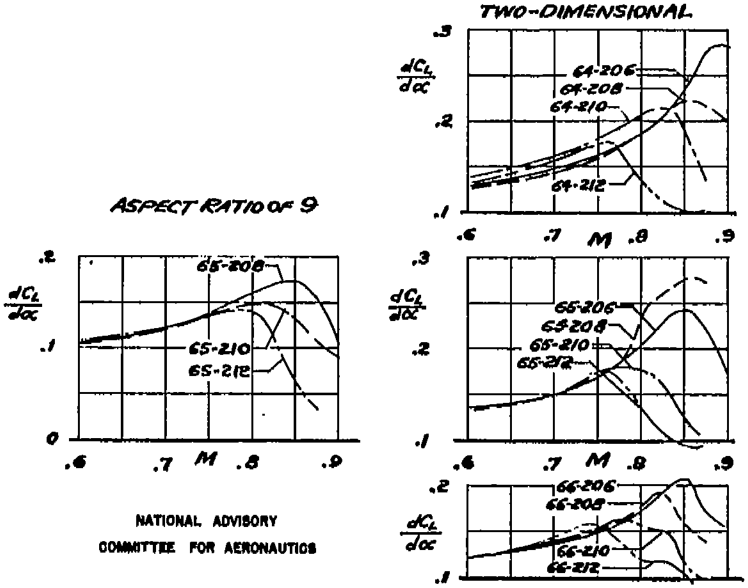
(a) DRAG COEFFICIENT



(b) CHANGES IN THE ANGLE OF ATTACK FOR ZERO LIFT

FIGURE 1.- EFFECT OF AIRFOIL THICKNESS ON THE AERODYNAMIC CHARACTERISTICS OF NACA 6-SERIES AIRFOILS.



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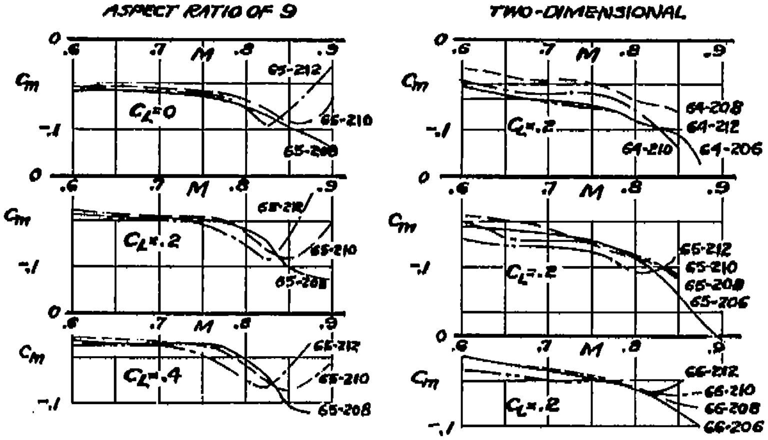
(c) LIFT-CURVE SLOPE



(d) PITCHING-MOMENT COEFFICIENT

FIGURE 1.- CONCLUDED.

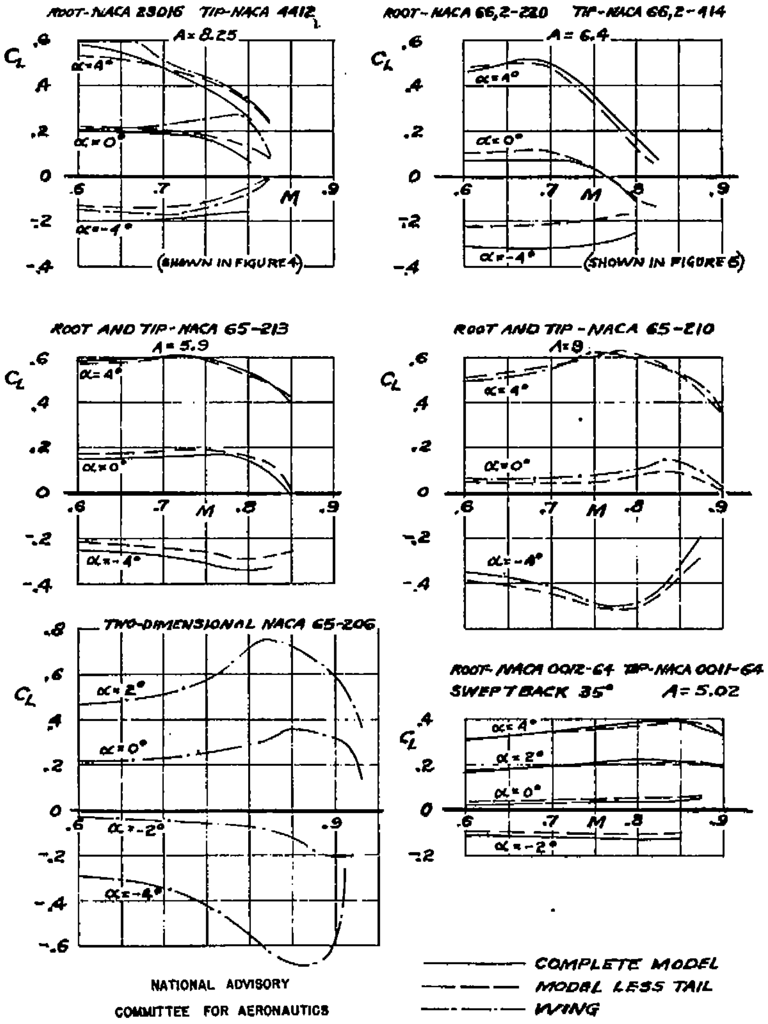
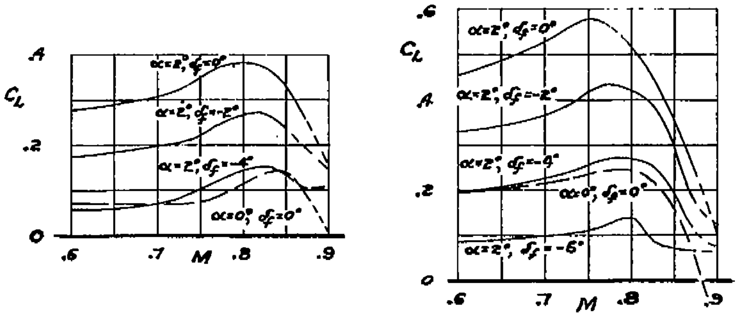
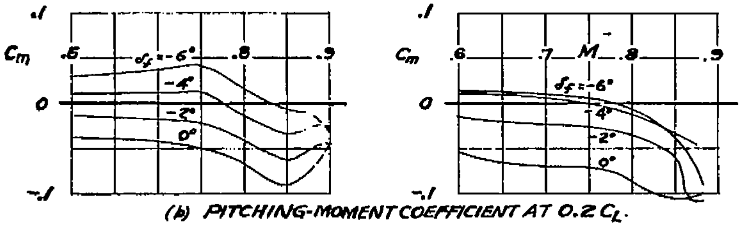


FIGURE 2.- VARIATION OF LIFT COEFFICIENT WITH MACH NUMBER AT CONSTANT ANGLES OF ATTACK FOR SEVERAL MODELS.



(a) LIFT COEFFICIENT.



(b) PITCHING-MOMENT COEFFICIENT AT 0.2 C_L.

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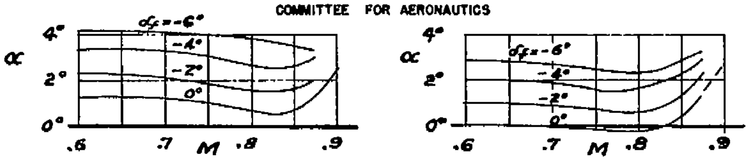
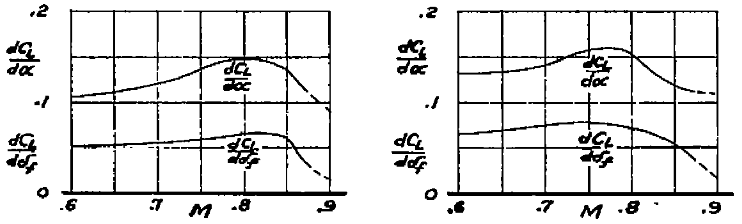


(c) ANGLE OF ATTACK FOR 0.2 C_L.



(d) LIFT-CURVE SLOPE AND FLAP EFFECTIVENESS

ASPECT RATIO OF 9 TWO-DIMENSIONAL

FIGURE 3.- EFFECT OF NEGATIVE FLAP DEFLECTION ON THE AERODYNAMIC CHARACTERISTICS OF THE NACA 65₁-210 AIRFOIL WITH A 0.2CHORD PLAIN FLAP.

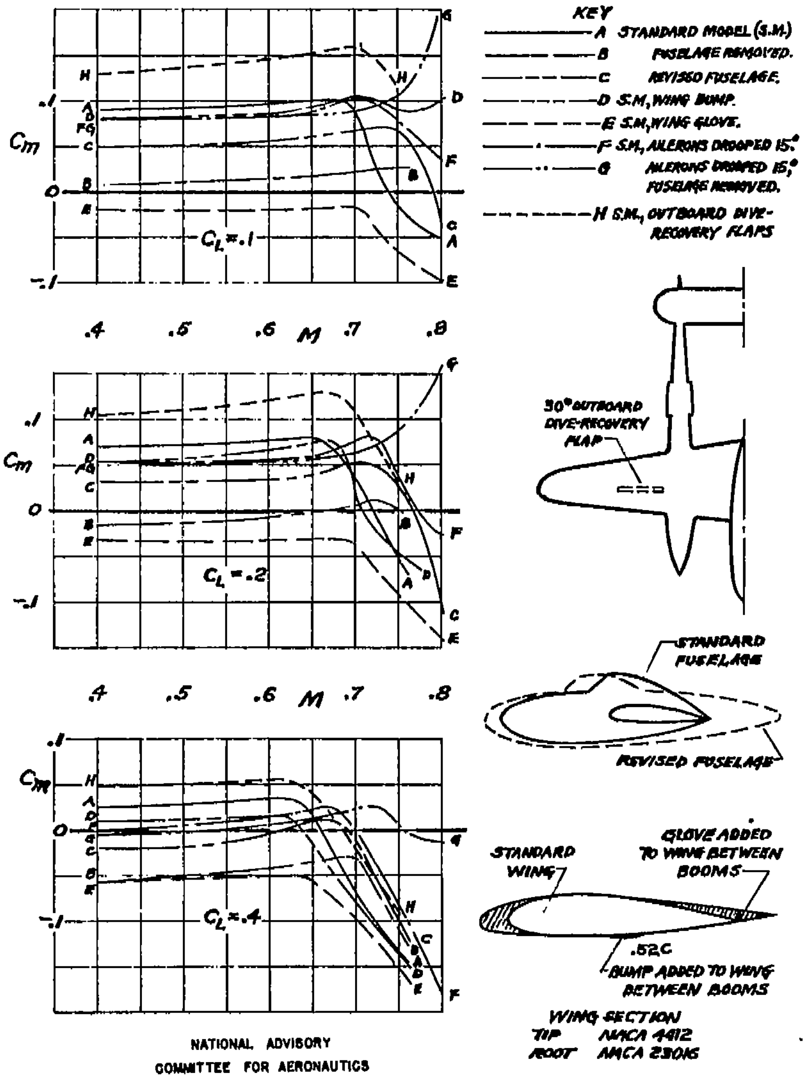


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FIGURE 4.- PITCHING-MOMENT CHARACTERISTICS FOR SEVERAL CONFIGURATIONS OF A $\frac{1}{6}$- SCALE MODEL OF A TWIN-BOOM PURSUIT AIRPLANE WITH ELEVATOR NEUTRAL.

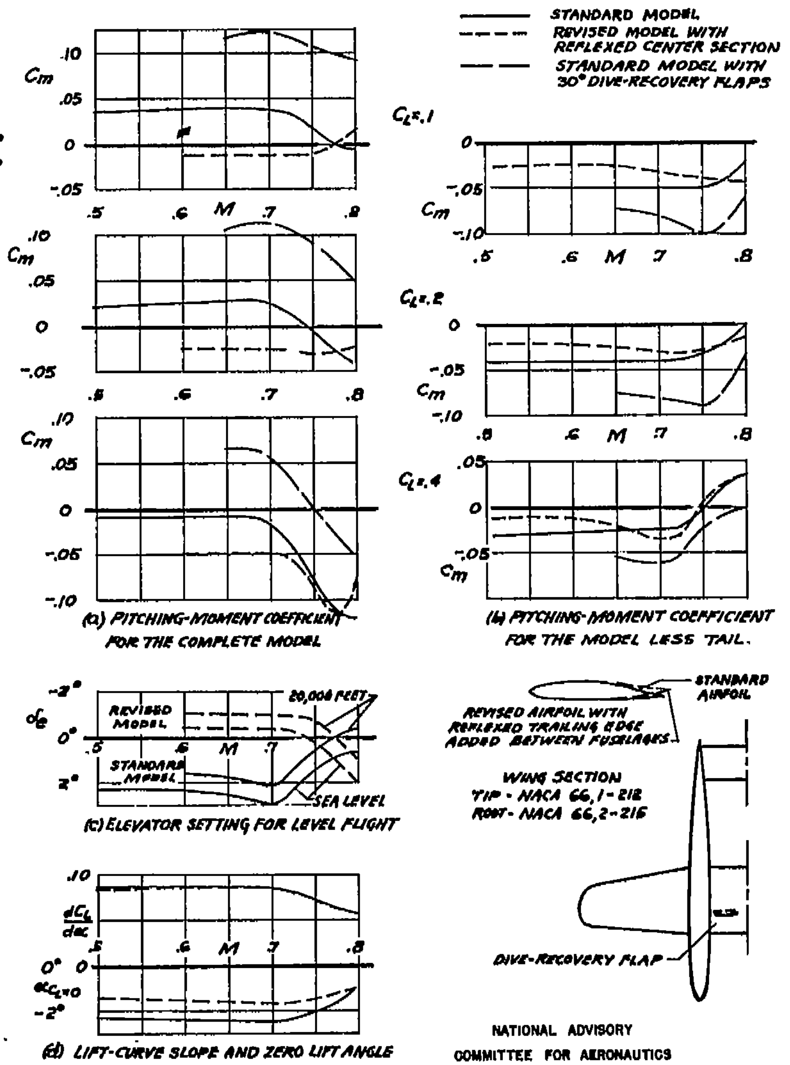

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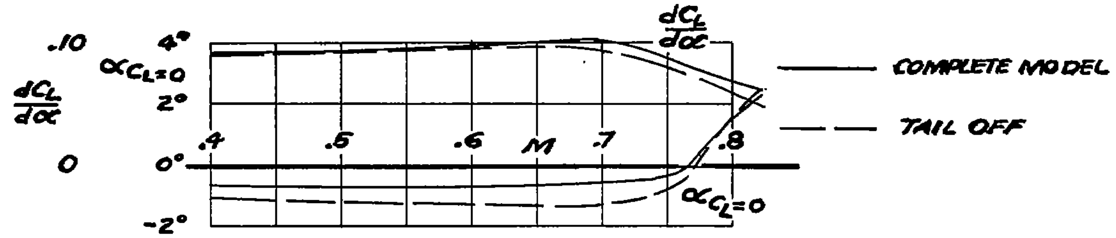
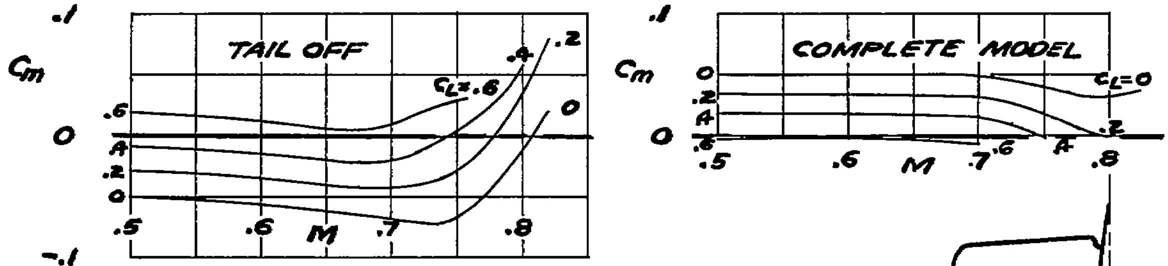
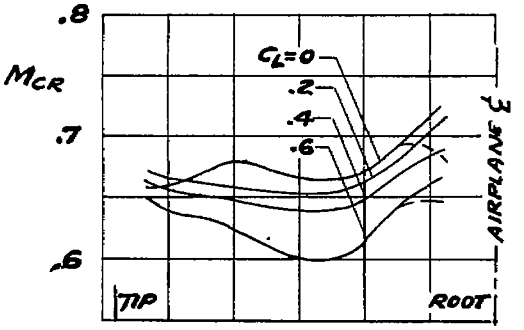
FIGURE 5.- EFFECT OF REVISED WING CENTER SECTION AND OF DIVE-RECOVERY FLAPS ON THE LONGITUDINAL STABILITY AND CONTROL CHARACTERISTICS OF A 0.22-SCALE MODEL OF A TWIN-FUSELAGE PURSUIT AIRPLANE.



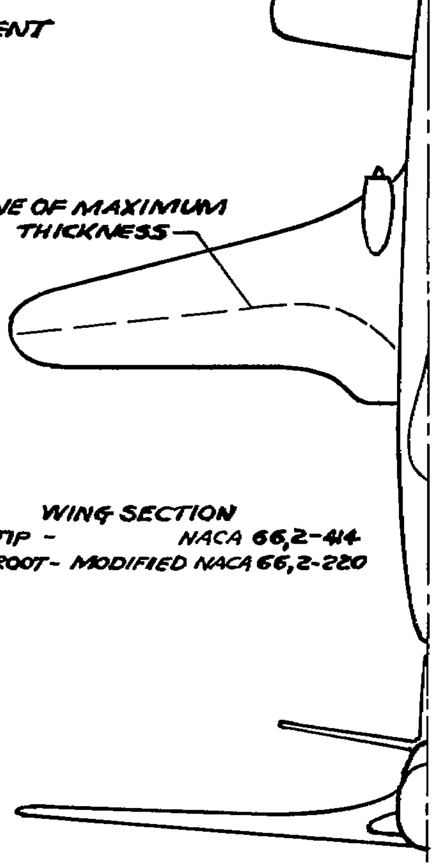
(a) LIFT-CURVE SLOPE AND ANGLE FOR ZERO LIFT



(b) PITCHING-MOMENT COEFFICIENT



(c) SPANWISE VARIATION OF CRITICAL MACH NUMBER



WING SECTION
TIP - NACA 66,2-414
ROOT - MODIFIED NACA 66,2-220

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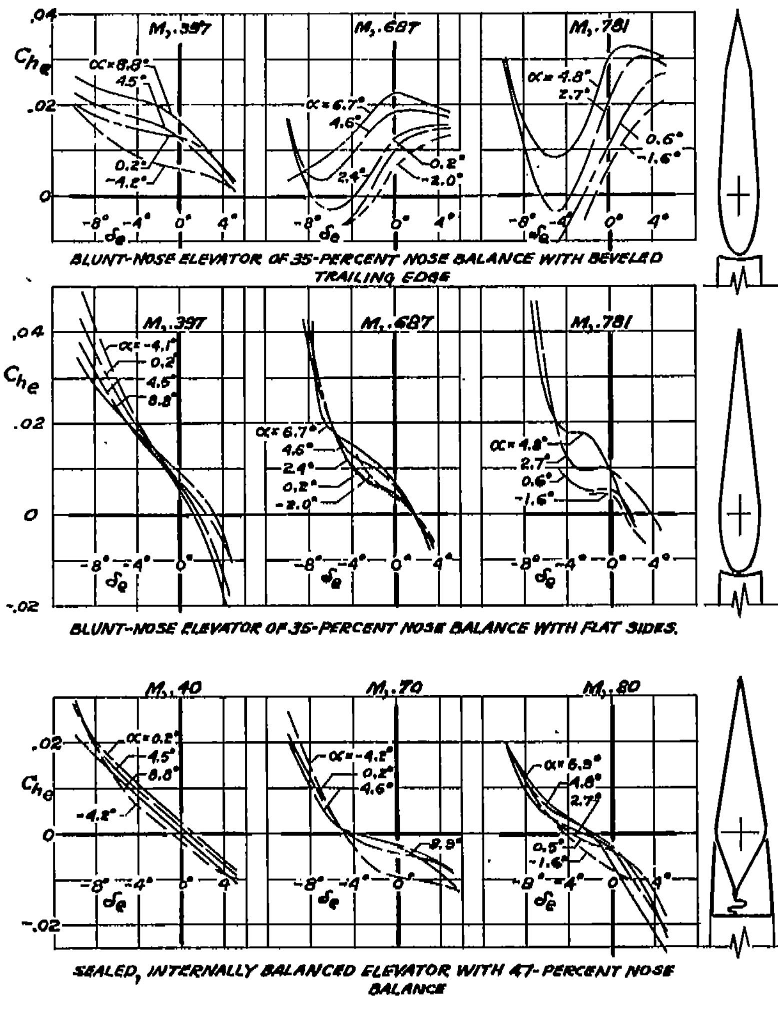
FIGURE 6.- LONGITUDINAL STABILITY CHARACTERISTICS OF A 2/7-SCALE MODEL OF A TWIN-JET NAVY FIGHTER



BLUNT-NOSE ELEVATOR OF 35-PERCENT NOSE BALANCE WITH BEVELED TRAILING EDGE

BLUNT-NOSE ELEVATOR OF 35-PERCENT NOSE BALANCE WITH FLAT SIDES.

SEALED, INTERNALLY BALANCED ELEVATOR WITH 47-PERCENT NOSE BALANCE

(a) VARIATION OF ELEVATOR HINGE-MOMENT COEFFICIENT WITH ELEVATOR DEFLECTION

FIGURE 7.- LONGITUDINAL CONTROL CHARACTERISTICS OF A MODEL OF A TWIN-JET NAVY FIGHTER WITH THREE DIFFERENT TYPES OF ELEVATORS

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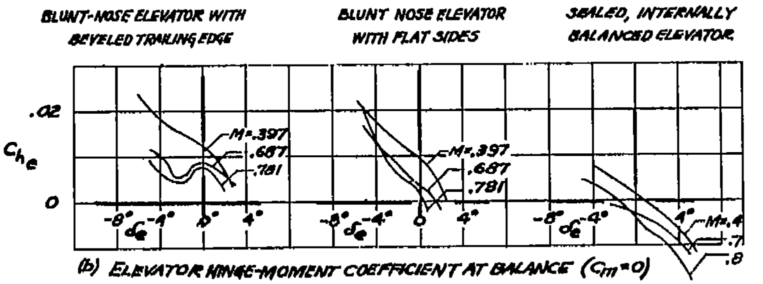
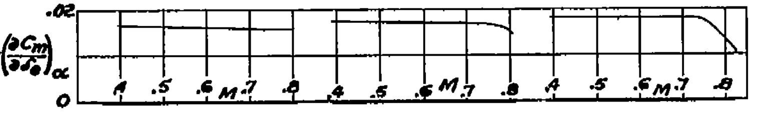
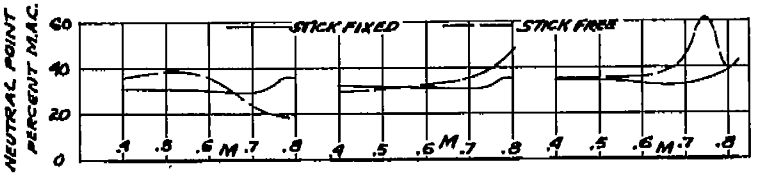


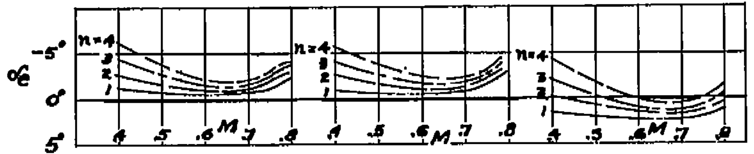
(b) ELEVATOR HINGE-MOMENT COEFFICIENT AT BALANCE ($C_m = 0$)



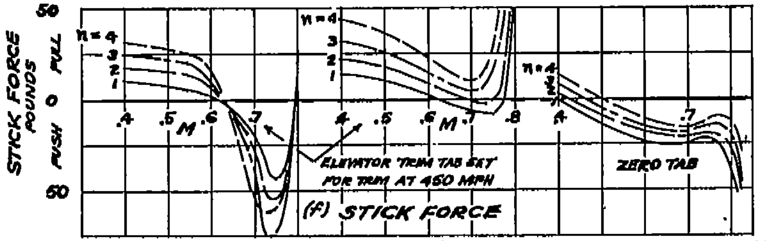
(c) ELEVATOR EFFECTIVENESS



(d) NEUTRAL POINT LOCATIONS



(e) ELEVATOR DEFLECTION



CALCULATIONS FOR 10,000 FT ALTITUDE, CG AT 18.6 % MAC, WING LOADING OF 27.8 LB. PER SQ. FT.

FIGURE 7.- CONCLUDED.

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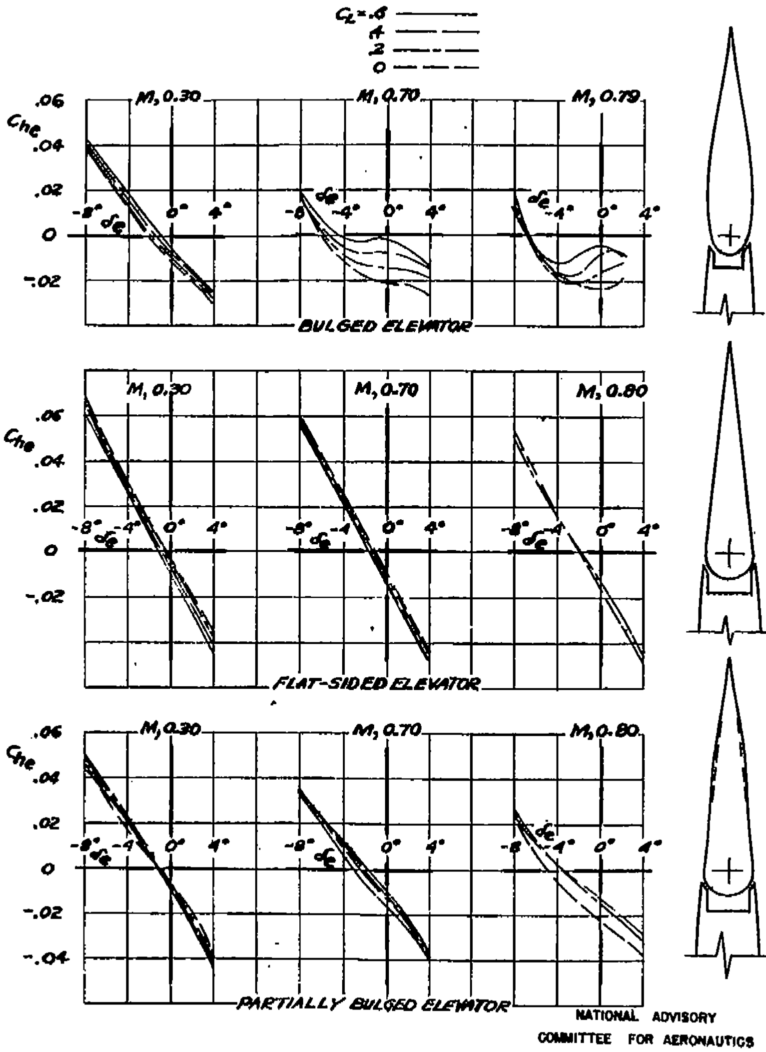
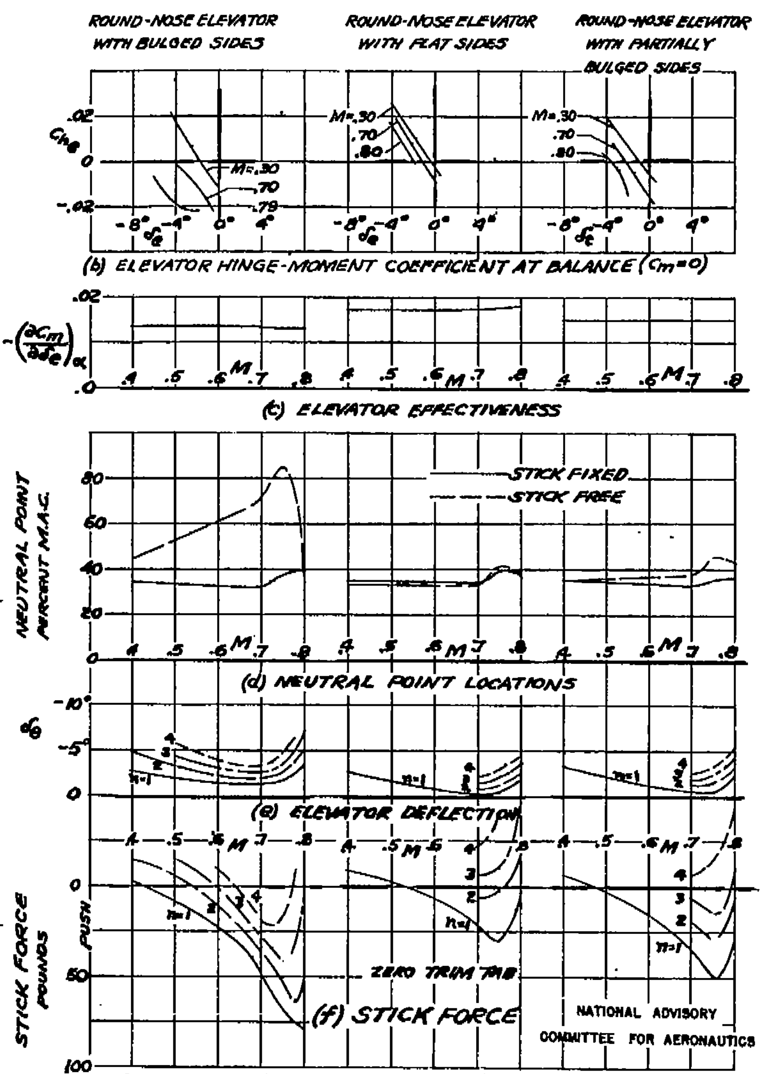


(a) VARIATION OF ELEVATOR HINGE-MOMENT COEFFICIENT WITH ELEVATOR DEFLECTION

FIGURE 8.- LONGITUDINAL CONTROL CHARACTERISTICS OF A MODEL OF AN ARMY PURSUIT AIRPLANE WITH THREE TYPES OF ROUND-NOSE ELEVATORS



CALCULATIONS FOR 20,000 FEET ALTITUDE, CG AT 24.6 % MAC, WING LOADING OF 38.9 LB PER SQ. FT.

FIGURE 8.- CONCLUDED.