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RESEARCH MEMORANDUM

SOME EFFECTS OF SPOILER HEIGHT, WING FLEXIBILITY, AND WING THICKNESS ON ROLLING EFFECTIVENESS AND DRAG OF UNSWEPT WINGS AT MACH NUMBERS BETWEEN 0.4 AND 1.7

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

Rolling effectiveness and drag tests of spoilers on unswept wings have been conducted over the Mach number range from 0.4 to 1.7 by the Langley Pilotless Aircraft Research Division utilizing rocket-propelled test vehicles in free flight. The wings which were of aspect ratio 3.7 were unswept and untapered, had thickness ratios of 3, 6, and 9 percent, and covered a range of flexibilities. Full-span solid sharp-edge spoilers were located at the 0.8-chord line.

Increasing the wing flexibility increased the rolling effectiveness at subsonic speeds and decreased it at supersonic speeds. Increasing the spoiler height increased the rolling effectiveness linearly near $M = 1.0$ but the increase was nonlinear at the other speeds tested. The rigid-wing rolling effectiveness of the 3-percent-thick wing, compared to that of the 9-percent-thick wing, was lower at subsonic speeds, higher at low supersonic speeds, and about the same at speeds above $M = 1.3$. The drag generally increased linearly with increased spoiler height except at the lower supersonic speeds.

INTRODUCTION

The Langley Pilotless Aircraft Research Division is conducting a general investigation of spoiler-type devices for roll control. Reference 1 shows that the 0.8-chord spoiler location resulted in rolling performance generally superior to that of the 0.4-chord or 0.6-chord locations. The present tests were conducted to determine the effects of spoiler height on rolling effectiveness and drag for the untapered and unswept 9-percent-thick wings having full-span, solid, sharp-edge spoilers located at the 0.8-chord station. Additional tests at one spoiler height were made with wings having 6-percent and 3-percent thickness ratios and different construction characteristics to determine the effects of wing thickness ratio and flexibility on rolling effectiveness.

A comparison is made of the rolling effectiveness loss due to wing flexibility for a spoiler and an aileron, and the drag for a spoiler and an aileron is presented for the case where both controls have the same estimated value of rolling effectiveness.

SYMBOLS

b	diameter of circle swept by wing tips, 2.185 ft
c	wing chord parallel to model center line, 0.59 ft
A	aspect ratio, b/c, 3.7
ρ	density of air, $slug/ft^3$
V	model flight-path velocity, ft/sec
q	dynamic pressure of the undisturbed stream, $\rho V^2/2$, lb/sq ft
S	exposed area of three wings, 1.563 sq ft
C_D	drag coefficient of test vehicle, Drag/qS
h	spoiler height above wing surface, ft
M	Mach number
p	rolling velocity of test vehicle, radians/sec
pb/2V	wing-tip helix angle, positive for down-moving wing with spoiler on upper surface, radians
R	Reynolds number, based on c
θ	angle of wing twist due to, and measured in plane of, applied couple m, radians
m	concentrated couple applied near wing tip in a plane parallel to test-vehicle center line and perpendicular to wing-chord plane, ft-lb

$(\theta/m)_r$ — (θ/m) measured at the mid-exposed-span station, radians/ft-lb

ϕ — fraction of rigid-wing rolling effectiveness retained by the flexible wing

$(1 - \phi)/(\theta/m)_r$ — fraction of rigid-wing rolling effectiveness lost by the flexible wing per unit torsional flexibility parameter, 1/(radians/ft lb)

t — wing maximum thickness, ft

MODELS AND TEST TECHNIQUE

Geometric details of the test vehicles and construction details of the test wings used in the present investigation are presented in figure 1. The three wings on any one test vehicle were spaced 120° apart around the test-vehicle fuselage and were nominally identical. The full-span, solid, sharp-edge spoilers were attached to the wings along the 0.8-chord line with no gaps between the spoiler and wing surface.

The torsional flexibility characteristics of the test wings were obtained by applying a twisting couple near the wing tip and measuring the resulting twist along the span as indicated in figure 2.

The flight tests were made at the Langley Pilotless Aircraft Research Station at Wallops Island, Va. The test vehicles were propelled to a maximum Mach number of approximately 1.7 by a two-stage rocket-propulsion system, and test data were taken during the free-flight coasting period following second-stage propulsion-unit burnout. The test data consisted of time histories of the model rolling velocity and flight-path velocity as obtained by special (spinsonde) radio equipment and CW Doppler radar, respectively. These data, in conjunction with atmospheric data obtained from radiosondes and SCR 584 radar, permit the evaluation of the rolling effectiveness parameter $pb/2V$ and drag coefficient C_D as a function of Mach number. The Reynolds number and free-stream dynamic pressure of the tests are shown as functions of the test Mach number in figure 3.

ACCURACY AND CORRECTIONS

From mathematical analysis and previous experience, the accuracy of the results is estimated to be within the following limits:

	Subsonic	Supersonic
$pb/2V$	± 0.003	± 0.002
C_D	$\pm .003$	$\pm .002$
M	$\pm .01$	$\pm .01$

All the $pb/2V$ data presented herein have been corrected by the method of reference 2 for the effects of wing incidence resulting from construction tolerances. The $pb/2V$ data have not been corrected for the effect of the test-vehicle moment of inertia about the roll axis, since analysis (ref. 3) shows that this correction is negligible except where abrupt changes in $pb/2V$ occur as in the transonic region where it may be of the order of 20 percent or less.

RESULTS AND DISCUSSION

The basic data obtained from the present investigation are presented in figure 4 as the variation of drag coefficient and rolling effectiveness with Mach number and represent the data that would be obtained from a test vehicle with two semispan wings having a spoiler on each wing and neglecting interference effects. Included is the drag coefficient for the body alone (ref. 4) and, from unpublished data and reference 2, the drag coefficient and rolling effectiveness, respectively, for a 9-percent-thick wing having no controls but an average wing incidence of 0.04° for each of the three wings. The data for the no-control wing are included to show the small irregularity in the rolling effectiveness in the transonic region for the wing without a spoiler and to give some drag-coefficient values for the $\frac{h}{c} = 0$ case. No drag data were obtained for model 1.

Rolling Effectiveness

Effect of wing flexibility.- The rolling effectiveness data for the 3-percent-thickness-ratio models (fig. 4a) were plotted against $(\theta/m)_r$ for a given Mach number and the slope of the straight line drawn through the data points is $(1 - \phi)(pb/2V)_{rigid}/(\theta/m)_r$; extrapolating the straight line to $(\theta/m)_r = 0$ gives the rigid-wing rolling effectiveness value at that Mach number (see ref. 5). The same procedure was used with the 9-percent-thickness ratio models 7 and 8 of figure 4(c), with the assumption that the differences in rolling effectiveness for the 65- and 65A profiles were small in the rigid case. The fraction of rigid-wing rolling effectiveness lost by the spoiler-equipped flexible wing per unit torsion parameter $(1 - \phi)/(\theta/m)_r$ measured for the thickness ratios of 3 percent and 9 percent are shown plotted against Mach number in figure 5. Negative values indicate an effectiveness gain for the flexible wing; whereas positive values indicate an effectiveness loss. The gain in effectiveness for the spoiler-equipped flexible wing at subsonic speeds may be explained by pressure measurements (ref. 6) showing a negative pressure area behind the spoiler of sufficient intensity to give a nose-down twisting moment about the 0.4-chord line (spoiler on the upper surface at 0.7 chord).

Loss-parameter data from reference 7 for an unswept and untapered wing having thickness ratios of 3 percent and 9 percent and a full-span aileron hinged at the 0.8-chord location are included for comparison. It can be seen that the flexible aileron-equipped wing loses effectiveness at all speeds tested; whereas the flexible spoiler-equipped wing gains effectiveness at subsonic speeds and loses effectiveness at supersonic speeds. The percent-effectiveness change for the spoiler is less than one-half that for the aileron at all speeds tested. Since the change is proportional to the wing twisting moment (ref. 5), the wing twisting moment due to the spoiler is less than one-half that due to the aileron for a given $pb/2V$ at any given Mach number.

The curve for the $\frac{t}{c} = 0.06$ spoiler-equipped wing in figure 5 was obtained by arbitrarily averaging the values for the 3- and 9-percent-thick wings and was used to correct the rolling effectiveness of model 4 to rigid-wing $pb/2V$ since only one value of wing flexibility was tested for the 6-percent-thick wings.

Effect of airfoil thickness ratio.- Shown in figure 6 is the variation of rigid-wing rolling effectiveness with Mach number for three airfoil-thickness ratios, with $\frac{h}{c} = 0.02$ for all wings. The values for the 3- and 9-percent-thick wings were calculated from data obtained by testing two wing flexibilities of the same configuration, and the values for the 6-percent-thick wing were estimated from the information contained in figures 4(b) and 5. It should be noted that the measured values (fig. 4(b)) of the rolling effectiveness for the 6-percent-thick wing are essentially those for a rigid wing, since the test wing is estimated to be only slightly more flexible than a solid aluminum-alloy wing. The maximum flexibility correction applied to the measured data was 11 percent and, consequently, any errors resulting from the method of interpolating the data in figure 5 would have small effect on the estimated rigid-wing values for the 6-percent-thick wing in figure 6. The 3-percent-thick wing had the lowest rolling effectiveness at subsonic speeds whereas the 9-percent-thick wing had the lowest rolling effectiveness at supersonic speeds below $M = 1.3$, both thickness ratios having about the same rolling effectiveness above $M = 1.3$. The rolling effectiveness of the 6-percent-thick wing was approximately the same as that of the 9-percent-thick wing at subsonic speeds and that of the 3-percent-thick wing at supersonic speeds, the difference at supersonic speeds being only slightly greater than the quoted accuracy of the tests.

Effect of spoiler height.- The variation of flexible-wing rolling effectiveness with spoiler height is presented in figure 7 for several Mach numbers; the data from figure 4(c) for all models having the same wing flexibility were utilized. The variation of rolling effectiveness with spoiler height is nonlinear except near $M = 1.0$. The tendency toward reversed rolling effectiveness at $M = 0.6$ for the $\frac{h}{c} = 0.005$ spoiler may be attributed to an effective cambering of the airfoil resulting from a thickening of the boundary layer by the small spoiler projection (ref. 8).

Drag

Drag comparison for spoiler and aileron.- In figure 8, for arbitrary levels of $pb/2V$ at subsonic and supersonic speeds, a drag comparison for 9-percent-thick wings is made between full-span aileron-type controls hinged at the 0.8-chord location and full-span spoiler-type controls located at the 0.8-chord position. The drag coefficients at each $pb/2V$ level were obtained from the data of figure 4(c) (models 5, 6, 7, 9, 10) for the spoiler-type control and from unpublished data for the aileron-type control. For either type of control, $pb/2V$ was plotted against C_D at a given Mach number and an extrapolation or interpolation was made along a straight line between data points to obtain the C_D for the desired $pb/2V$. The drag advantage of the aileron is less pronounced at supersonic speed than at subsonic speeds. Since the addition of the spoiler resulted in approximately equal drag coefficient increments at both subsonic and supersonic speeds, the favorable yawing-moment coefficient due to the spoiler drag should be approximately equal at subsonic and supersonic speeds for the case of the spoiler on one wing, if negligible spanwise movement of the drag center of pressure is assumed.

Effect of airfoil thickness ratio.- The test-vehicle total-drag coefficient is plotted against Mach number for three airfoil thickness ratios in figure 9. The data were taken from the $\frac{h}{c} = 0.02$ tests of figure 4 and are average values where data are available for more than one test of a given configuration. The results for sweptback tapered wings in reference 9 lead to the conclusion that the effects of wing flexibility are probably negligible. It can be seen that the drag generally increased with increased airfoil thickness ratio, and the variation of drag with airfoil thickness ratio is fairly linear above $M = 1.2$.

Effect of spoiler height.- In figure 10 the drag data of figure 4(c) have been utilized to plot the test-vehicle drag against spoiler height at several Mach numbers for the 9-percent-thick wings. The variation of drag with spoiler height was essentially linear at subsonic speeds and the higher supersonic speeds tested but increased nonlinearly at the lower supersonic speeds.

CONCLUSIONS

Rolling effectiveness and drag tests have been conducted over the Mach number range from 0.4 to 1.7 utilizing rocket-propelled test vehicles in free flight. The wings with an aspect ratio 3.7 were unswept and untapered, varied in thickness ratio from 3 percent to 9 percent, and had full-span solid, sharp-edge spoilers located at the 0.8-chord line. From these tests the following conclusions have been drawn:

1. The variation of rolling effectiveness with spoiler height for the 9-percent-thick wings was nonlinear except near $M = 1.0$. Very low spoiler heights indicated a tendency toward roll reversal at some subsonic speeds.

2. Increasing the wing flexibility increased the rolling effectiveness at subsonic speeds and decreased it at supersonic speeds. Compared with an aileron, the spoiler twisting moments are considerably less at supersonic speeds and opposite in sign at subsonic speeds for the wing-spoiler arrangement of these tests.

3. The rigid-wing rolling effectiveness of the 3-percent-thick wing, compared to that of the 9-percent-thick wing, is lower at subsonic speeds, higher at low supersonic speeds, and is about the same at speeds above $M = 1.3$.

4. The drag generally increased with an increase in airfoil thickness ratio or spoiler height. For a 9-percent-thick wing, the spoiler had more drag than an aileron for the same rolling effectiveness at subsonic speeds but the difference was less pronounced at supersonic speeds.

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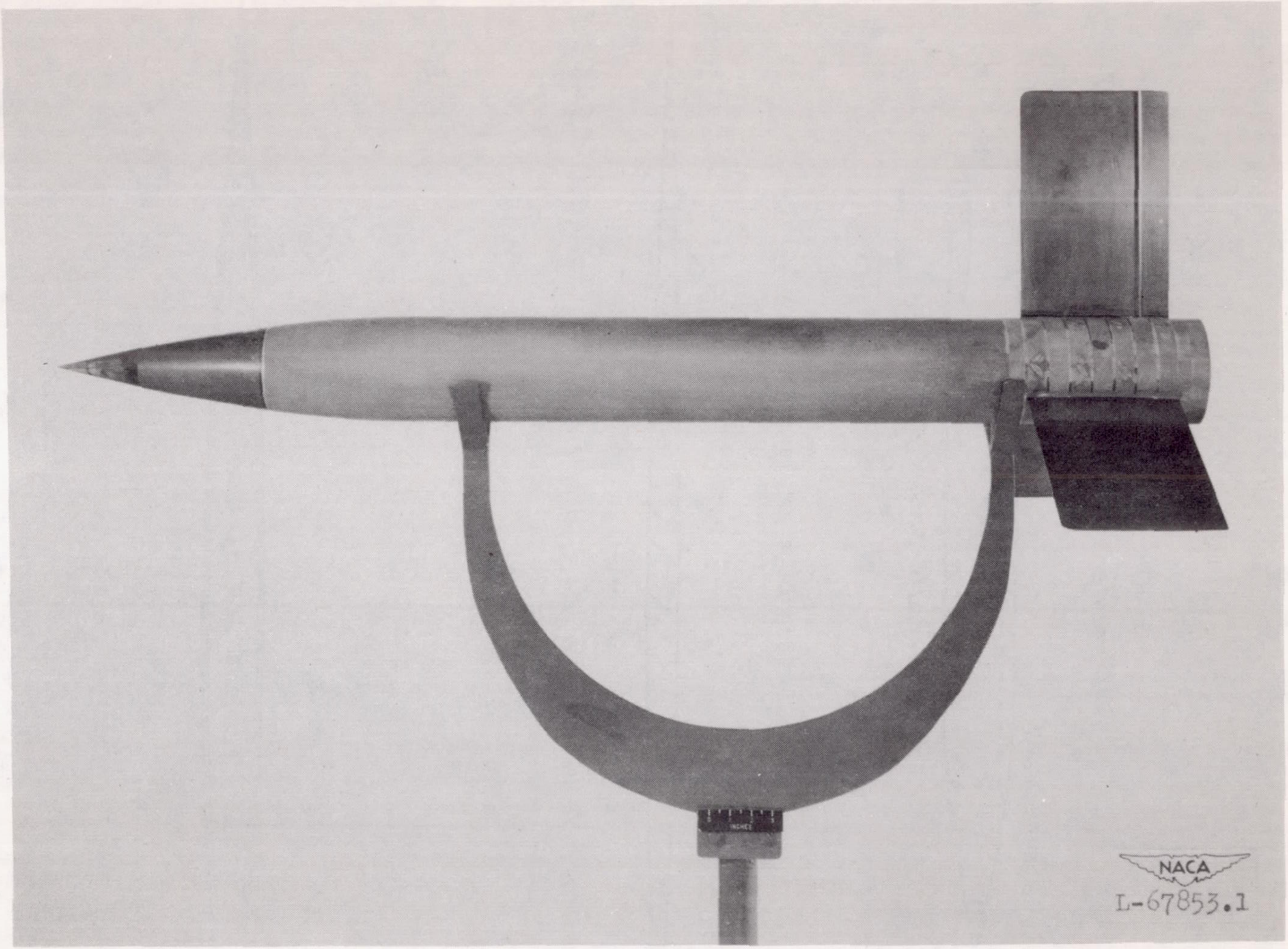
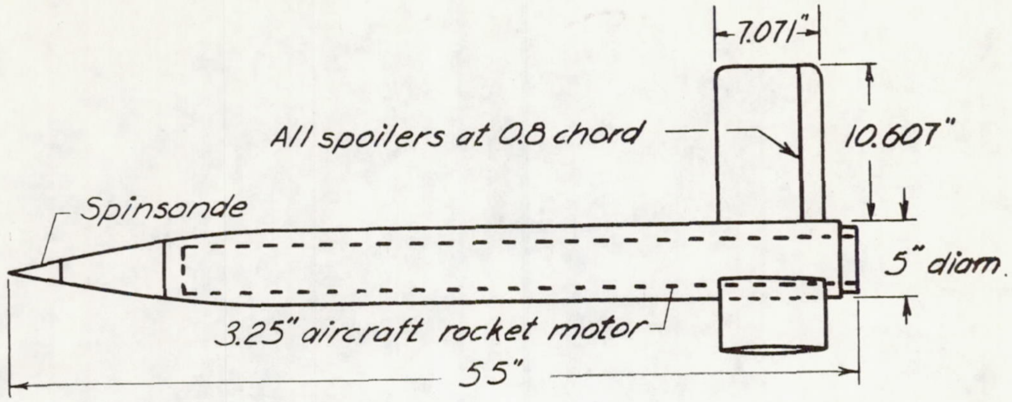
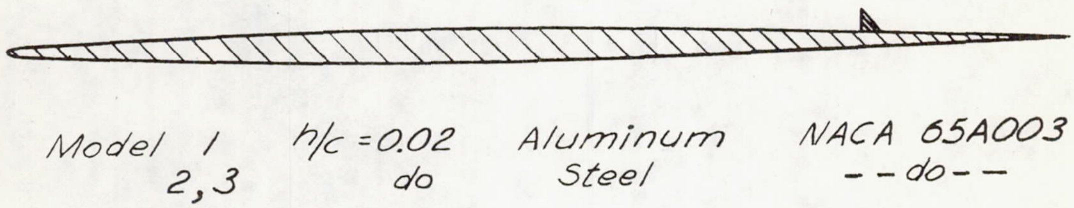


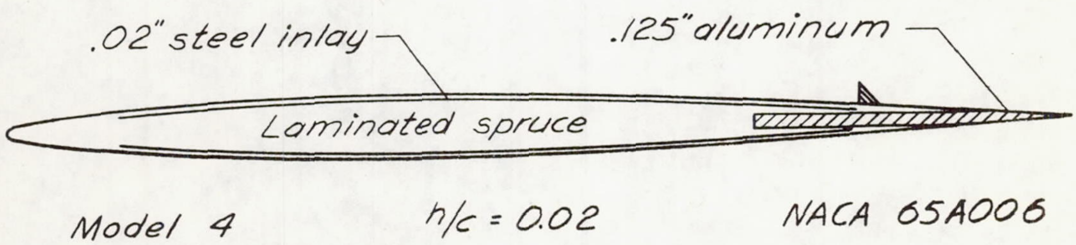
(a) Photograph of a typical test vehicle.

Figure 1.- Test vehicles.



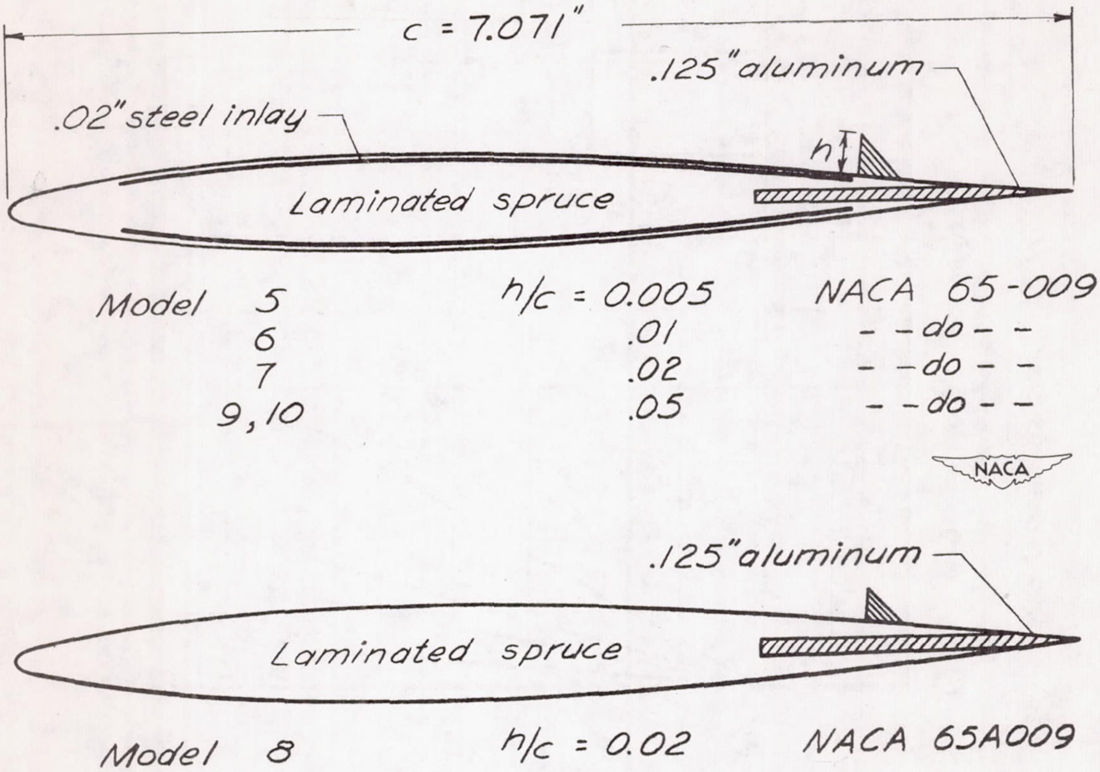
(b) Sketch of a typical test vehicle.





(c) Wing construction.

Figure 1.- Continued.



(c) Concluded.

Figure 1.- Concluded.

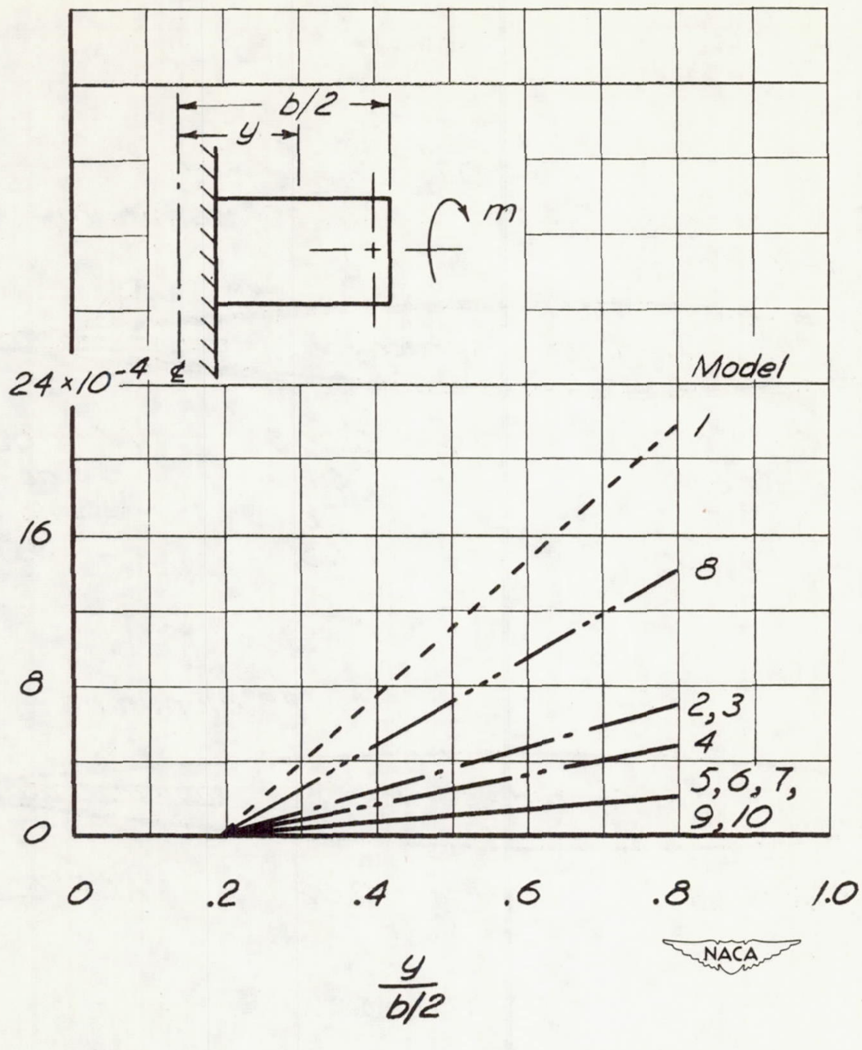
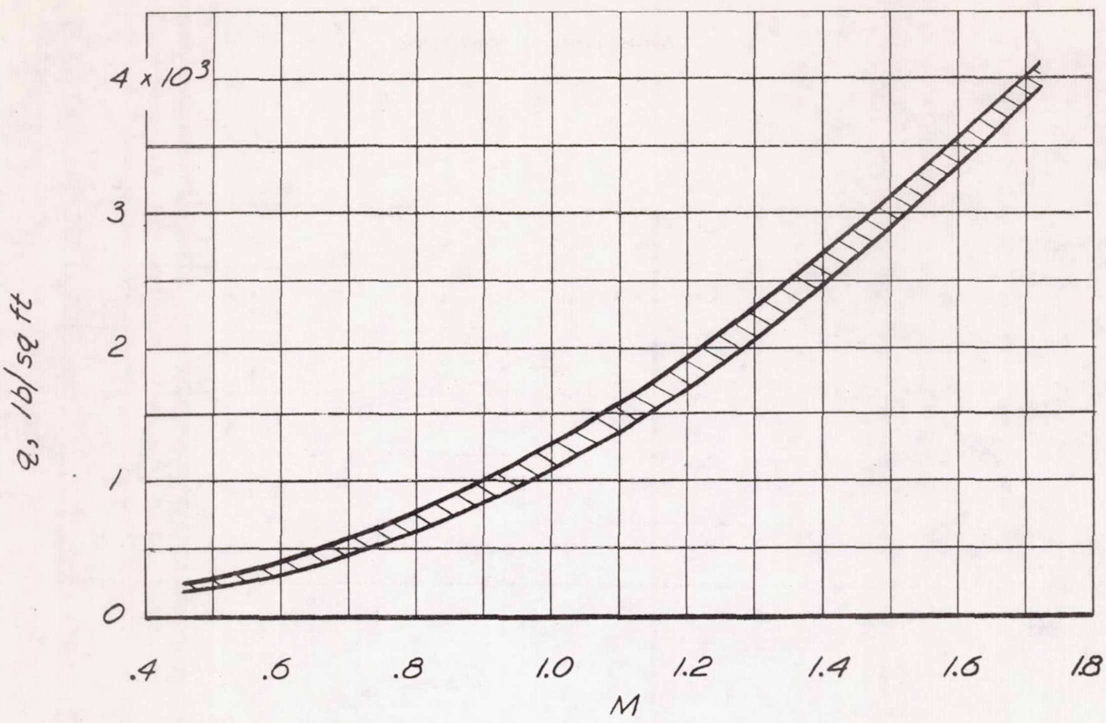
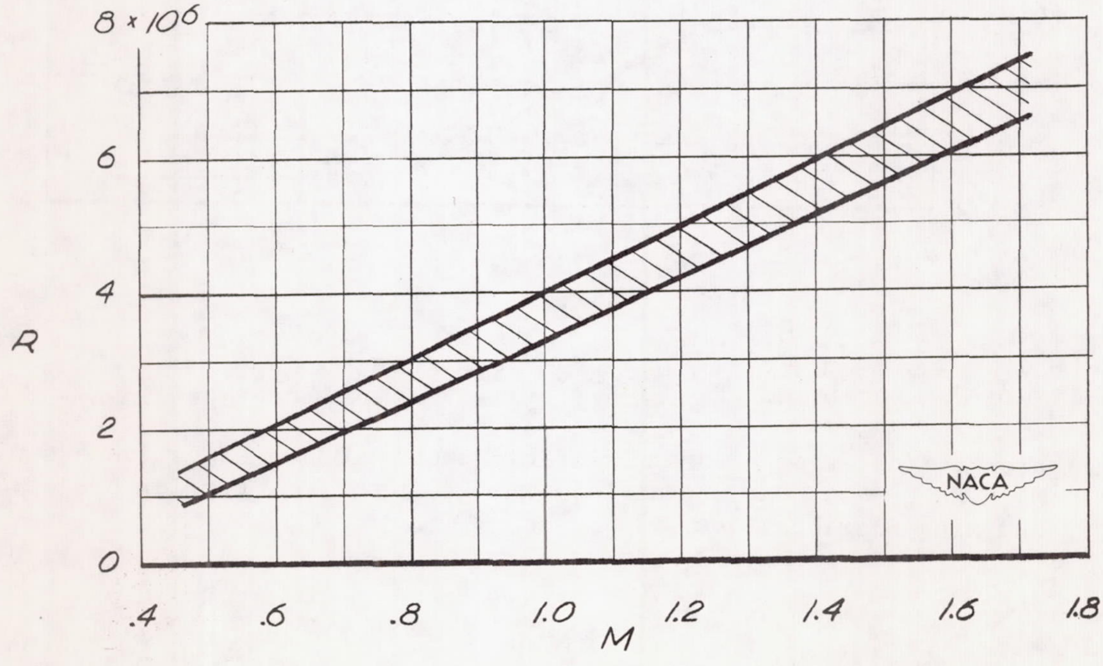


Figure 2.- Torsional flexibility characteristics of test wings.

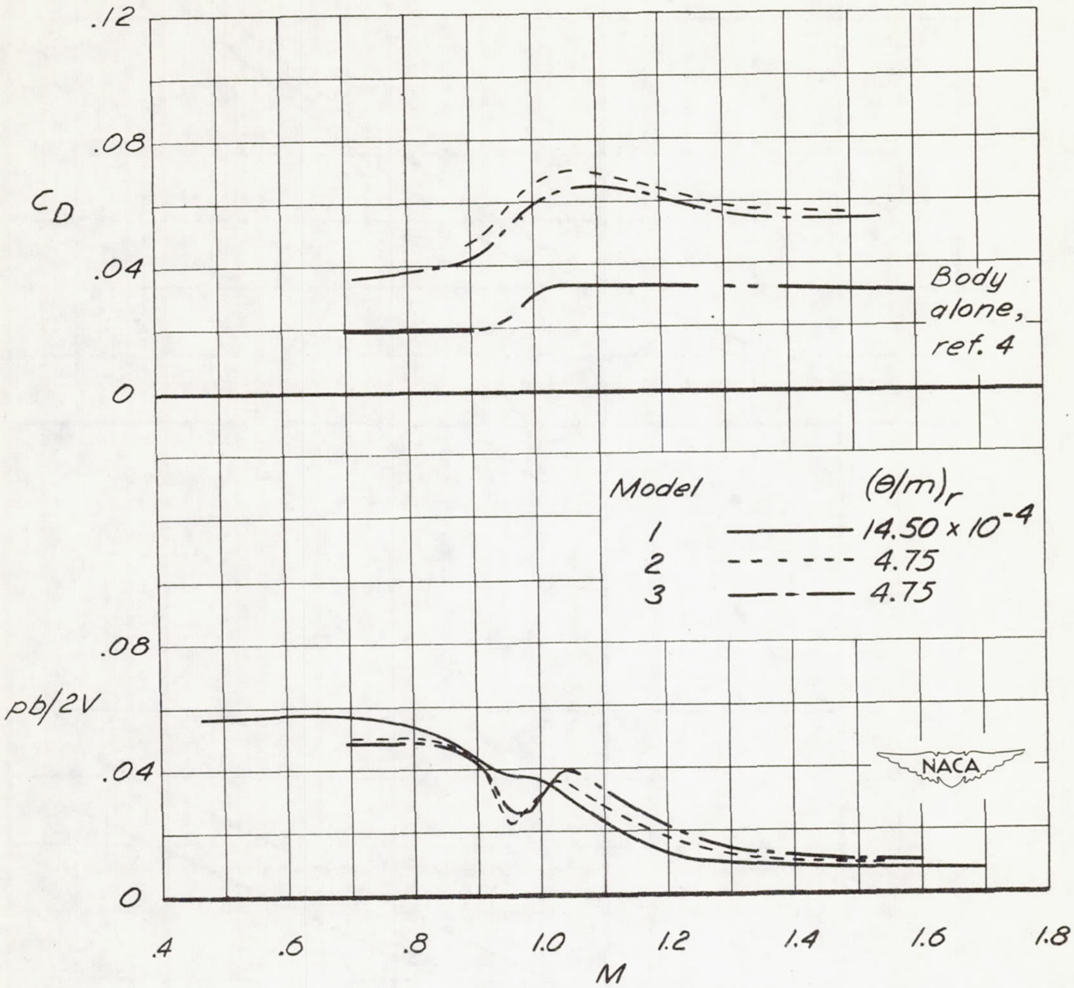


(a) Dynamic pressure.



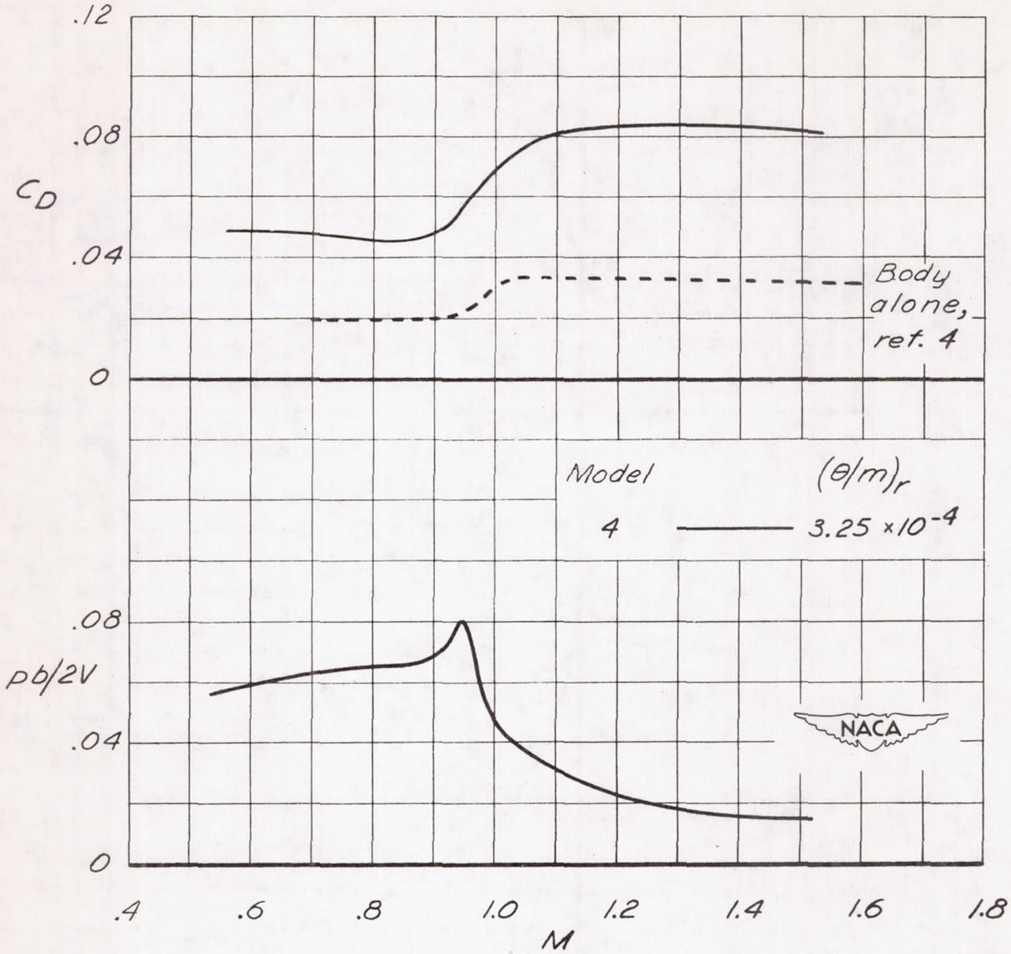
(b) Reynolds number.

Figure 3.- Variation of dynamic pressure and Reynolds number with Mach number.



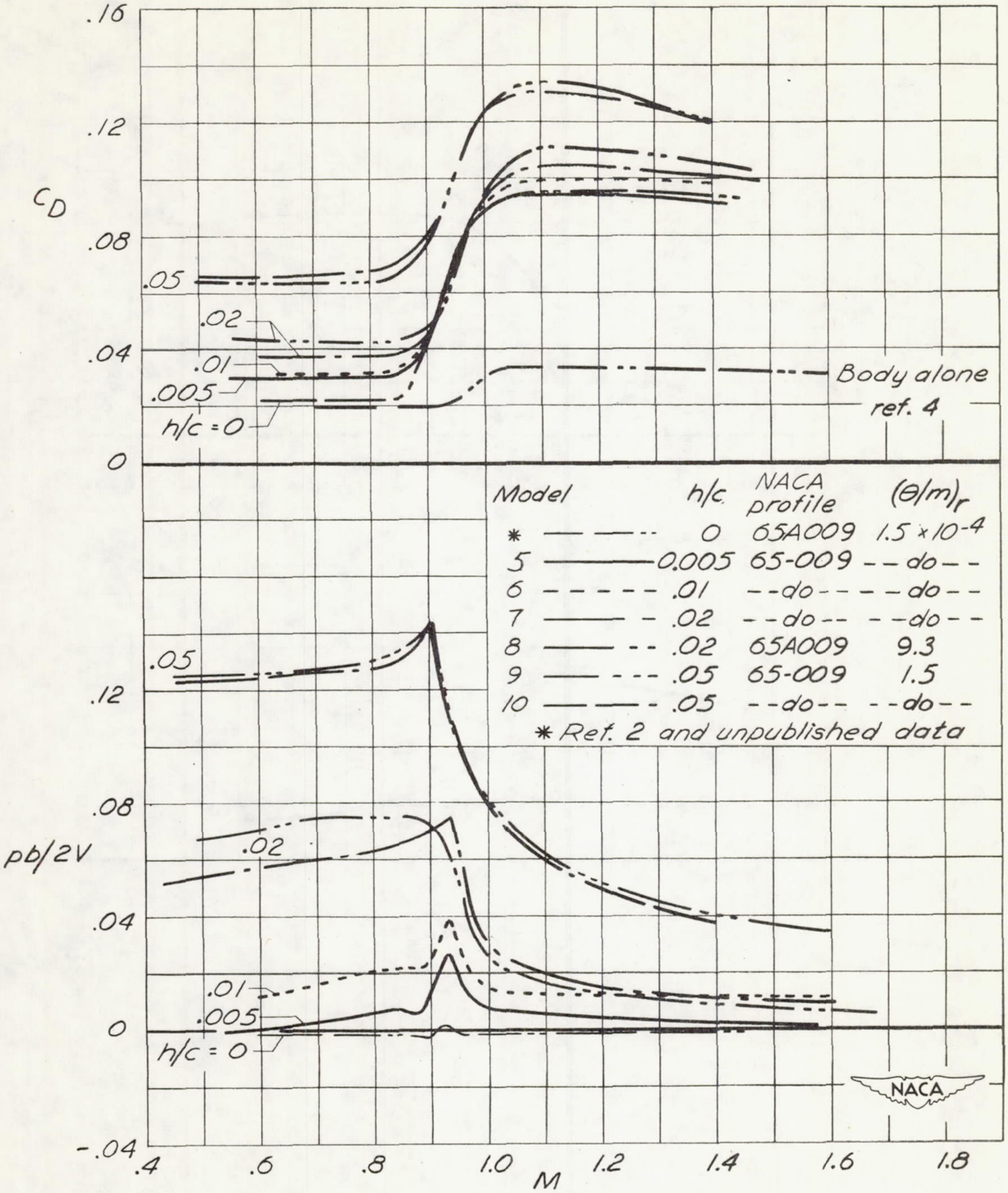
(a) NACA 65A003 airfoil, $\frac{h}{c} = 0.02$.

Figure 4.- Variation of drag coefficient and rolling effectiveness with Mach number for various airfoil thickness ratios, spoiler projections, and wing flexibilities.



(b) NACA 65A006 airfoil, $\frac{h}{c} = 0.02$.

Figure 4.- Continued.



(c) NACA 65A009 and 65-009 airfoils, h/c varies.

Figure 4.- Concluded.

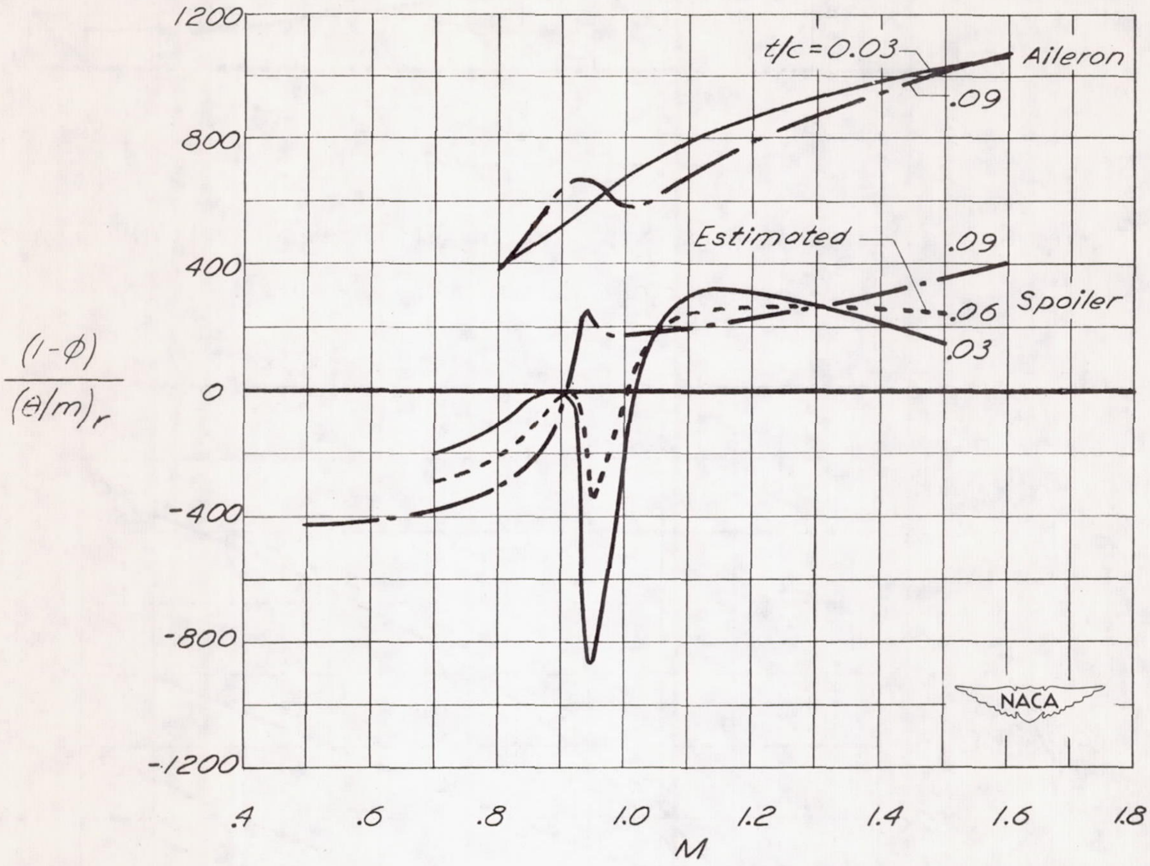


Figure 5.- Variation of flexible-wing effectiveness-loss parameter with Mach number for aileron and spoiler corrected to standard sea-level conditions. Values for $\frac{t}{c} = 0.06$ were obtained by averaging those for $\frac{t}{c} = 0.03$ and 0.09.

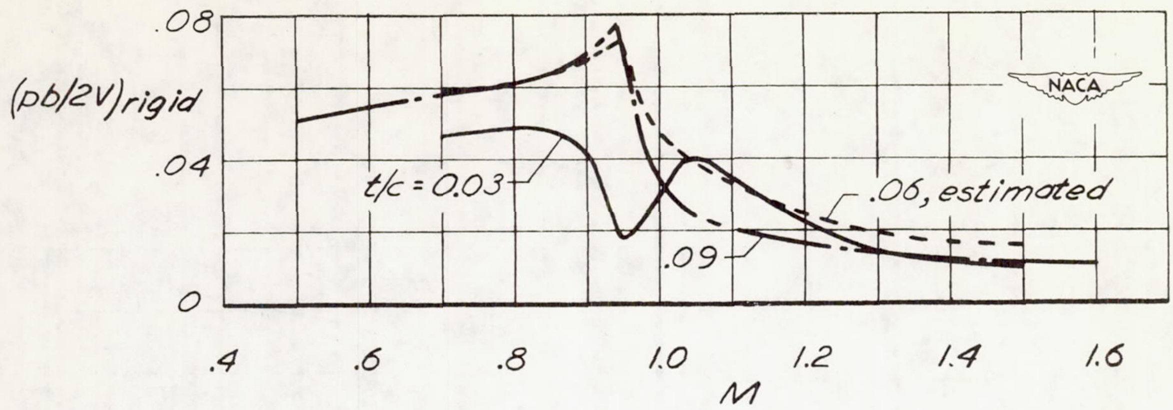


Figure 6.- Variation of rigid-wing rolling effectiveness with Mach number for three airfoil thicknesses. $\frac{h}{c} = 0.02$.

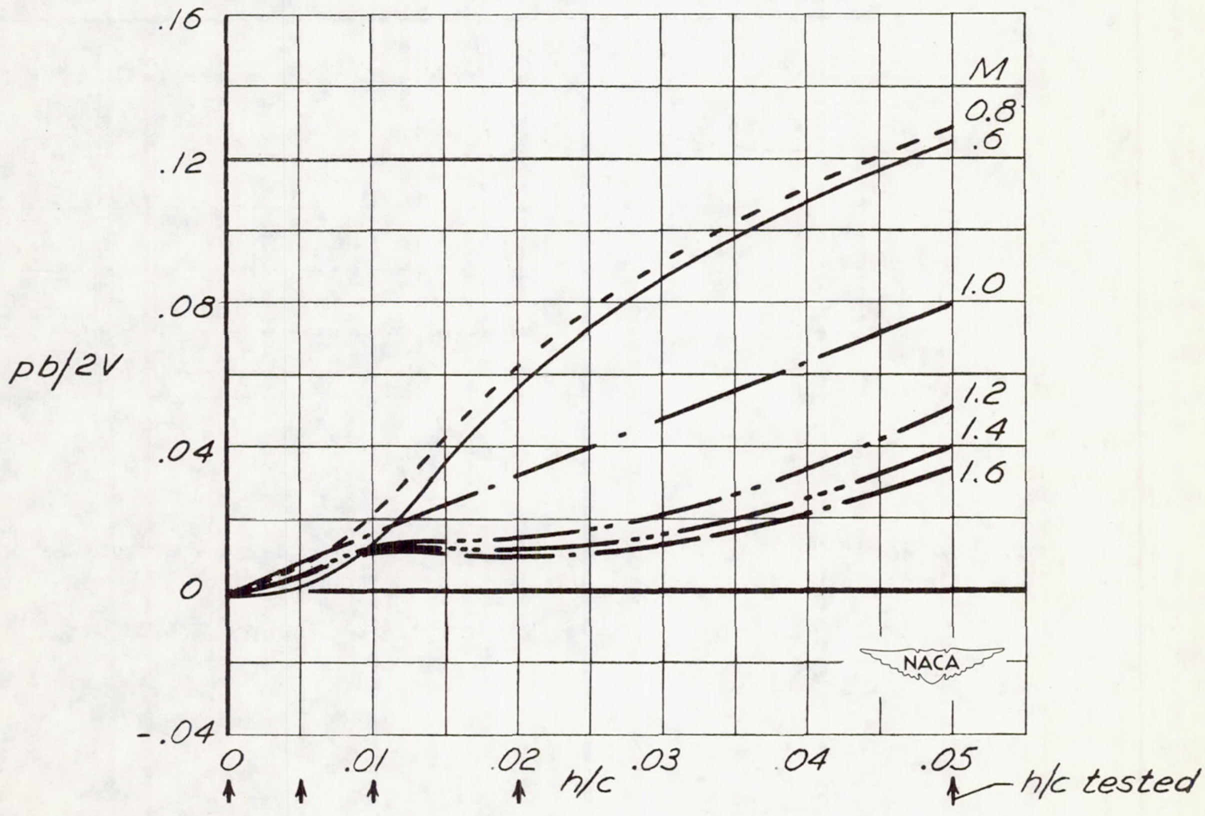


Figure 7.- Variation of flexible-wing rolling effectiveness with spoiler height for several Mach numbers. NACA 65-009 profile. $\left(\frac{\theta}{m}\right)_r = 1.5 \times 10^{-4}$ radians/ft lb.

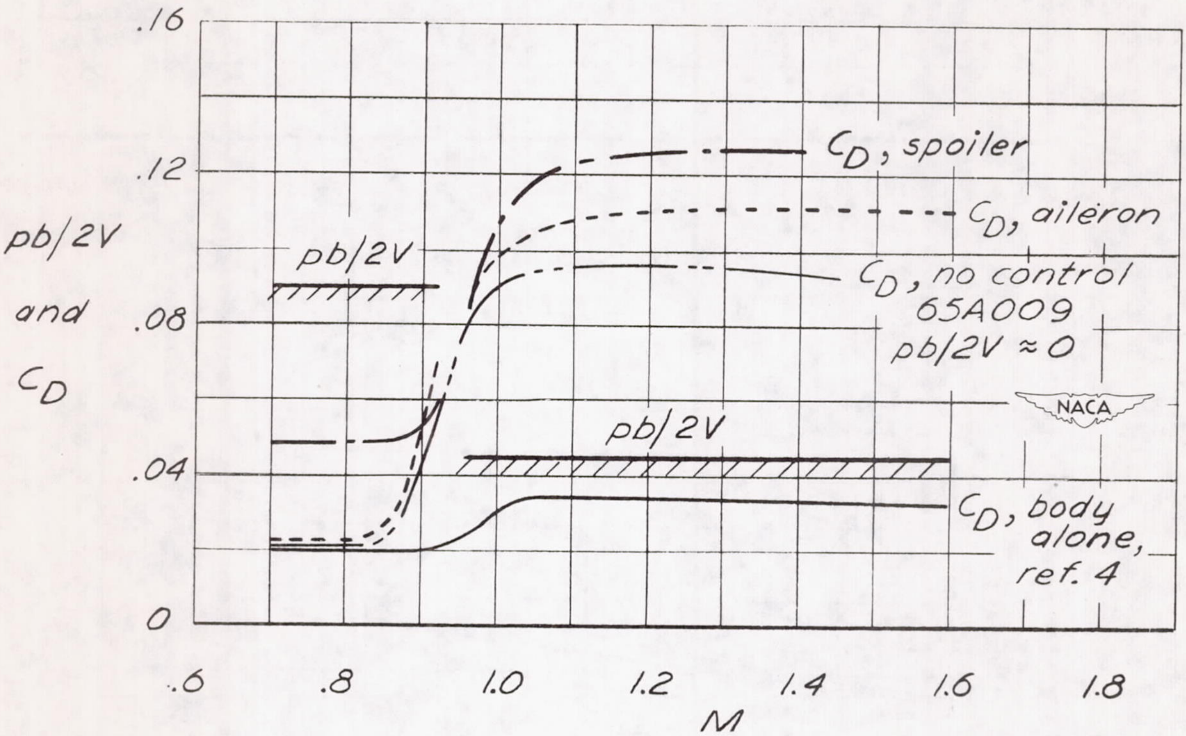


Figure 8.- Variation of drag coefficient with Mach number for spoiler and aileron having the same rolling effectiveness. NACA 65-009 profile. $\left(\frac{\theta}{m}\right)_r = 1.5 \times 10^{-4}$ radians/ft lb.

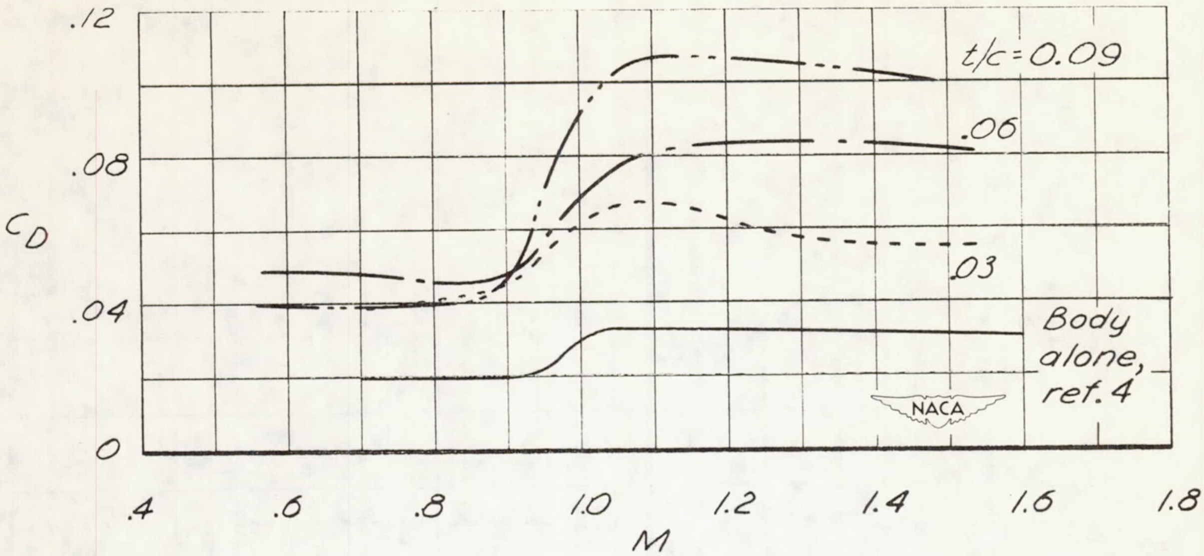


Figure 9.- Variation of drag coefficient with Mach number for several wing thickness ratios. $\frac{h}{c} = 0.02$.

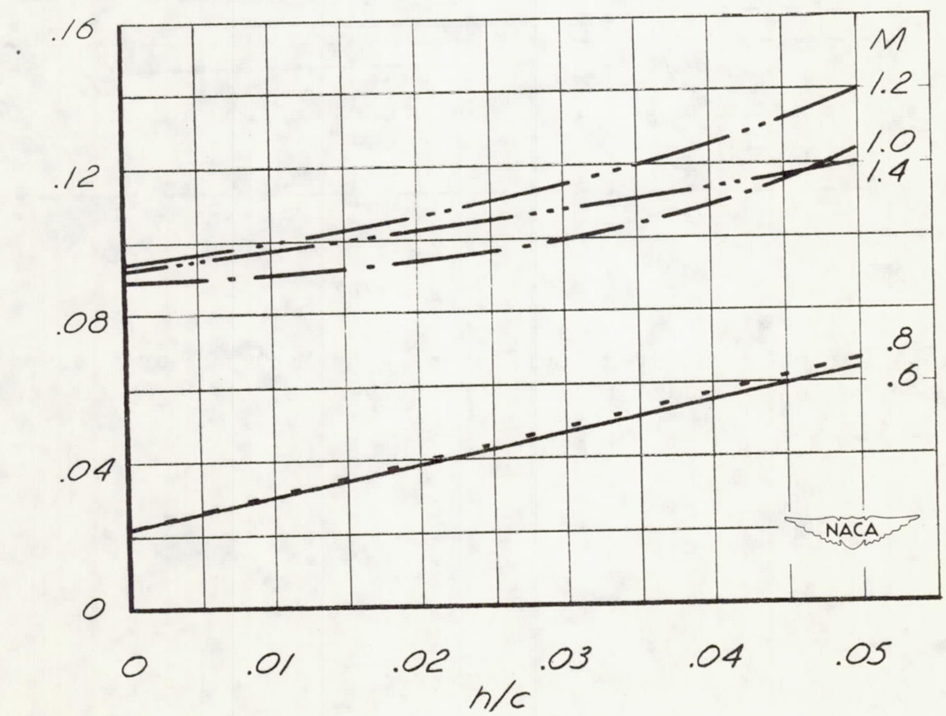


Figure 10.- Variation of drag coefficient with spoiler height for several Mach numbers. $\frac{t}{c} = 0.09$.