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RESEARCH MEMORANDUM

INVESTIGATION OF THE EFFECTS OF VARIATIONS IN THE REYNOLDS NUMBER BETWEEN 0.4×10^6 AND 3.0×10^6 ON THE LOW-SPEED AERODYNAMIC CHARACTERISTICS OF THREE LOW-ASPECT-RATIO SYMMETRICAL WINGS WITH RECTANGULAR PLAN FORMS

By George W. Jones, Jr.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The results are presented of an investigation of the effect of Reynolds number (between 0.4×10^6 and 3.0×10^6) and the addition of leading-edge roughness on the aerodynamic characteristics of three wings of aspect ratio 1, 2, and 3, each having a rectangular plan form, square-cut wing tips, and NACA 0012 airfoil sections. The lift curves increase in slope beyond the low-angle linear range, with the bend becoming more prominent as the aspect ratio is decreased. In the region where the lift curves start to bend, the slope of the curve of pitching moment about the quarter-chord point changes from positive to negative values. There is a small but definite scale effect on the lift-curve slope at zero lift, and the experimental values of the lift-curve slope are slightly higher than theoretical values obtained by the Weissinger method. There is a substantial increase in maximum lift coefficient with increasing Reynolds number for smooth wings, but with leading-edge roughness added most of this increase disappears. Scale effect on the section maximum lift is similar to that on the wing maximum lift, but the wing values are somewhat lower because of three-dimensional effects.

INTRODUCTION

In connection with some studies of hydrodynamic control surfaces, three low-aspect-ratio rectangular airfoils were tested at low subsonic Mach numbers in the Langley low-turbulence pressure tunnel. The three wings were of NACA 0012 airfoil sections, had aspect ratios of 1, 2, and 3, and were investigated at Reynolds numbers ranging from 0.4×10^6 to 3.0×10^6. Since the lift and moment characteristics of these wings, particularly as affected by aspect ratio, Reynolds number, and roughness, may be of general interest, the results of the investigation are presented herein.

SYMBOLS

A	aspect ratio
C_L	wing lift coefficient
$C_{L_{max}}$	maximum wing lift coefficient
$\left(C_{L_\alpha}\right)_{\alpha = 0^\circ}$	wing lift-curve slope at $\alpha = 0^\circ$
$C_{m_{c/4}}$	wing pitching-moment coefficient for moment about quarter-chord point
α	wing angle of attack
R	Reynolds number
M	free-stream Mach number

APPARATUS AND TESTS

Models.- The three wings used in the tests were made of aluminum alloy which was polished to give a smooth surface. The wings had rectangular plan forms, symmetrical NACA 0012 airfoil sections, and aspect ratios of 1, 2, and 3. The wing spans were 14 inches for the wing with $A = 1$ and 20 inches for the wings with $A = 2$ and $A = 3$. The wing tips of each wing were cut off square (as by a plane perpendicular to the leading edge). A sketch of one of the wings mounted on the sting balance is shown in figure 1.

Wind tunnel and test methods.- The investigation was conducted in the Langley low-turbulence pressure tunnel. The test section of the tunnel measures 3 feet by 7.5 feet. The Reynolds number was varied by changing the tunnel speed and tunnel air density. A complete description of the tunnel is presented in reference 1.

The models were mounted on a sting which employs a conventional 6-component strain-gage balance. Measurements of the normal force, chord force, and pitching moment were taken with the balance. The normal force and chord force were resolved to give the lift values. The sting was attached to each wing at the quarter-chord point through a notch cut in the wing so that the sting touched the wing only at the point of attachment. The sting body projected above and below the wing contour; therefore, two faired sheet-metal hoods were fitted over the sting to give a smooth flow of air. The hoods were fastened to the wing alone and they were not allowed to touch the sting. No effort was made to subtract the effects of the sting fairing from the balance readings, so that the aerodynamic characteristics presented are those of the wing plus support interference.

It was felt that the inclusion of the support interference would not change the scale effects on the aerodynamic characteristics under consideration although the absolute values of the measured characteristics would be slightly in error because of the support interference.

Tests.- The tests of each smooth plain wing consisted of measurements of the chord force, normal force, and pitching moment at Reynolds numbers of 0.4×10^6, 0.7×10^6, 1.0×10^6, 1.5×10^6, 2.0×10^6, 2.5×10^6, and 3.0×10^6. The angle-of-attack range used was $\alpha = -12^\circ$ to $\alpha = 26^\circ$. The following table gives the free-stream Mach number corresponding to each Reynolds number:

R	M for wing of aspect ratio of -		
	1	2	3
0.4×10^6	0.20	0.28	0.21
.7	.25	.20	.18
1.0	.20	.18	.13
1.5	.19	.13	.13
2.0	.12	.12	.10
2.5	.11	.09	.07
3.0	.11	.08	.07

Standard leading-edge roughness was applied to the wings and the aforementioned procedure was repeated. The standard leading-edge roughness was the same as that used in previous investigations and consisted of 0.011-inch-diameter carborundum grains spread over a surface length of 8 percent of the chord measured from the leading edge on the upper and lower surfaces of the airfoil.

RESULTS AND DISCUSSION

Lift and moment.- The results of the tests are given in figure 2 in the form of lift and pitching-moment data for each of the wings with both smooth surfaces and leading-edge roughness throughout the Reynolds number range. Although no tare corrections have been applied, the results have been corrected for tunnel-wall effects (ref. 2). The lift curves for the wing of aspect ratio 1 are not extended to the stall because the limit on the angle-of-attack range of the sting mount was less than the stall angle. In general, the lift curves are not linear but show an increase in slope at some positive lift coefficient. This bend is more prominent for the wing with $A = 1$ than for the wings with $A = 2$ and $A = 3$. It is interesting to note that the moment curves show changes from a small positive slope to a small negative slope at about the same angle as that where the bend in the lift curve appears. At some higher angle there occurs a sharp negative break in the moment curve (or a sudden rearward movement of the center of pressure). This sharp break occurs at $C_{L_{max}}$ for the wings with $A = 2$ and $A = 3$ but for the wing with $A = 1$ at the lower Reynolds numbers the sharp break occurs before $C_{L_{max}}$ at a point where there is a slight break (or reduction in slope) in the lift curve. Since no pressure measurements or tuft studies were made, a detailed correlation of these force and moment breaks with the accompanying flow cannot be given. However, such phenomena are believed to be related to the development of the separated tip vortices and to the development of boundary-layer separation on the inboard areas. Similar flows and their mechanisms are discussed in references 3 and 4.

Lift-curve slope.- In figure 3 the lift-curve slopes, at $\alpha = 0^{\circ}$, are plotted against Reynolds number for the smooth and rough conditions. In general, roughness reduced the slopes only slightly and there appears to be a slight but definite increase of slope with Reynolds number. In order to show a comparison between the experimental lift-curve slopes obtained in the tests and the lift-curve slopes predicted by an acceptable theory, the following table is given. In the table, the theoretical values of $C_{L_{\alpha}}$ are taken from figure 11 of reference 5 (the slopes were computed by Weissinger's method and based on a section lift-curve slope of 2π). The experimental values of $C_{L_{\alpha}}$ in the table are for the smooth airfoils at $R = 3.0 \times 10^{6}$:

A	Theoretical $\left(C_{L_{\alpha}}\right)_{\alpha = 0^{\circ}}$	Experimental $\left(C_{L_{\alpha}}\right)_{\alpha = 0^{\circ}}$
1	0.024	0.029
2	.042	.044
3	.054	.057

The experimental values are slightly higher than the theoretical values; however, they follow the theoretical trend rather closely.

Maximum lift.- For the wings of aspect ratio 2 and 3, as shown in figure 4, there is a definite increase in maximum lift coefficient $C_{L_{max}}$ with increasing Reynolds number through the range of these tests. As previously explained, because of the limit on the angle-of-attack range of the sting mount, the values of $C_{L_{max}}$ for the wing with $A = 1$ could not be included in figure 4. However, a comparison of that portion of the lift curve obtained for the wing with $A = 1$, particularly at the lower Reynolds numbers, with the lift curve for the wing with $A = 2$ (fig. 2) shows that the highest values of C_L obtained for the wing with $A = 1$ were generally as high or higher than the $C_{L_{max}}$ values at corresponding R for the wing with $A = 2$ even though the wing with $A = 1$ had not reached $C_{L_{max}}$. Therefore, it may be inferred that there is an increase in $C_{L_{max}}$ as the aspect ratio is decreased from 2 to 1. This phenomenon is due to an increase, with decreasing aspect ratio, in the relative area covered by the tip vortices, which have the effect of preserving reattachment of the flow after separation at the forward part of the wing to larger angles of attack. The "bubble" formed by reattachment of the flow has a definite camber effect, hence, the high lift coefficients (see, for example, ref. 3).

For the wings with leading-edge roughness, there is only a slight increase in $C_{L_{max}}$ with increasing R and the values of $C_{L_{max}}$ are lower than the corresponding values for smooth airfoil surfaces. From the results of reference 4, it would be expected that lower values of $C_{L_{max}}$ would be obtained for wings with leading-edge roughness.

A comparison of the section maximum lift values (obtained from ref. 6) with the values of $C_{L_{max}}$ of figure 4 at Reynolds numbers from 0.7×10^6 to 3.0×10^6 showed that the section and wing curves of maximum lift against Reynolds number have the same shape. As expected, however, the wing maximum lift values are lower than the section maximum lift values for both smooth and rough conditions because of the three-dimensional effects of the wing.

CONCLUSIONS

From an investigation of the aerodynamic characteristics of three low-aspect-ratio wings ($A = 1$, $A = 2$, and $A = 3$) with rectangular plan forms, square-cut wing tips, and NACA 0012 airfoil sections at seven Reynolds numbers from 0.4×10^6 to 3.0×10^6, the following conclusions can be drawn:

1. The lift curves increase in slope beyond the low-angle-of-attack linear range, with the bend becoming more prominent as the aspect ratio is decreased. In the region where the lift curves start to bend, the slope of the curve of pitching moment about the quarter-chord point changes from small positive to small negative values. At high angles of attack there is a sharp stable break in the moment curve which occurs at the stall for the wings of aspect ratio 2 and 3. For the wing of aspect ratio 1 the sharp break occurs before the stall, at a point where the lift curve shows a reduction in slope.

2. There is a slight scale effect on the lift-curve slope at zero lift. A comparison of the experimental values of lift-curve slope with theoretical values obtained by the Weissinger method shows the experimental values to be slightly higher than predicted by theory.

3. For the wings with smooth surfaces, there is a definite increase in maximum lift coefficient with increasing Reynolds number. For the wings with leading-edge roughness added, there was only a slight increase in the maximum lift coefficient with Reynolds number. A comparison of curves of the wing maximum lift values against Reynolds number with similar curves for section maximum lift values shows the curves to have the same shape although the wing values are lower than section values because of three-dimensional effects.

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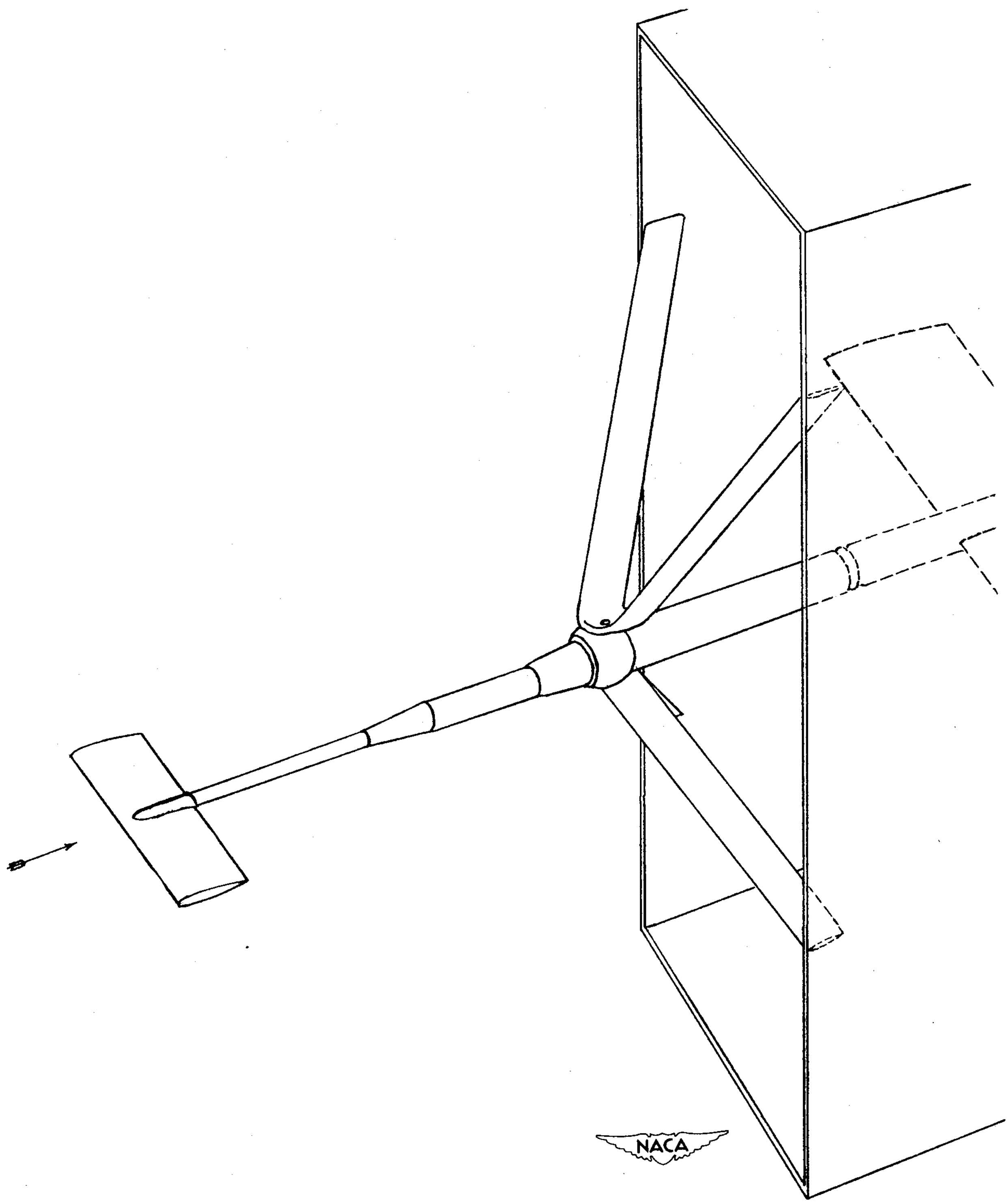
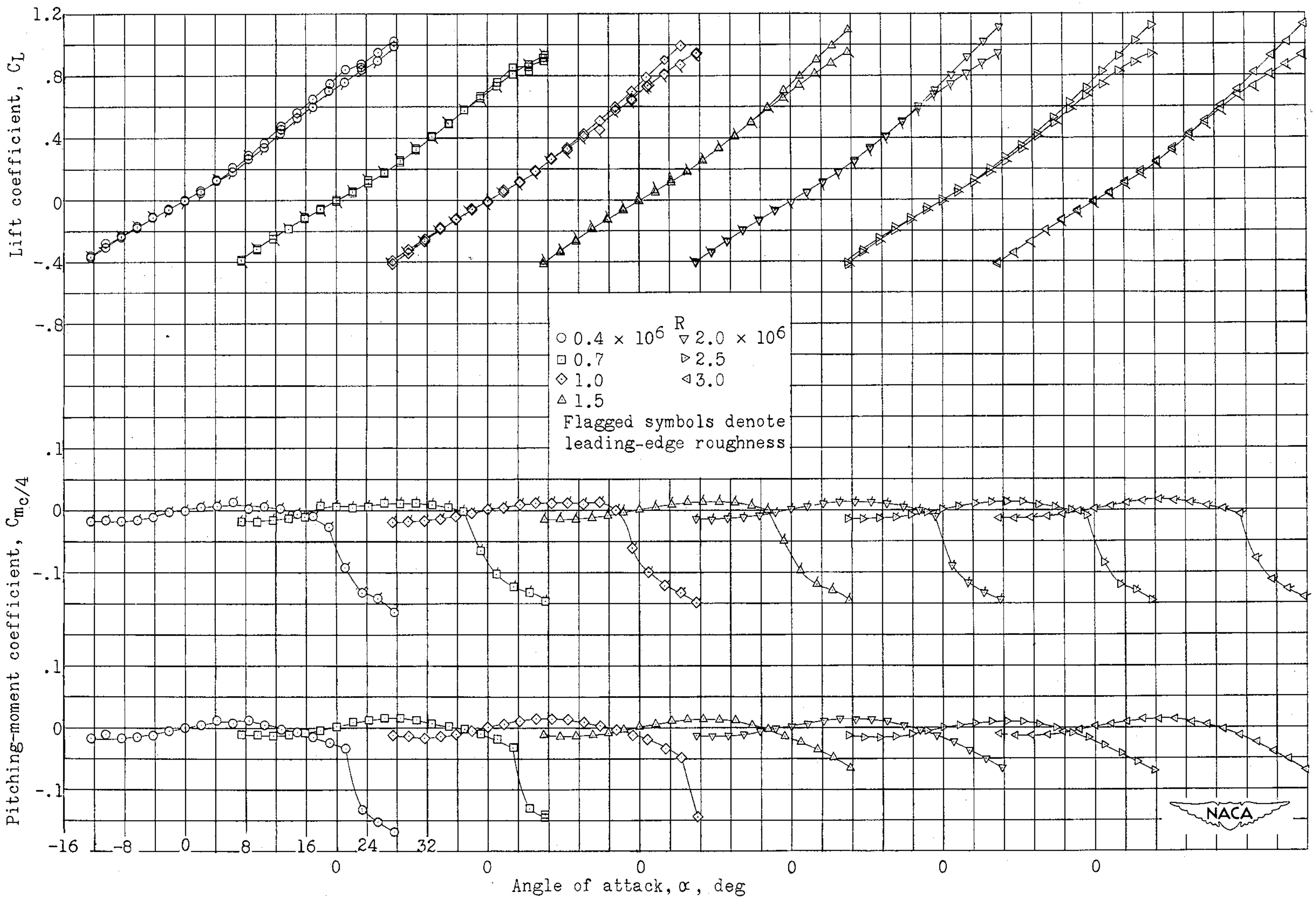
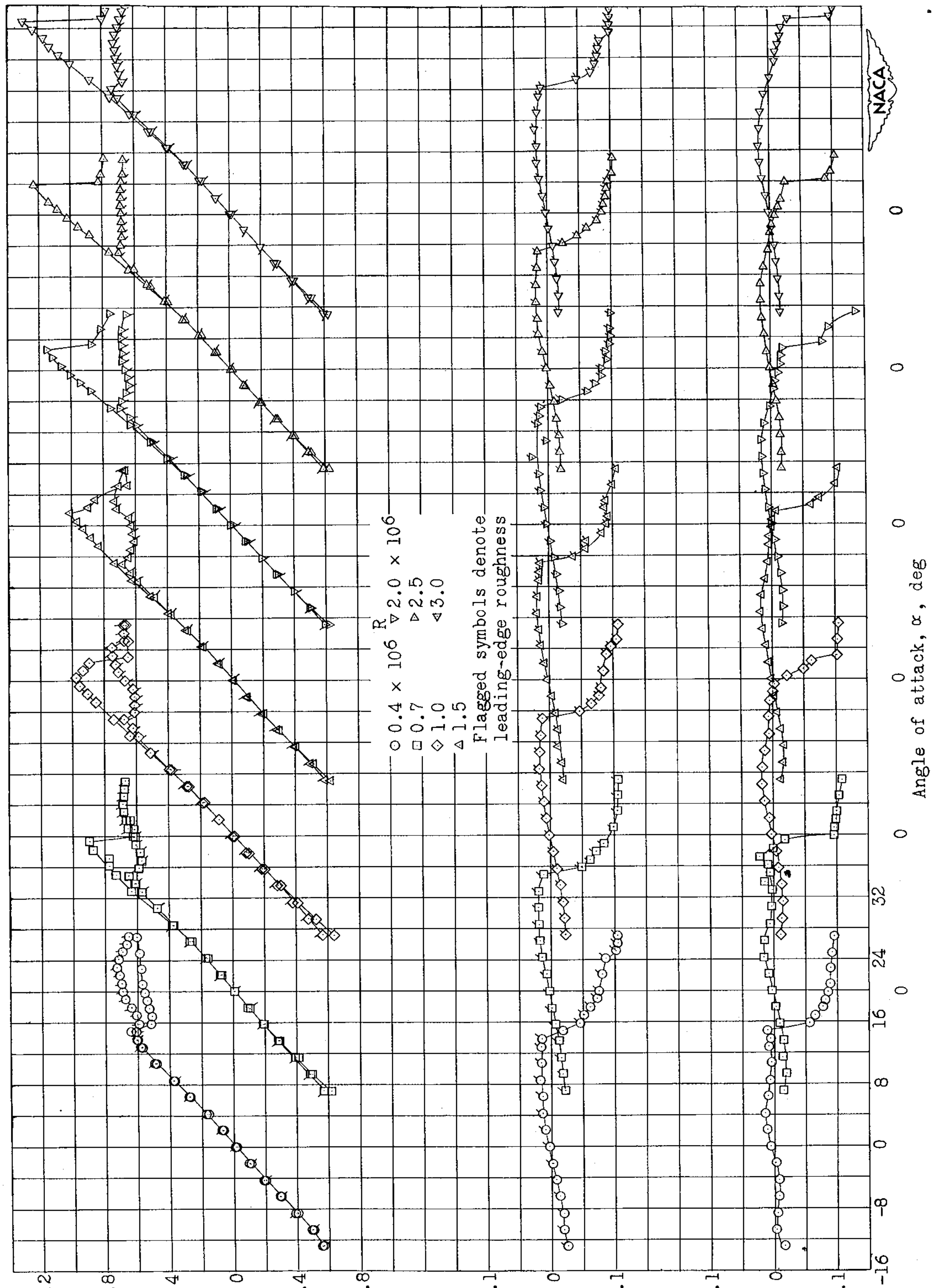


Figure 1.- Model mounted on sting balance.



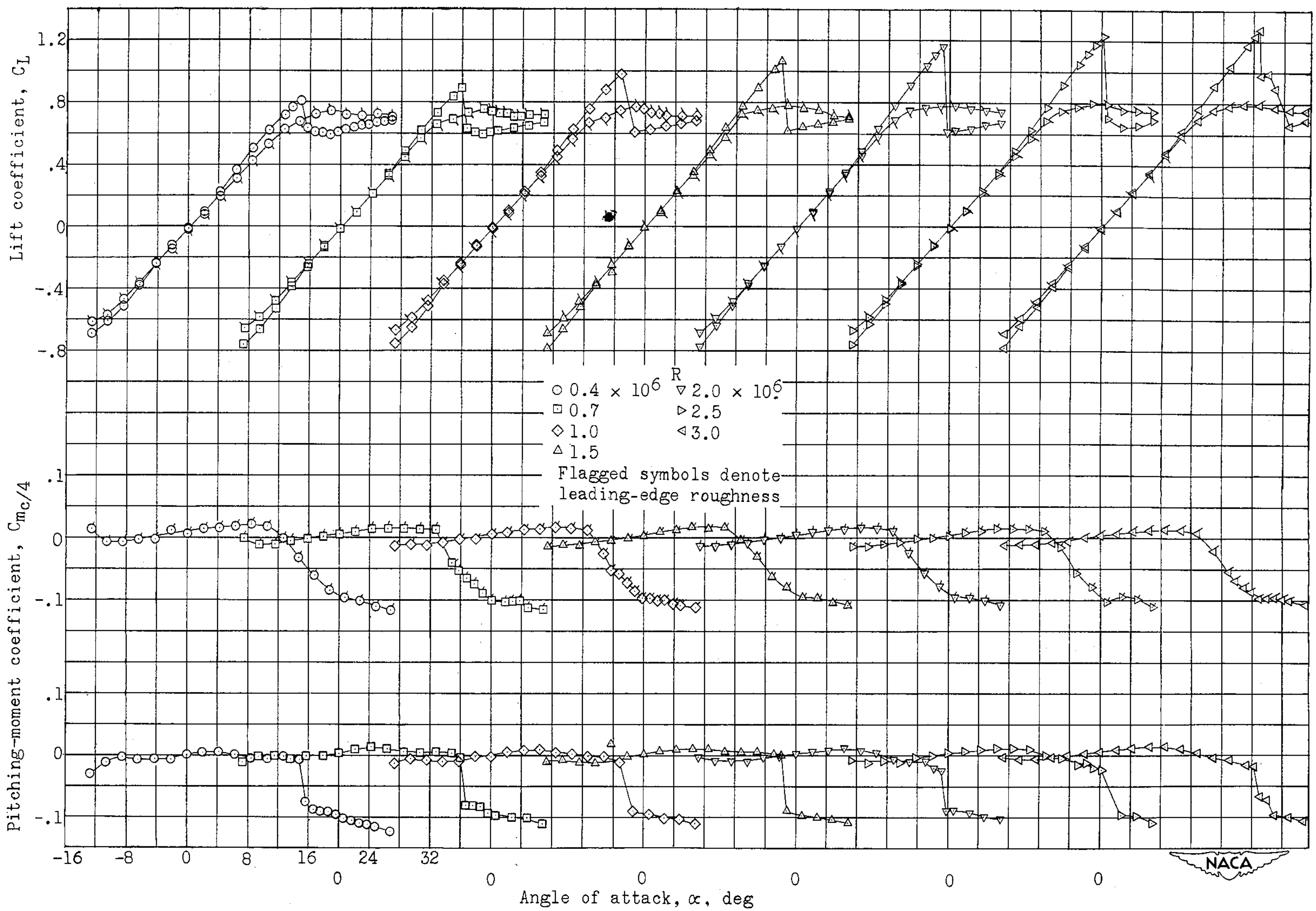
(a) Wing of aspect ratio 1.

Figure 2.- Lift and pitching-moment characteristics of three low-aspect-ratio wings of rectangular plan form and NACA 0012 airfoil section.



(b) Wing of aspect ratio 2.

Figure 2.- Continued.



(c) Wing of aspect ratio 3.

Figure 2.- Concluded.

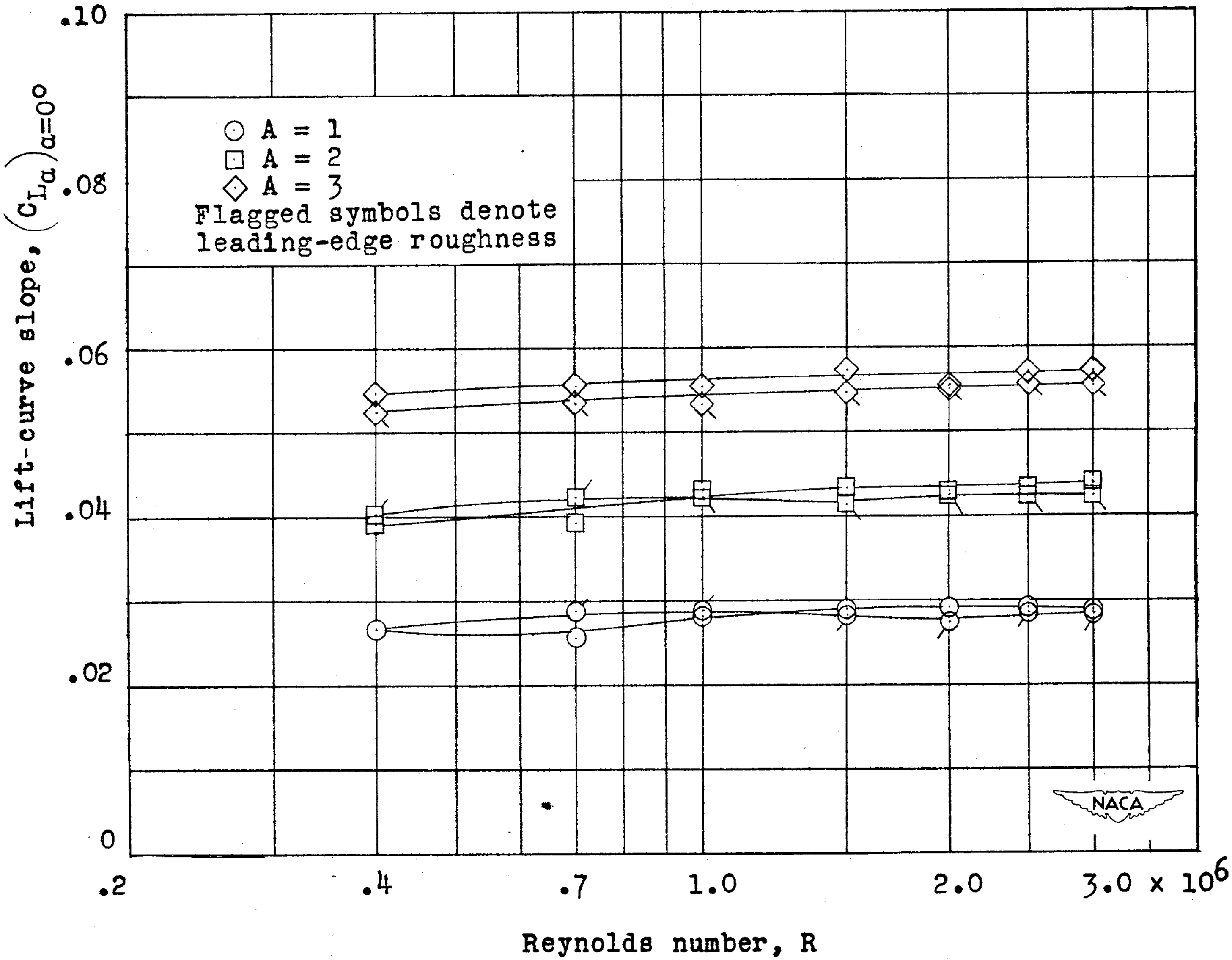


Figure 3.- Variation with Reynolds number of the lift-curve slopes at $\alpha = 0^\circ$ of three low-aspect-ratio wings.

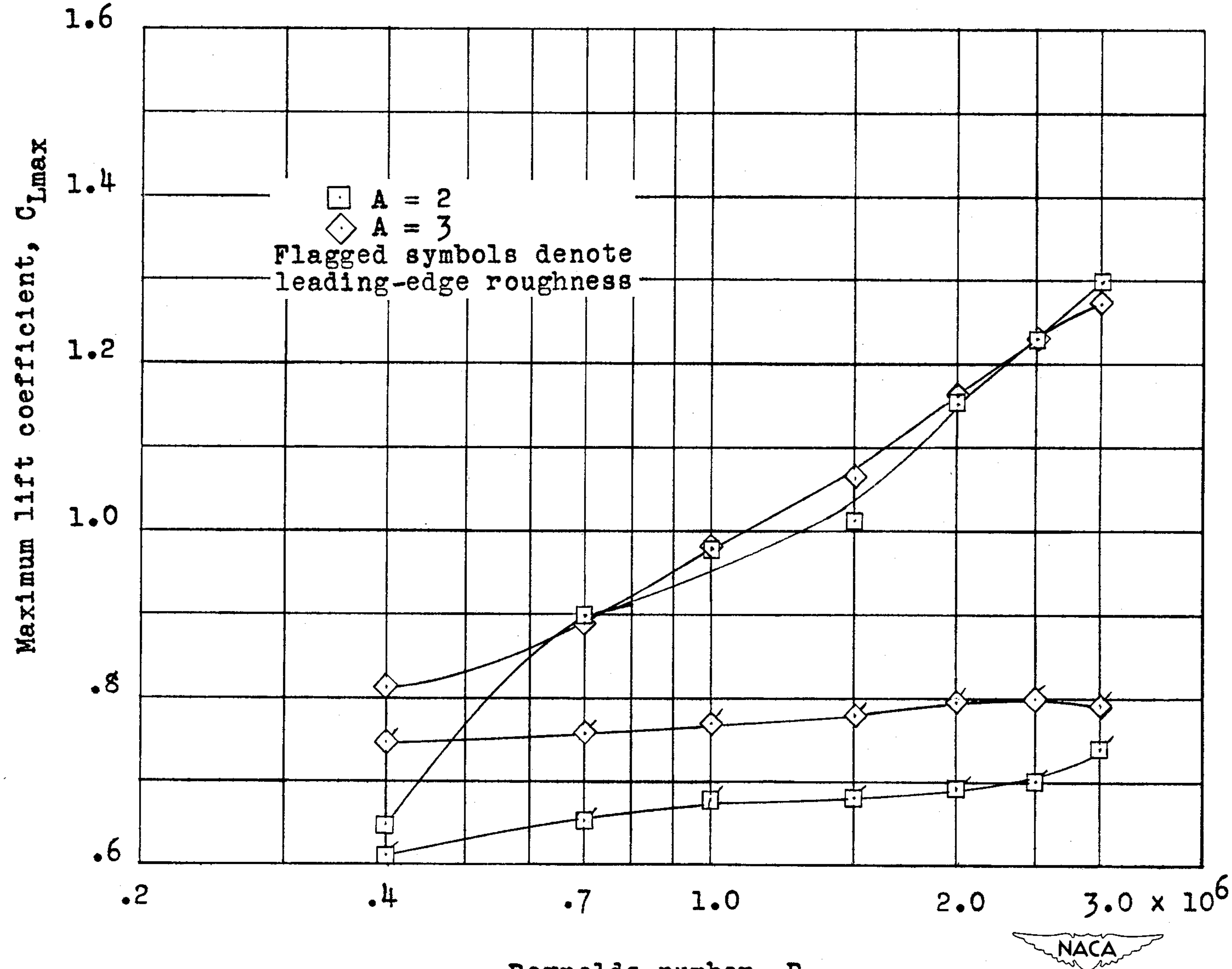


Figure 4.- Variation with Reynolds number of maximum lift coefficient of two low-aspect-ratio wings with smooth and rough leading edges.

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The effects of Reynolds number on the aerodynamic characteristics of three symmetrical wings of aspect ratio 1, 2, and 3 each having a rectangular plan form and an NACA 0012 airfoil section is given for a range of seven Reynolds numbers between 0.4 x 10^6 and 3.0 x 10^6. The data show the effects of Reynolds number on the lift, the lift-curve slope, maximum lift coefficient, and the pitching moment about the quarter-chord point.

Copies obtainable from NACA, Washington

1. Wings, Complete - Aspect Ratio (1.2.2.2.2)
2. Reynolds Number Effects - Complete Wings (1.2.2.5)
3. Boundary Layer - Complete Wings (1.2.2.8)

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