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TECHNICAL NOTE 2074

AERODYNAMIC CHARACTERISTICS AT REYNOLDS NUMBERS
OF 3.0×10^6 AND 6.0×10^6 OF THREE AIRFOIL SECTIONS
FORMED BY CUTTING OFF VARIOUS AMOUNTS FROM THE REAR
PORTION OF THE NACA 0012 AIRFOIL SECTION

By Hamilton A. Smith and Raymond F. Schaefer

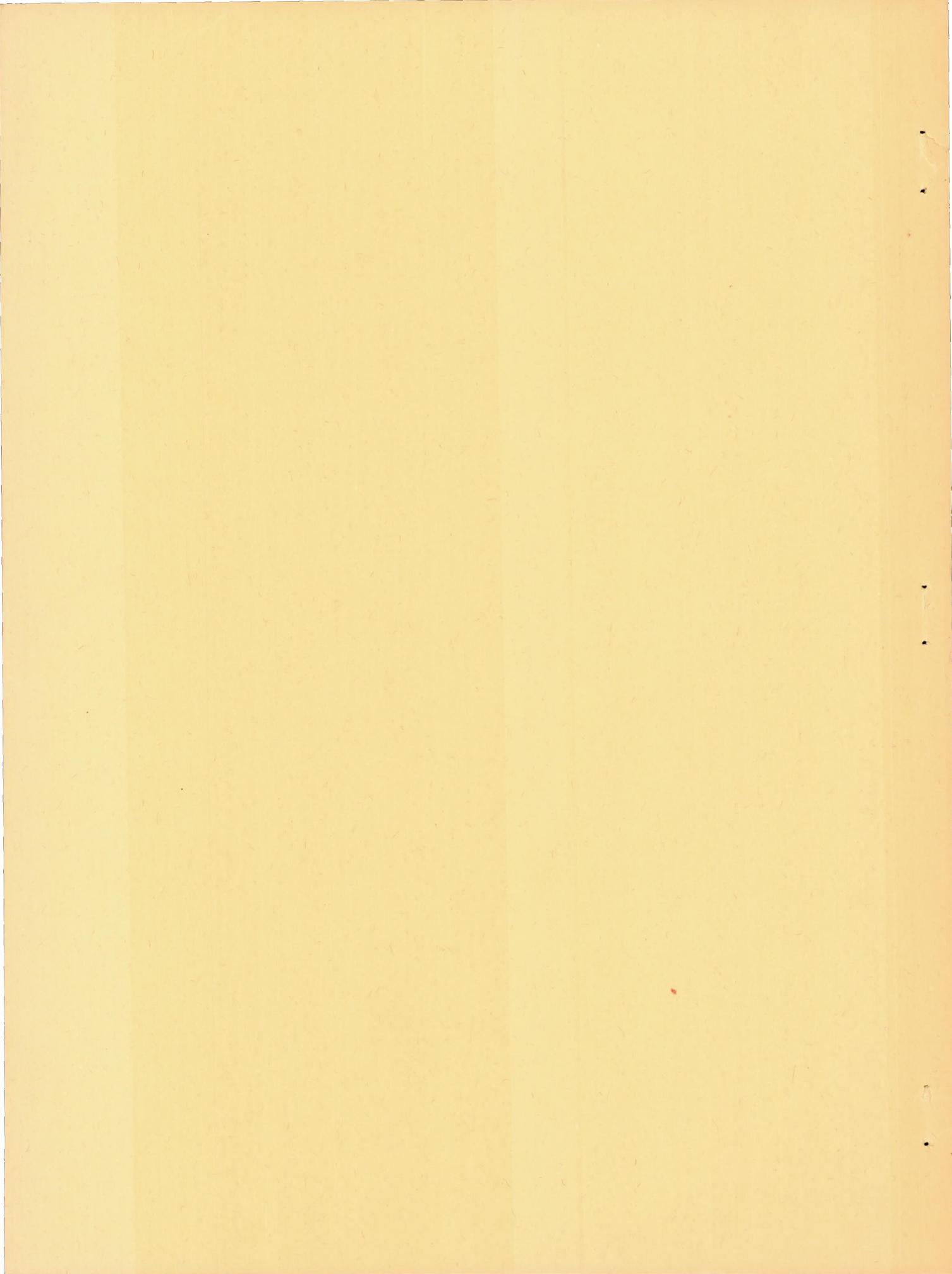
Langley Aeronautical Laboratory
Langley Air Force Base, Va.



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AERODYNAMIC CHARACTERISTICS AT REYNOLDS NUMBERS
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SUMMARY

An investigation has been made of the two-dimensional aerodynamic characteristics of three airfoil sections formed by removing 1.5, 4.0, and 12.5 percent of the original chord from the trailing edge of the NACA 0012 airfoil section. The tests consisted of measurements of section lift, drag, and pitching-moment coefficients at Reynolds numbers of 3.0×10^6 and 6.0×10^6 for the airfoil sections both in the smooth condition and with roughened leading edges. The characteristics of the airfoil section obtained by cutting off 1.5 percent chord were also determined with a spanwise row of rivet heads on each surface near the trailing edge.

The results indicate that, when the trailing edge is thickened by removing portions from the rear of the NACA 0012 section, the drag coefficient for most lift coefficients becomes higher, the maximum lift coefficient varies by a relatively small amount for the smooth airfoil and progressively increases for the rough leading-edge condition, and the aerodynamic-center position consistently moves rearward. Applying rivet heads to the section formed by cutting away 1.5 percent chord altered the aerodynamic characteristics to a degree which, in most cases, was barely perceptible.

INTRODUCTION

The use of airfoil sections having relatively thick trailing edges is frequently expedient in the structural design of helicopter blades and is sometimes considered desirable for those portions of airplane wings containing control surfaces. A method sometimes employed to obtain an airfoil having a thick trailing edge consists of removing a sufficient amount from the rear of an existing conventional airfoil section to result in the desired trailing-edge thickness. The effects

upon the section aerodynamic characteristics of such a modification, however, have not been extensively investigated. The investigation reported in the present paper was made in an attempt to evaluate the effects upon the aerodynamic characteristics of the NACA 0012 airfoil section of removing various amounts from the rear portion of the airfoil.

The investigation consisted of measurements of the lift, drag, and pitching-moment characteristics of the NACA 0012 airfoil with 1.5, 4.0, and 12.5 percent of the original chord removed from the rear of the airfoil. The first two modifications are of the type which might be desirable from stress or fabrication considerations; whereas the third modification is of the type which might be required in the application of jet exhausts to helicopter blades. In the fabrication of metal-covered rotor blades, rivets are frequently used to fasten the skin to a trailing-edge strip. The present investigation, therefore, included experiments to ascertain the effects of a representative rivet installation on the aerodynamic characteristics of the NACA 0012 airfoil with 1.5 percent of the chord removed. The experiments were made at Reynolds numbers of 3.0×10^6 and 6.0×10^6 .

COEFFICIENTS AND SYMBOLS

α_0	section angle of attack
c_d	section drag coefficient
c_l	section lift coefficient
$c_{l_{max}}$	maximum section lift coefficient
c_{m_p}	section pitching-moment coefficient about model pivot axis
$c_{m_c/4}$	section pitching-moment coefficient about quarter-chord point
$c_{m_{ac}}$	section pitching-moment coefficient about aerodynamic center
$dc_l/d\alpha_0$	slope of section lift curve per degree
R	Reynolds number, based on model chord and free-stream velocity
c	airfoil chord

x distance along chord from leading edge
y distance perpendicular to chord

APPARATUS AND TESTS

Wind tunnel.- All the tests were performed in the Langley two-dimensional low-turbulence pressure tunnel. The rectangular test section of this tunnel measures 3 feet by $7\frac{1}{2}$ feet, and each model completely spanned the smaller dimension and had the ends sealed to the tunnel walls to prevent air leakage. Drag measurements were made by means of a wake-survey apparatus. Lift was obtained from measurements of the pressure reactions on the floor and ceiling of the tunnel. Measurements of the pitching moment were taken with a torque balance. A description of the tunnel, the measuring apparatus, and the method of correcting data can be found in reference 1.

Models.- The models used for the tests were obtained from a 24-inch-chord model of the NACA 0012 section constructed of laminated mahogany. The portions removed from the trailing-edge region of the NACA 0012 model were 1.5, 4.0, and 12.5 percent of the original chord. For convenience, the airfoil sections resulting from these modifications are designated in this paper as A, B, and C, respectively. The cut-offs, which were made normal to the chord plane, resulted in thicknesses at the trailing edge of approximately 0.68, 1.40, and 4.01 percent of the resulting chords, in comparison with a trailing-edge thickness of 0.25 percent chord for the NACA 0012 section. The maximum thicknesses of airfoils A, B, and C were 12.2, 12.5, and 13.7 percent chord, respectively. Comparative geometric characteristics of the NACA 0012 section and airfoils A, B, and C are given in figure 1.

An additional configuration investigated consisted of airfoil A equipped with a spanwise row of rivet heads secured to the upper and lower surfaces near the trailing edge (shown in fig. 1). The distance from the line of centers of the rivets to the trailing edge was 1.1 percent of the model chord (0.26 in.) and the spanwise spacing was 2.7 percent chord (0.65 in.). The rivet heads used had been cut from standard $\frac{3}{32}$ -inch-diameter brazier-head rivets, and the head diameter and height were, respectively, 1.0 percent chord (0.23 in.) and 0.2 percent chord (0.05 in.).

In the preparation of the basic model the surfaces were covered with glazing compound and sanded with No. 400 carborundum paper until they were aerodynamically smooth and fair. The trailing edges of airfoils A,

B, and C were prepared in the same manner. For the tests with leading-edge roughness, 0.011-inch-diameter carborundum grains were scattered into a thin coat of shellac spread from the model leading edge over a distance on each surface amounting to 8 percent of the original chord. This roughness was sufficient to cause transition at the leading edge.

Ordinates for the NACA 0012 airfoil section at standard chordwise stations are contained in table I. Ordinates for stations corresponding to the trailing edges of the modified sections have been calculated according to the method of reference 2 and are also included in table I.

Tests.- Valid comparisons between the data previously obtained for the NACA 0012 section and the data obtained for the three airfoils of the present investigation were considered essential. Prior to making the modifications to the model, therefore, measurements in the regions of maximum lift and minimum drag were made at a Reynolds number of 6.0×10^6 for the NACA 0012 section. The agreement between the results of these check tests and corresponding data previously obtained for the NACA 0012 section (reference 3) is shown in figure 2.

Measurements of section coefficients of lift, drag, and pitching moment for the smooth surface condition were made at Reynolds numbers of 3.0×10^6 and 6.0×10^6 for airfoils A and B, and at one Reynolds number of 6.0×10^6 for airfoil C. With the exception of the pitching moment for airfoil C, each of the tests was also performed with leading-edge roughness applied to the airfoil. Section lift, drag, and pitching moments were also measured for airfoil A with simulated rivets at Reynolds numbers of 3.0×10^6 and 6.0×10^6 for both smooth and rough leading-edge conditions. The Mach number attained in these tests did not exceed 0.15.

RESULTS

Experimental data for the NACA 0012 airfoil section (from reference 3) are contained in figure 2. These results were obtained for test conditions similar to those for the three airfoils of the present investigation and are included for convenience in making comparisons. Also contained in this figure are the results of the maximum-lift and minimum-drag check tests made for the NACA 0012 airfoil before the trailing edge was modified.

The basic results of the present investigation are presented in figures 3 to 5 as plots of section lift, drag, and pitching-moment characteristics. All the coefficients are based on the actual chord lengths of the airfoils. In many cases, the drag data plotted in figures 3 to 5 are values averaged from wake measurements made at several spanwise positions.

Since the models were not mounted in the tunnel on axes corresponding to the quarter-chord positions, the moments about the actual quarter-chord points were computed from the values measured about the pivot axis. The pitching-moment coefficients about the quarter-chord position and about the aerodynamic center are presented for the three airfoils in figures 3 to 5. The calculated aerodynamic-center positions based on the actual chords of the airfoils are also included in these figures.

All the results have been corrected for tunnel-wall and blocking effects in accordance with the procedure outlined in reference 1. As an indication of the magnitude of the corrections for the influence of the tunnel boundaries, the following equations, in which the primed symbols denote measured quantities, are given for airfoil A:

$$c_l = 0.982c_l'$$

$$c_d = 0.994c_d'$$

$$c_{m_p} = 0.994c_{m_p}'$$

$$\alpha_o = 1.012\alpha_o'$$

DISCUSSION

An analysis of the experimental data obtained has been made to show the effects on the more important aerodynamic characteristics of increasing the trailing-edge thickness by cutting off portions of the NACA 0012 airfoil section near the trailing edge. The aerodynamic characteristics considered are the section lift, drag, and pitching moment. To aid in this analysis, cross plots are used to show the variation of certain aerodynamic parameters with thickness of the airfoil trailing edge (fig. 6).

Lift.- The lift-curve slopes, which were measured over a range of lift coefficient in which they remained relatively constant (around zero lift), usually tended to increase as the trailing-edge thickness was increased (fig. 6).

Like those for the NACA 0012 section, the maximum-lift values for airfoils A and B in either surface condition are higher at a Reynolds number of 6.0×10^6 than at 3.0×10^6 (figs. 2 to 4). From a consideration of data given in figure 6, the maximum section lift coefficient can be seen to be somewhat lower for smooth airfoils A and B in comparison with the NACA 0012 section. For airfoil C, however, the maximum lift coefficient at a Reynolds number of 6.0×10^6 is about the same as that for the smooth NACA 0012 section. (All the data plotted in fig. 6 for the NACA 0012 section were derived from the results given in reference 3.)

A progressive increase in maximum section lift coefficient occurs for the sections with roughened leading edges as the trailing-edge thickness is increased.

Some of the effect of trailing-edge thickness on the maximum lift shown by the data of figure 6 may possibly be attributed to the fact that as the trailing-edge thickness is increased from 0.25 percent to 4.01 percent chord, the airfoil thickness ratio increases from 12.0 to 13.7 percent (fig. 1). The maximum-lift data of reference 2 for symmetrical NACA 4-digit-series airfoils in the smooth condition indicate that increasing the thickness ratio from 12 to 18 percent of the chord has no appreciable effect on the maximum lift. The fact that the maximum lift does not vary much for the smooth surface condition as the airfoil thickness is successively increased from 12.0 to 13.7 percent chord is, therefore, not surprising. The reason for the slight variations in the maximum lift of the modified airfoils, as compared with the NACA 0012 section, is not apparent. On the other hand, an extrapolation of the maximum-lift data of references 3 and 4 for symmetrical NACA 4-digit-series airfoils in the rough surface condition indicates that an increase in thickness ratio from 12.0 to 13.7 percent would give about the same increment in maximum lift as that shown (fig. 6) between the NACA 0012 section and airfoil C in the rough surface condition.

For a comparable Reynolds number and surface condition, the presence of rivet heads on airfoil A may be considered as having an unimportant effect on the section lift characteristics of this airfoil (figs. 3(a) and 3(b)).

Drag.- For airfoil A the drag polars given in figure 3(a) are, like those for the NACA 0012 section (fig. 2), of near-parabolic form for both the smooth and the rough surface conditions. For airfoil B in the smooth surface condition (fig. 4) and particularly for airfoil C in both the smooth and rough conditions (fig. 5), however, quite unfavorable rises in drag coefficient occur around zero lift. (This same trend may be noticed to a smaller degree for smooth airfoil A with rivet heads (fig. 3(b)) at a Reynolds number of 6.0×10^6 .) The exact character of the flow phenomena responsible for the peculiar shape of the drag polars of airfoils B and C is not completely understood. Presumably, with increasing angle of attack, the more favorable pressure distribution on the lower surface results in a thinner boundary layer and a more complete closing in of the lower-surface separation streamline toward the upper-surface separation streamline.

Figure 6 shows that the drag coefficient at zero lift for the airfoils in either surface condition progressively increases with increasing thickness of trailing edge. The magnitude of this increase is smaller for the airfoils in the rough condition, as compared with the increase for the smooth surface condition, when the trailing-edge thickness is

less than 1.4 percent chord, and is larger for the rough condition when the trailing-edge thickness is greater than about this value.

The drag coefficients corresponding to lift coefficients within the normal operating range progressively increase as more chord is removed (compare figs. 2 to 5) but, because of the previously mentioned unusual form of the drag polars near zero lift, the data contained in figure 6 do not give a complete picture of the effect of trailing-edge thickness on the drag at values of the lift coefficient other than zero. To show this effect more clearly, the variation of drag with lift at a Reynolds number of 6.0×10^6 for the airfoils having smooth surfaces is shown in figure 7. The drag curves for the smooth airfoils having trailing-edge thicknesses of 1.4 percent chord and less tend to converge at a lift coefficient of about 1.0; whereas the drag for the airfoil having a trailing-edge thickness of 4.0 percent chord remains appreciably higher at all values of lift coefficient. Since the values of the drag vary erratically with angle of attack, the drag should be compared in relation to the particular range of lift coefficient of the intended application.

Application of rivet heads near the trailing edge of airfoil A influences the section drag coefficient at zero lift to a small degree but does not seem to have a large effect on the general shape of the drag polars (figs. 3(a) and 3(b)).

Pitching moment and aerodynamic center.- The value of the quarter-chord pitching-moment coefficient corresponding to a zero angle of attack is virtually zero for all the airfoils in both surface conditions (figs. 2 to 5). For most lift coefficients, the pitching-moment coefficient about the aerodynamic center is essentially zero for each of the airfoil sections either in the smooth condition or with roughened leading edge (figs. 2 to 5). The position of the aerodynamic center, expressed in relation to the actual airfoil chord in figures 2 to 5, progressively moves rearward as successive cut-offs are made from the region of the trailing edge of the basic airfoil. Changes in Reynolds number and surface condition do not appear to have consistent effects on the variation of the aerodynamic-center position. Applying rivet heads to airfoil A results in minor, inconsistent changes in aerodynamic-center position.

CONCLUSIONS

From an investigation conducted at Reynolds numbers of 3.0×10^6 and 6.0×10^6 of the aerodynamic characteristics of three airfoil sections

formed by cutting 1.5, 4.0, and 12.5 percent of the original chord from the rear portion of the NACA 0012 airfoil, the following conclusions may be drawn:

1. As the trailing-edge thickness was increased by cutting off portions near the trailing edge, the maximum section lift coefficient varied by a relatively small amount for the smooth airfoil condition and progressively increased for the rough leading-edge condition.

2. The section drag coefficient over a large range of lift coefficient increased progressively as the trailing-edge thickness was increased by cutting off more of the chord. The magnitude of this increase, however, varied erratically with lift coefficient for the smooth airfoil having a trailing-edge thickness of 1.4 percent chord and particularly for both the smooth and rough conditions of the airfoil having a trailing-edge thickness of 4.0 percent chord.

3. The value of the quarter-chord pitching-moment coefficient at zero angle of attack remained virtually zero as the trailing-edge thickness increased, and the position of the aerodynamic center consistently moved rearward.

4. The application of rivet heads near the trailing edge of the airfoil formed by cutting off 1.5 percent of the original chord caused relatively minor changes in lift, drag, and pitching-moment characteristics.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Air Force Base, Va., February 7, 1950

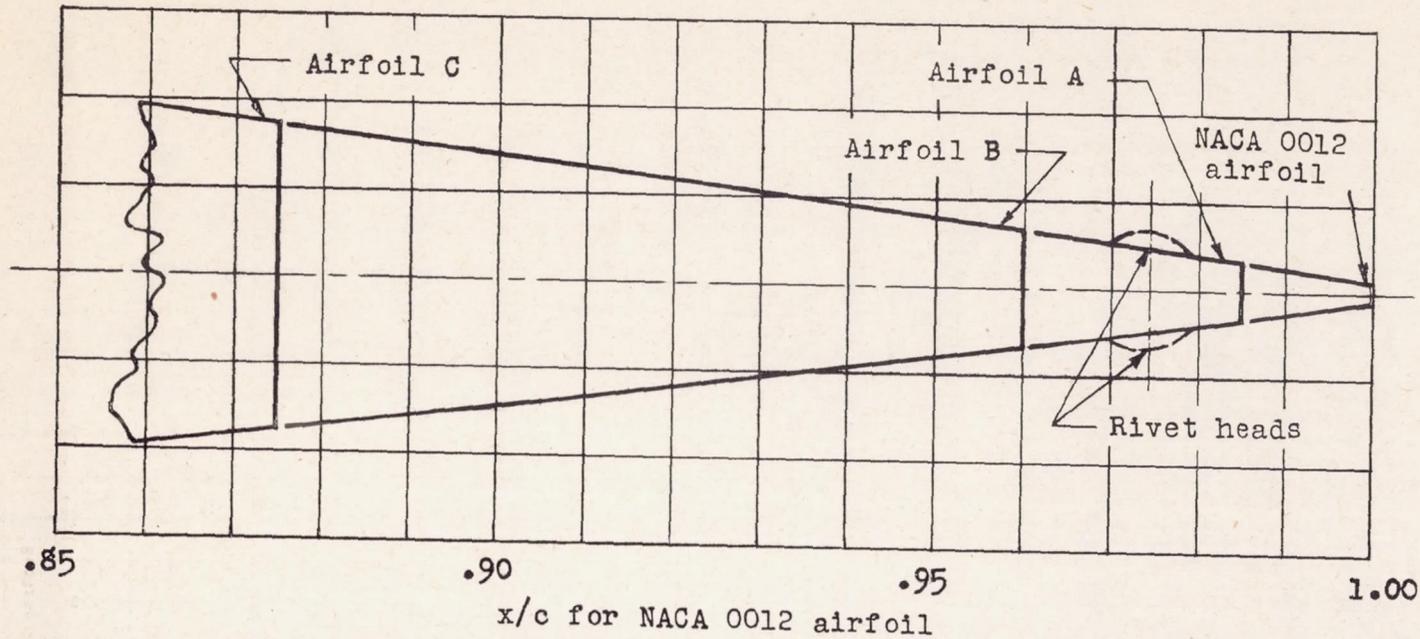
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1. Von Doenhoff, Albert E., and Abbott, Frank T., Jr.: The Langley Two-Dimensional Low-Turbulence Pressure Tunnel. NACA TN 1283, 1947.
2. Jacobs, Eastman N., Ward, Kenneth E., and Pinkerton, Robert M.: The Characteristics of 78 Related Airfoil Sections from Tests in the Variable-Density Wind Tunnel. NACA Rep. 460, 1933.
3. Loftin, Laurence K., Jr., and Smith, Hamilton A.: Aerodynamic Characteristics of 15 NACA Airfoil Sections at Seven Reynolds Numbers from 0.7×10^6 to 9.0×10^6 . NACA TN 1945, 1949.
4. Abbott, Ira H., Von Doenhoff, Albert E., and Stivers, Louis S., Jr.: Summary of Airfoil Data. NACA Rep. 824, 1945.

TABLE I
ORDINATES OF THE
NACA 0012 AIRFOIL SECTION

[Stations and ordinates given in
percent of airfoil chord]

Upper surface		Lower surface	
Station	Ordinate	Station	Ordinate
0	0	0	0
1.25	1.894	1.25	-1.894
2.5	2.615	2.5	-2.615
5.0	3.555	5.0	-3.555
7.5	4.200	7.5	-4.200
10	4.683	10	-4.683
15	5.345	15	-5.345
20	5.738	20	-5.738
25	5.941	25	-5.941
30	6.002	30	-6.002
40	5.803	40	-5.803
50	5.294	50	-5.294
60	4.563	60	-4.563
70	3.664	70	-3.664
80	2.623	80	-2.623
(87.5)	(1.755)	(87.5)	(-1.755)
90	1.448	90	-1.448
95	.807	95	-.807
(96)	(.674)	(96)	(-.674)
(98.5)	(.335)	(98.5)	(-.335)
100	.126	100	-.126
L.E. radius: 1.58			



Geometric characteristic Airfoil	Percent of chord removed from NACA 0012 airfoil	Actual chord of model, in.	Trailing-edge thickness, percent of actual chord	Airfoil maximum thickness, percent of actual chord
NACA 0012	---	24.0	0.25	12.0
A	1.5	23.6	.68	12.2
B	4.0	23.0	1.40	12.5
C	12.5	21.0	4.01	13.7

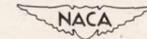


Figure 1.- Geometry of airfoil sections obtained by cutting off portions near trailing edge of NACA 0012 airfoil section.

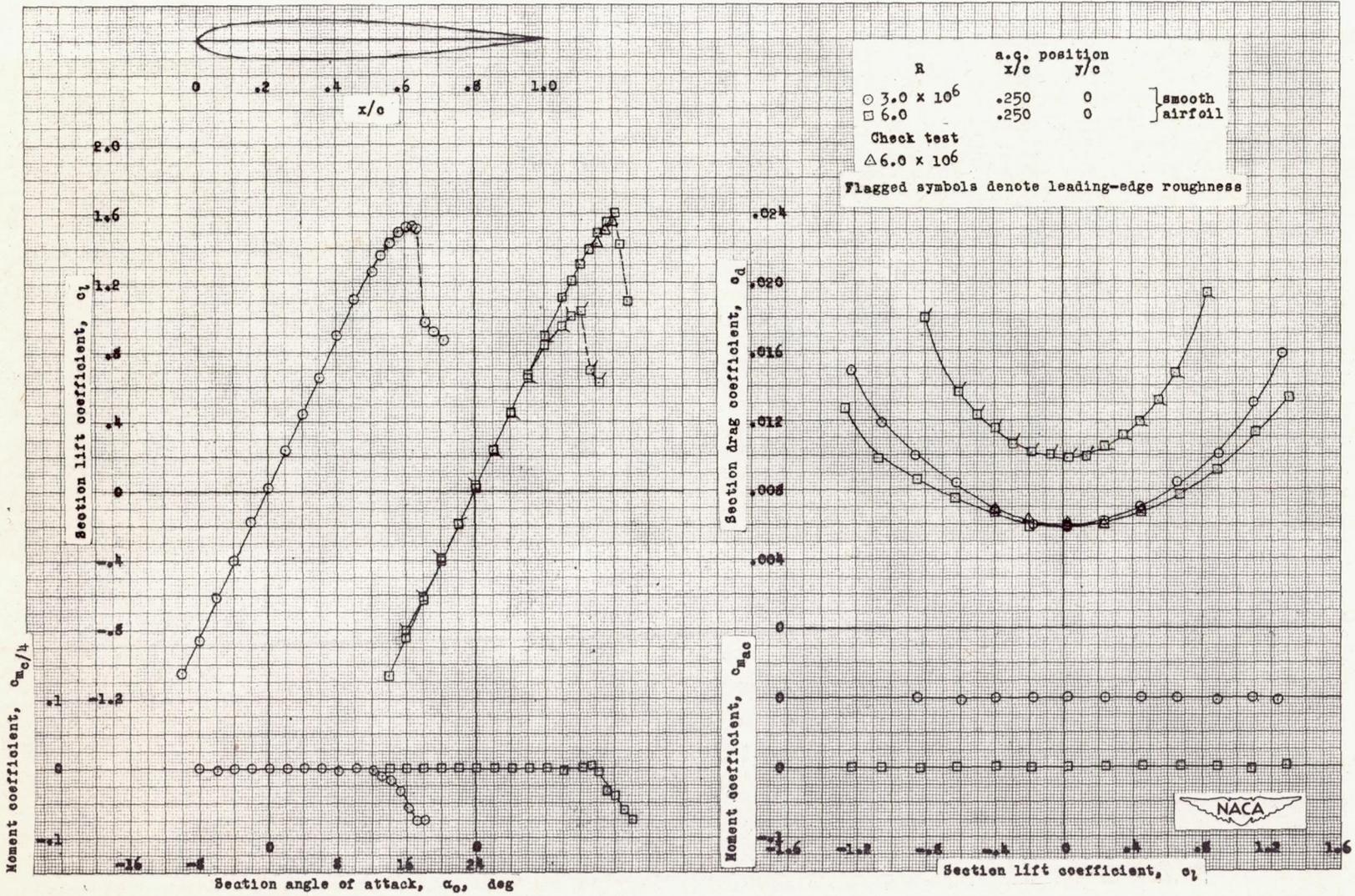
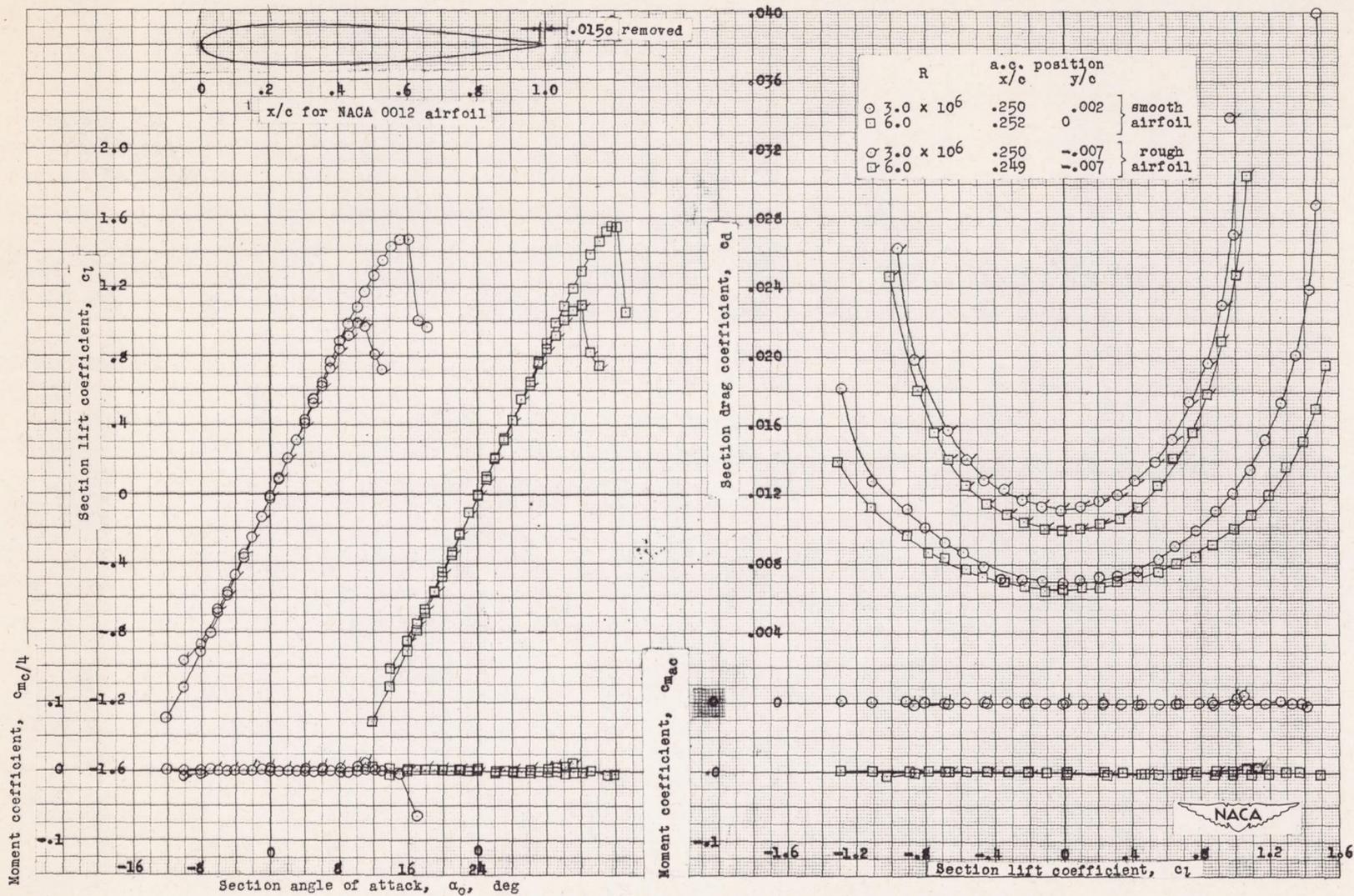
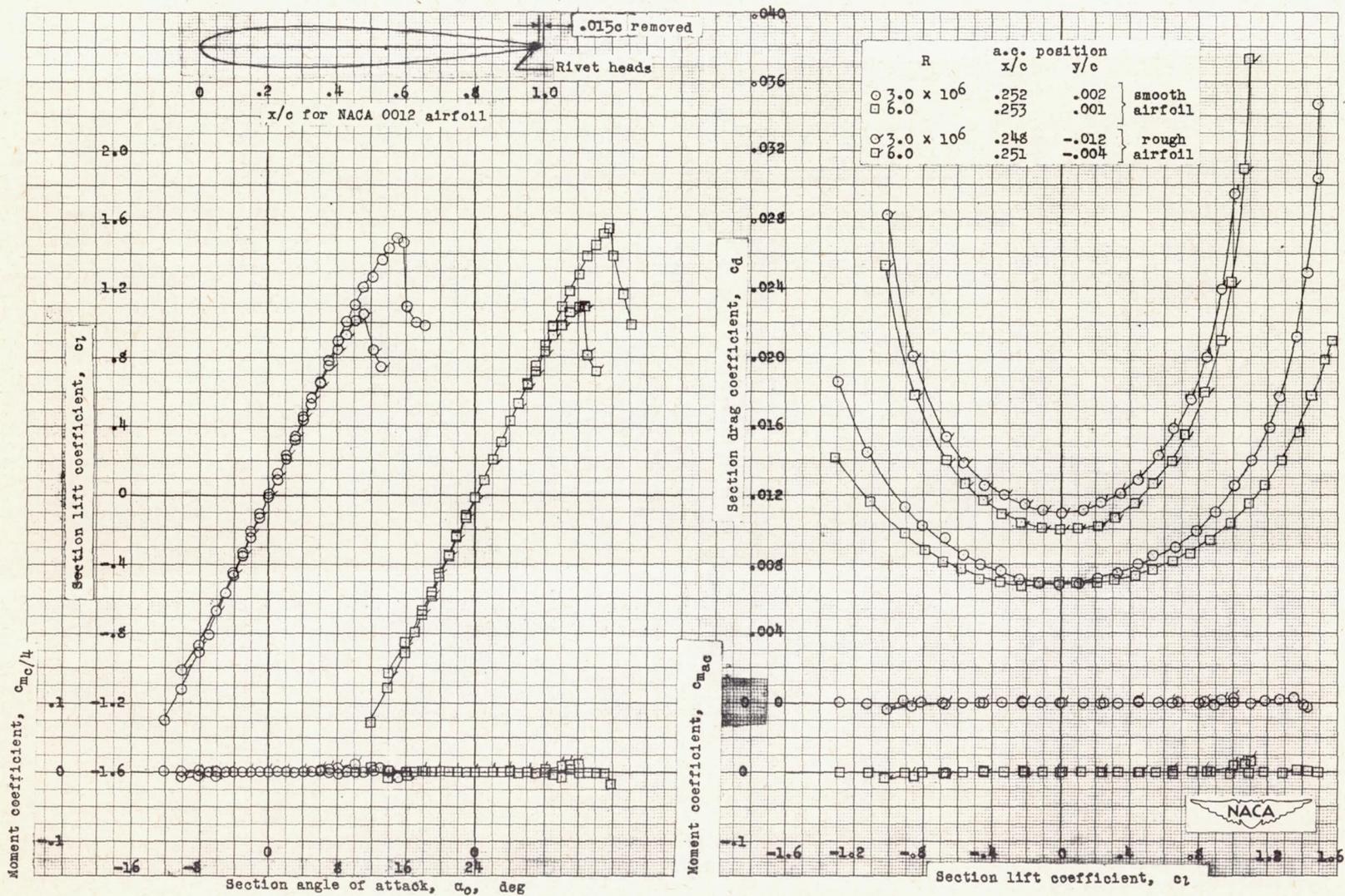


Figure 2.- Section lift, drag, and pitching-moment characteristics of NACA 0012 airfoil section (from reference 3).



(a) Plain airfoil.

Figure 3.- Section lift, drag, and pitching-moment characteristics of airfoil A.



(b) Airfoil with rivet heads near the trailing edge.

Figure 3.- Concluded.

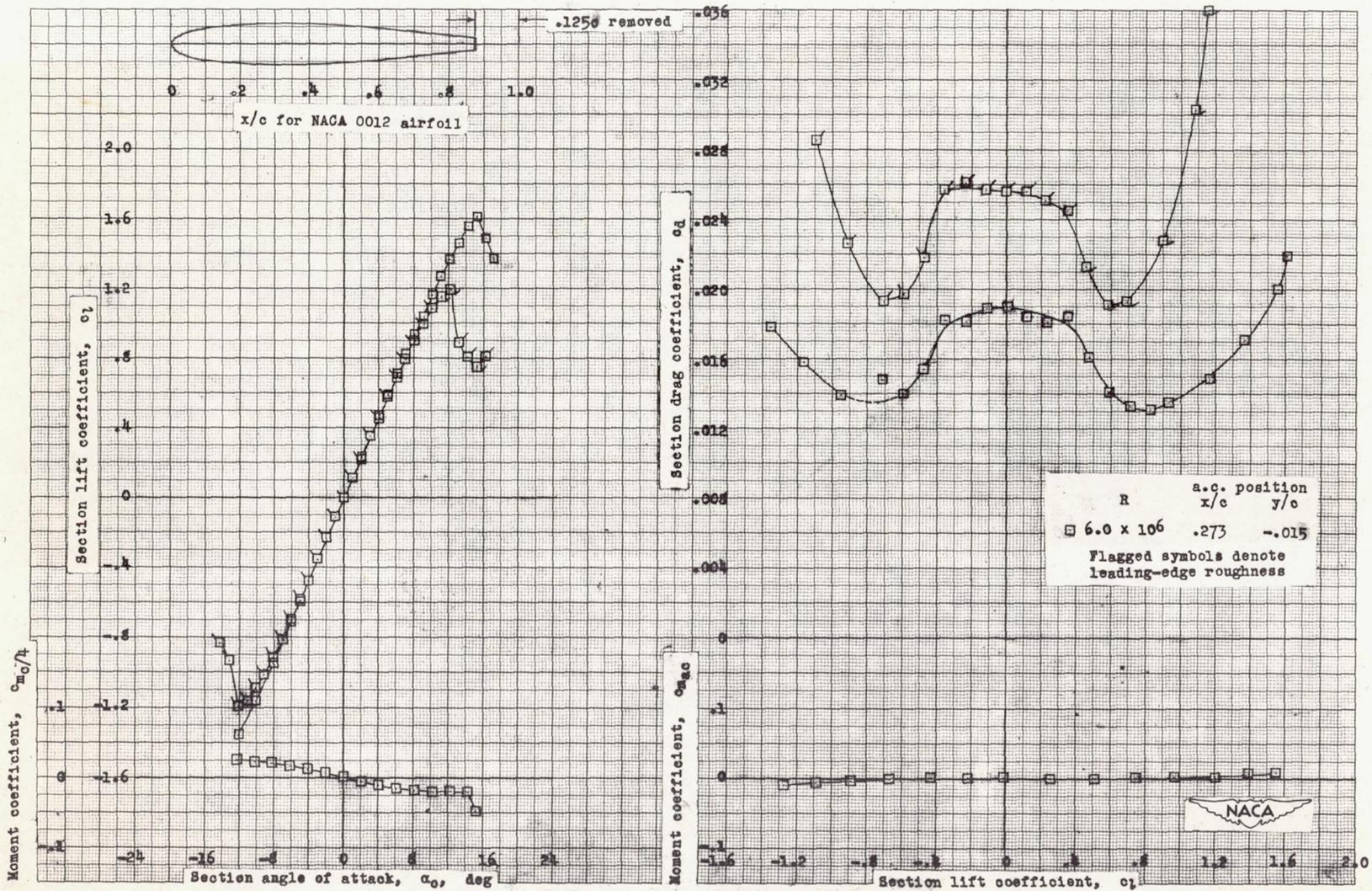


Figure 5.- Section lift, drag, and pitching-moment characteristics of airfoil C.

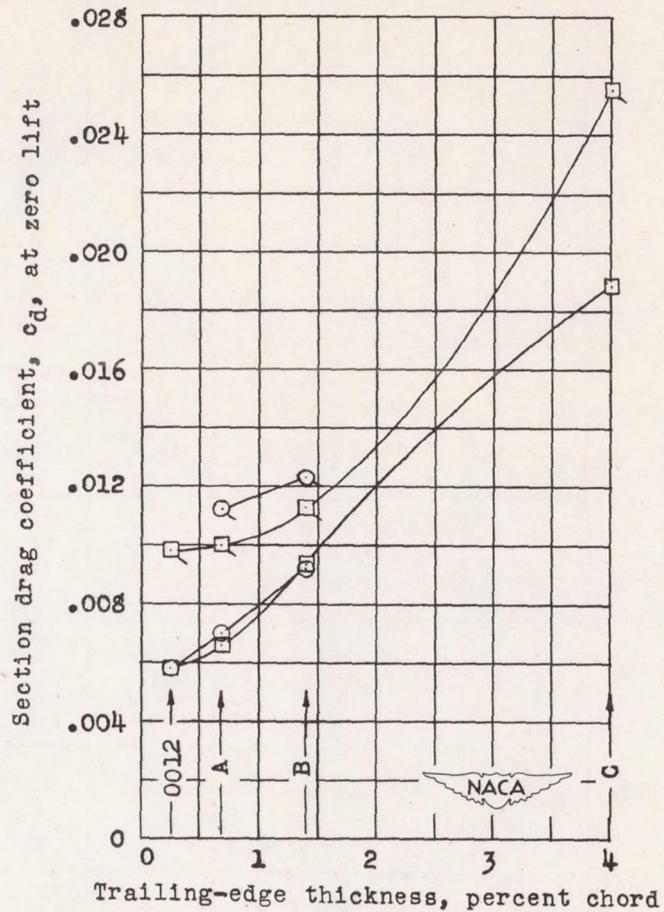
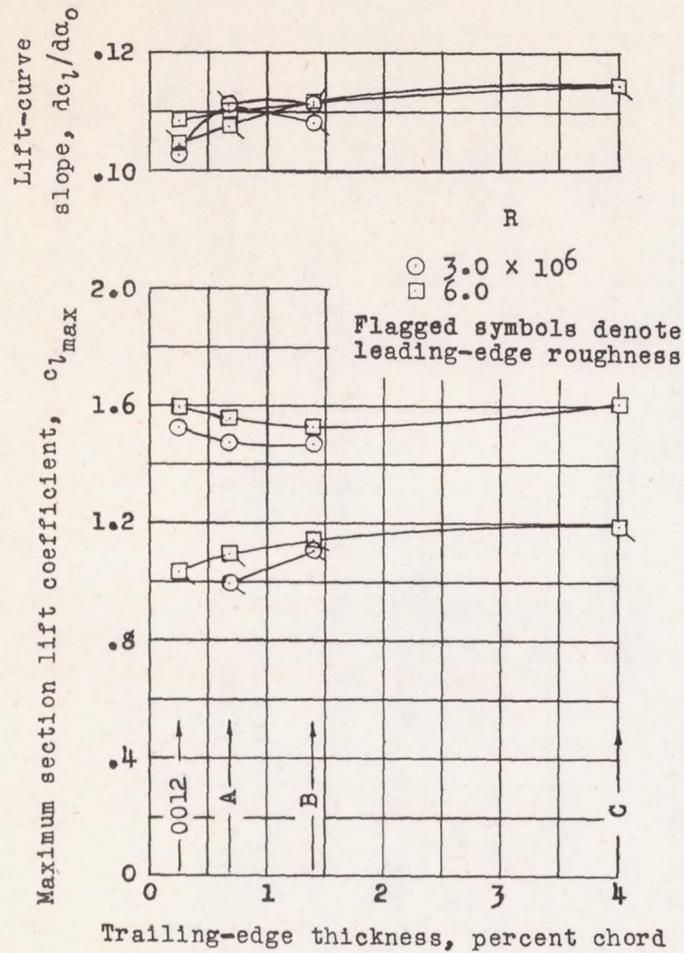


Figure 6.- Variation of slope of section lift curve, maximum section lift coefficient, and section drag coefficient at zero lift for NACA 0012 airfoil section and three airfoils of various trailing-edge thicknesses.

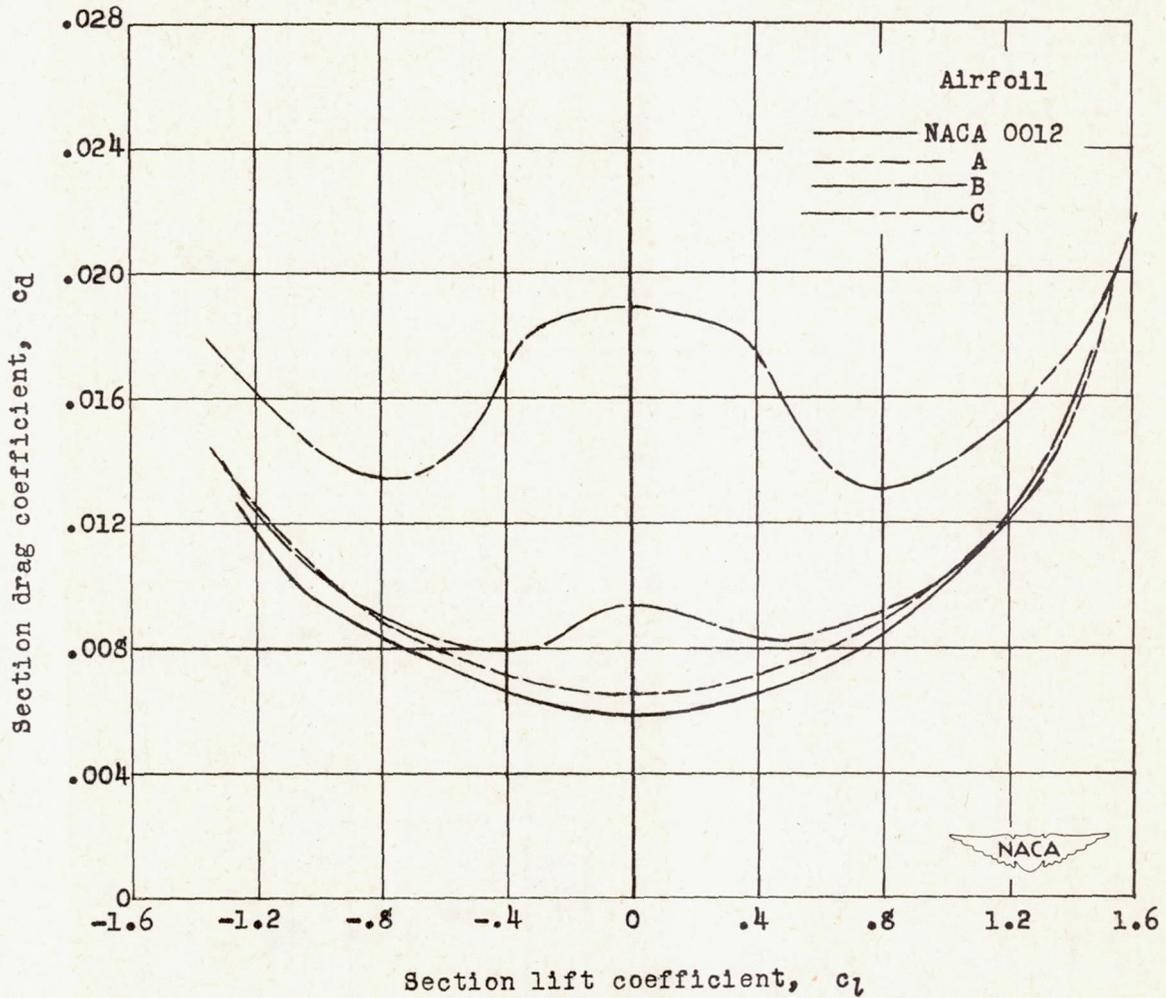


Figure 7.- Section drag characteristics of NACA 0012 airfoil and airfoils A, B, and C in smooth surface condition. $R, 6.0 \times 10^6$.