NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3241

AIRFOIL SECTION CHARACTERISTICS AT HIGH ANGLES OF ATTACK

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Washington
August 1954

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SUMMARY

Information from the literature and from recent investigations is used herein to summarize briefly the effects of airfoil section parameters and flow variables on the aerodynamic characteristics of two-dimensional symmetrical airfoils at high angles of attack. The results presented indicate that airfoil thickness ratio, Reynolds number, Mach number, and surface roughness can all have an important effect on the maximum lift coefficient. The effect of surface roughness seems to be particularly important. Not only can surface roughness cause large decreases in maximum lift coefficient, but also the magnitudes of the effects of Reynolds number, Mach number, and airfoil thickness ratio are much reduced by surface roughness. Beyond the stall, changes in section thickness ratio appear to have little effect on the aerodynamic characteristics of airfoil sections. An investigation of one section through an angle-of-attack range of from 0° to 360° shows that the drag coefficient reaches a value of 2 at an angle of attack of 90°.

INTRODUCTION

The present paper is concerned with certain aspects of the behavior of airfoil sections at high angles of attack with particular emphasis on the needs of the helicopter designer. The state of our knowledge of the effects of several airfoil design parameters and flow variables on the maximum lift coefficient will be summarized first. This summary will be limited to symmetrical airfoils operating in the range of Mach number below 0.4 and is based on information which has been in the literature for a number of years (refs. 1 to 4). Some of the trends shown by recent investigations of the lift, drag, and pitching-moment characteristics of airfoil sections in the angle-of-attack range well beyond the stall will then be presented. The investigations leading to these results were made in response to a need of the designer for airfoil characteristics corresponding to conditions on the retreating blade of a high-speed helicopter and are only partially reported at the present time (ref. 5).

SYMBOLS

c	airfoil chord
c_d	section drag coefficient
c_l	section lift coefficient
$c_{l_{MAX}}$	maximum section lift coefficient
M	Mach number
R	Reynolds number
t	maximum thickness of airfoil section
x_{CP}	center-of-pressure position, percent c
α	angle of attack, deg

RESULTS AND DISCUSSION

The nature of the effects of airfoil thickness, leading-edge surface condition, and Reynolds number on the maximum lift coefficient is shown in figure 1 for a Mach number of about 0.15. The maximum lift coefficient is plotted on the ordinate and the airfoil thickness is on the abscissa. The curves shown are based on results contained in references 1 to 3 for NACA 63-series and 64-series thickness forms. These particular thickness forms were chosen for discussion because their characteristics are thought to represent a good compromise between various desirable qualities at both high and low speeds. The trends in figure 1, however, may be considered typical of other symmetrical thickness forms having reasonably large leading-edge radii, such as, for example, thickness forms of the NACA 4-digit-series family. The solid lines are for airfoils with smooth surfaces and the dotted lines are for airfoils with roughened leading edges. The smooth condition referred to here is one in which the contour of the model is held very close to the specified ordinates and the surface is kept completely free of all dust, dirt, lint, paint blisters, and other disturbances which can be felt or seen. The rough surface condition is one in which the leading edge of the 24-inch-chord model is covered with 0.011-inch-diameter carborundum grains. The two surface conditions are thought to represent about the best and the worst that could be obtained in practice.

The trend of maximum lift with thickness shown in figure 1 for smooth sections at a Reynolds number of 6.0×10^6 is characterized by a large increase in maximum lift coefficient with airfoil thickness in the range of thickness between 6 and 12 percent. A gradual decrease in maximum lift is noted as the thickness is increased to 18 percent. Somewhat the same trend is evidenced by the results at a Reynolds number of 20×10^6 except for the continued increase in maximum lift as the thickness is increased to 18 percent. A very large reduction in the maximum lift of most of the airfoils is noted as the Reynolds number is reduced from 6.0×10^6 to 1.0×10^6, with the result that increases in airfoil thickness have a very much reduced effect on the maximum lift coefficient at a Reynolds number of 1.0×10^6 in comparison with 6.0×10^6. The trends shown for Reynolds numbers of 1.0×10^6 and 20.0×10^6 may be thought of as limits, in that variations in Reynolds number outside of this range would be expected to have only a small effect on the maximum lift coefficient. The results for a Reynolds number of 6.0×10^6 indicate that, for airfoils in the thickness range between 9 and 15 percent, the major portion of the scale effect takes place between Reynolds numbers of 1.0×10^6 and 6.0×10^6; whereas, for airfoils outside this range of thickness, variations in Reynolds number above 6.0×10^6 cause increases in maximum lift which may be significant. In any case, the exact shape of the curve of maximum lift coefficient against Reynolds number varies with airfoil section design. Fortunately, however, sufficient airfoil section data are available so that, by proper interpolation and comparison, a reasonable estimate can be made of the maximum lift coefficient corresponding to some particular Reynolds number.

A comparison of the data at a Reynolds number of 6.0×10^6 for the airfoils with rough and smooth surfaces indicates that leading-edge roughness can cause a very large reduction in maximum lift. The magnitude of the effect is greatest for thickness ratios of the order of 12 percent of the chord, is somewhat reduced for the larger thickness ratios, and is negligible for a thickness ratio of 6 percent of the chord. As a result, increasing thickness is relatively much less powerful as a means of increasing the maximum lift of airfoils in the rough surface condition than in the smooth surface condition. Leading-edge roughness is seen to have only a small effect on maximum lift for a Reynolds number of 1.0×10^6. This small effect would be expected since the values of the maximum lift coefficient for the smooth condition at this Reynolds number are approaching the flat-plate value. Comparison of the results for Reynolds numbers of 1.0×10^6 and 6.0×10^6 indicates that the scale effect is relatively small for airfoils in the rough surface condition. This is also the case for Reynolds numbers higher than 6.0×10^6 as is shown by results in reference 3 for a 9-percent-thick section for which

increasing the Reynolds number from 6.0×10^6 to 25.0×10^6 caused no change in the maximum lift coefficient for the rough surface condition.

Some indication of the effect of small increases in Mach number on the maximum lift coefficient can be obtained from data in reference 4 presented here in figure 2. The maximum lift coefficient is plotted against Mach number for Mach numbers from 0.1 to 0.4 and for a constant Reynolds number of 6.0×10^6. The airfoils are of 6-, 10-, and 15-percent thickness. The 10- and 15-percent-thick sections have approximately 1 percent camber whereas the 6-percent-thick section is symmetrical. Direct comparisons of the maximum lift coefficients of the 6-percent-thick section with those of the 10- and 15-percent-thick sections should not, therefore, be made. The results shown in this figure indicate rather large reductions in the maximum lift of smooth sections to accompany increases in Mach number from 0.1 to 0.4, at least for the 10- and 15-percent-thick sections. The Mach number has no effect on the maximum lift of the 6-percent-thick section except for the small rise at Mach number 0.2. In the rough surface condition, the Mach number has been found to have little effect on the maximum lift coefficient.

The trends shown in figures 1 and 2 indicate that airfoil thickness, Reynolds number, Mach number, and surface roughness can all have an important effect on the maximum lift coefficient. The effect of surface roughness seems to be particularly important. Not only can surface roughness cause large decreases in maximum lift coefficient, but also the magnitudes of the effects of Reynolds number, Mach number, and airfoil thickness ratio are much reduced by surface roughness. Thus, in a sense, severe surface roughness may tend to simplify airfoil selection problems. In view of the magnitude of the effect of surface condition, a means for estimating the nature of the surface condition of a rotor blade in relation to the smooth and rough leading-edge conditions employed in wind-tunnel investigations seems particularly important. Since this problem involves not only methods of blade construction and fabrication, but also the extent to which bugs and dirt have accumulated on the leading edge, general rules are difficult to formulate. It seems significant, however, that investigations of several rotors on the Langley helicopter test tower have yielded results which could be reproduced by calculations employing airfoil section maximum lift coefficients corresponding to the rough leading-edge condition.

With this brief summary of the maximum-lift problem, some of the trends shown by the more recent results obtained on airfoils at high angles of attack will be discussed. Six symmetrical airfoils of the NACA 64-series family were investigated through an angle-of-attack range extending from 0° to 30°. The airfoil thickness varied from 6 to 18 percent of the chord. In addition, an NACA 0012 section was tested. Although measurements were made at several subsonic Mach numbers, the trends to be

shown are for a Mach number of 0.5 and may be considered typical of all the results obtained.

The lift characteristics of the seven airfoils are shown in figure 3 in which the lift coefficient is plotted against angle of attack. The data are for a Reynolds number of 1.3×10^6 and a smooth surface condition. After the first peak in the lift coefficient, which is usually defined as the maximum lift coefficient, all the airfoils are characterized by a drop in lift after which the lift again increases with angle of attack. The important trend indicated by these results is that, after an angle of attack of about 14° to 16°, the lift characteristics of all the airfoils tend to look very much alike. Although some differences are seen in the curves for the various airfoils, these differences are not thought to be particularly important because of the relatively small values of the dynamic pressure which exist in the vicinity of the retreating blade on a helicopter. As would be expected on the basis of the results shown in figures 1 and 2, the maximum amount of the difference in maximum lift shown by all of the airfoils is only about 0.2. At higher Reynolds numbers and lower Mach numbers, the differences in the maximum lift coefficients of the airfoils would, of course, become larger. Beyond the stall, however, it is thought that the curves shown here can be interpreted in terms of lift results at higher Reynolds numbers. For example, if the maximum lift coefficient were 1.4 and this lift coefficient occurred at an angle of attack of 15°, the data shown in figure 3 would be expected to correspond to those at the higher Reynolds number for angles of attack above 18° or 19°. The addition of leading-edge roughness was found to have little effect on the lift characteristics of the airfoils beyond the stall.

The chordwise position of the center of pressure is shown plotted against angle of attack for the seven airfoils in figure 4. The center of pressure is seen to shift from about the 25-percent-chord station to about the 43-percent-chord station as the airfoil passes from the unstalled to the stalled condition. The angle of attack at which this transition begins varies with the airfoil section; however, beyond the stall, there appears to be little effect of airfoil section thickness on the position of the center of pressure, nor does the center of pressure shift very much with angle of attack.

The section drag coefficient is plotted against angle of attack in figure 5 for the seven airfoil sections. Again the obvious conclusion is that variations in airfoil thickness have little effect on the drag beyond the stall.

Relatively large portions of the retreating blade on a high-speed helicopter may be operating at angles of attack in the range between 0°

and 180°. In order to provide some indication of the characteristics of an airfoil section through such an angle-of-attack range, the NACA 0012 section has been tested through an angle-of-attack range extending from 0° to 360°. The Reynolds number of these tests was about 2.0×10^6 and the Mach number was no greater than 0.15. The lift and drag characteristics obtained are plotted against angle of attack in figure 6. The high value of the drag at an angle of attack of 90° is to be noted. This value of 2.0 checks the value of 2.0 given by Wieselsberger in reference 6 for a two-dimensional flat plate perpendicular to the wind. These same German results show a marked effect of aspect ratio on the drag at an angle of attack of 90°. For example, the drag coefficient of an aspect-ratio-20 flat plate is shown to be about 1.48 in comparison with the two-dimensional value of 2.0. This result emphasized a basic question as to how two-dimensional data should be applied to a rotating wing for those cases in which the flow over one surface is characterized by extensive regions of separation. Unfortunately, little information dealing with this problem is available at present.

CONCLUDING REMARKS

The results presented indicate that airfoil thickness ratio, Reynolds number, Mach number, and surface roughness can all have an important effect on the maximum lift coefficient. The effect of surface roughness seems to be particularly important. Not only can surface roughness cause large decreases in maximum lift coefficient, but also the magnitudes of the effects of Reynolds number, Mach number, and airfoil thickness ratio are much reduced by surface roughness. Beyond the stall, changes in section thickness ratio appear to have little effect on the aerodynamic characteristics of the airfoil sections. The high value of the drag coefficient obtained with an airfoil section at an angle of attack of 90° is in agreement with the value of 2 given in the literature for an infinite flat plate inclined normal to the flow; the marked effect of aspect ratio on the drag at an angle of attack of 90° emphasizes the question as to how two-dimensional data should be applied to a rotating wing on which extensive regions of separation are present.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., June 11, 1954.

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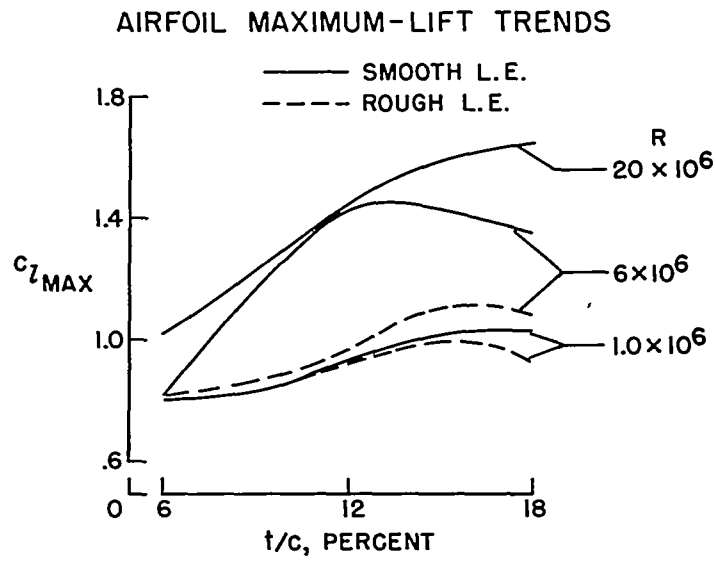

Figure 1

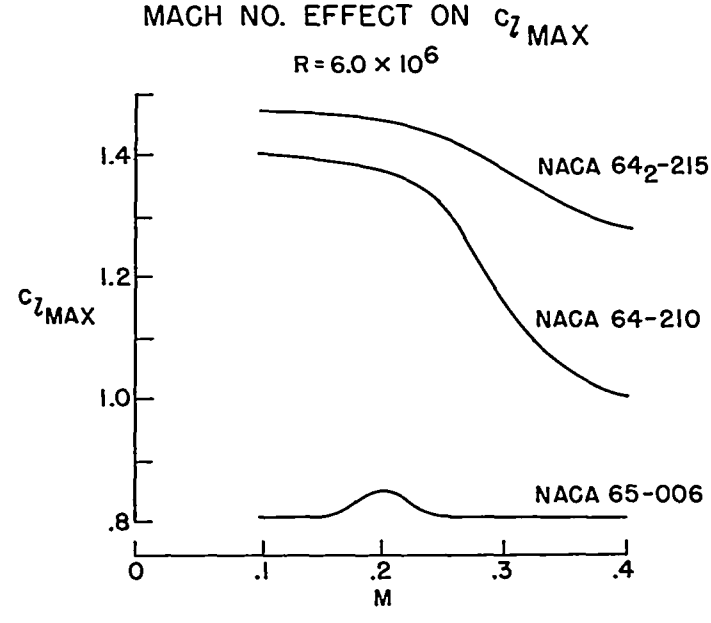

Figure 2

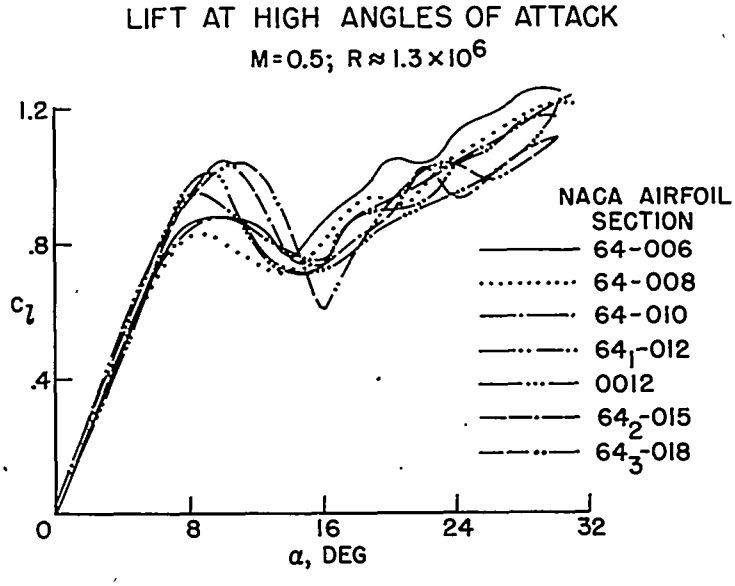

Figure 3

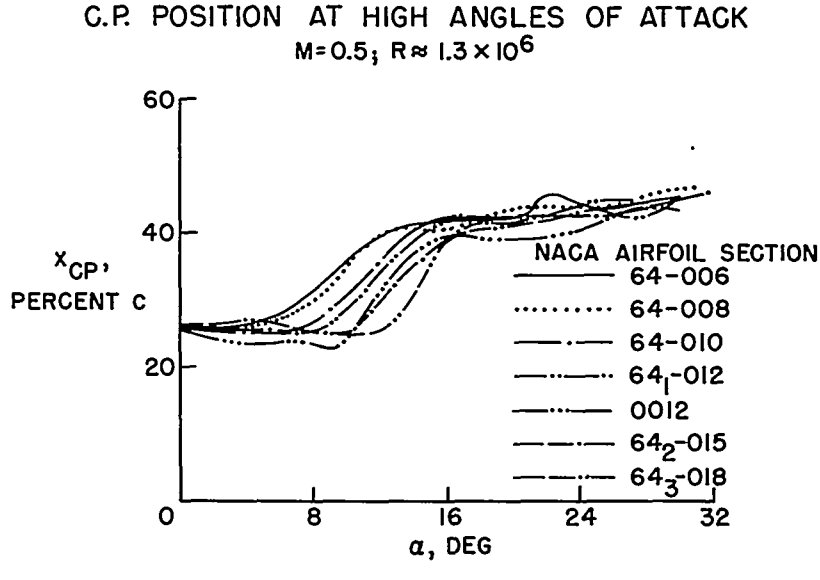

Figure 4

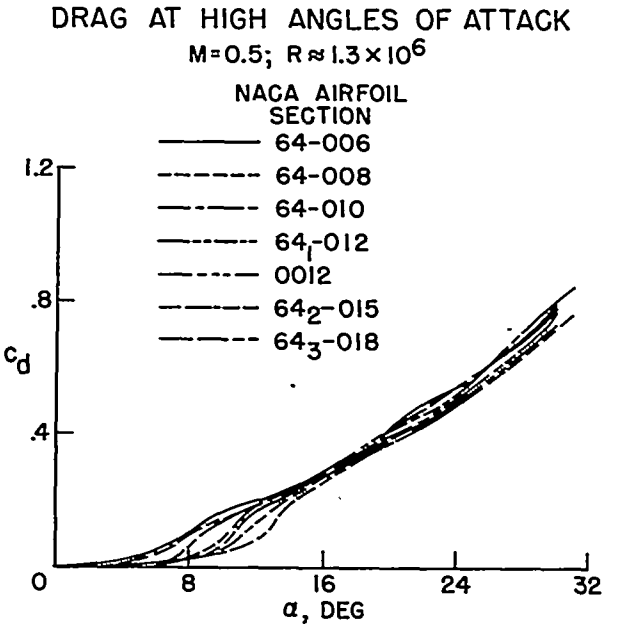

Figure 5

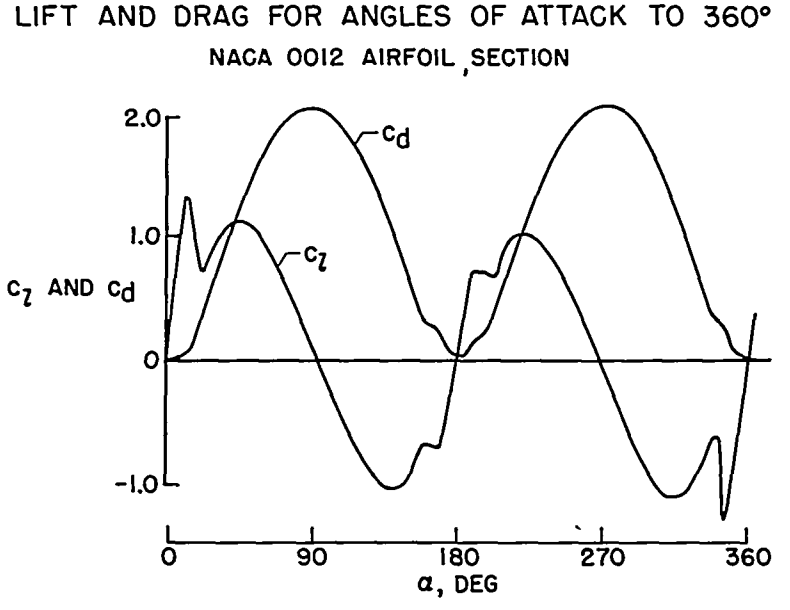

Figure 6

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