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**TECHNICAL NOTE 2591**

## THE EFFECTS OF REYNOLDS NUMBER ON THE APPLICATION OF NACA 16-SERIES AIRFOIL CHARACTERISTICS TO PROPELLER DESIGN

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# THE EFFECTS OF REYNOLDS NUMBER ON THE APPLICATION OF NACA 16-SERIES AIRFOIL CHARACTERISTICS TO PROPELLER DESIGN[1]

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## SUMMARY

An analysis has been made of airfoil data taken on several NACA 16-series propeller airfoils from tests of 5-inch-chord models in the Langley 24-inch high-speed tunnel and 12-inch-chord models in the Langley 8-foot high-speed tunnel.

This analysis has shown that the combined effects of Reynolds number changes and variations in airfoil characteristics resulting from differences in models and tunnels are such that, when 5-inch-chord and 12-inch-chord data are applied to full-scale propeller design at or near the design condition, differences of less than 1 percent in efficiency are involved.

## INTRODUCTION

The design of present-day propellers is usually based upon data obtained under conditions of scale which differ from those of operation. These propellers are made up to a great degree of high-speed airfoil sections for which data are obtained from tests of models of 2- to 5-inch chord. In addition, most of the tests of model propellers using NACA 16-series airfoil sections have been conducted on blades of this same width. The question therefore has arisen as to the validity of applying these test data directly to larger scale designs.

In order to provide at least a qualitative answer to these questions, an analysis has been made of some data available on several NACA 16-series airfoils of both 5- and 12-inch chord. A comparison of data from 5- and 12-inch-chord airfoils has additional significance because a 12-inch chord is representative of blade widths commonly used on full-scale propellers.

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[1]Supersedes the recently declassified NACA RM L7H12, "The Effects of Reynolds Number on the Application of NACA 16-Series Airfoil Characteristics to Propeller Design" by Harold E. Cleary, 1947.

## SYMBOLS

| | |
|---|---|
| $M$ | Mach number |
| $R$ | Reynolds number |
| $\alpha$ | angle of attack, degrees |
| $c_l$ | section lift coefficient |
| $c_{m_{c/4}}$ | section quarter-chord pitching-moment coefficient |
| $dc_l/d\alpha$ | lift-curve slope |
| $c_d$ | section drag coefficient |
| $\phi_o = \tan^{-1} \frac{V}{nD\pi x}$ | |
| $V$ | forward velocity |
| $n$ | rotational speed |
| $D$ | propeller diameter |
| $x$ | radius ratio |
| $\phi = \phi_o + \alpha_i$ | |
| $\alpha_i$ | induced angle of attack |
| $\gamma = \tan^{-1} \frac{c_d}{c_l}$ | |
| $\eta'$ | elemental propeller efficiency |

## APPARATUS AND METHODS

The tests were made in the Langley 8-foot high-speed tunnel and in the Langley 24-inch high-speed tunnel. At the time of these tests the Langley 8-foot high-speed tunnel was a closed-throat single-return tunnel and the speed was continuously controllable up to a Mach number of approximately 0.70. The Langley 24-inch high-speed tunnel was a nonreturn

induction type of tunnel with the speed continuously controllable to a Mach number of approximately 0.80 for a 5-inch, 15-percent-thick airfoil. Both tunnels have degrees of turbulence which are small though slightly higher than that of free air. In both tunnels the models completely spanned the jet; thus, the results are essentially two-dimensional.

The chord of the models tested in the Langley 8-foot high-speed tunnel was 12 inches; that of the models tested in the Langley 24-inch high-speed tunnel was 5 inches. The airfoils tested were the following NACA 16-series sections: 16-209, 16-215, 16-509, 16-515, 16-709, and 16-715, that is, sections having thickness ratios of 0.09 and 0.15 and design lift coefficients of 0.2, 0.5, and 0.7.

The data obtained were lift, drag, and pitching moment. The data on the 5-inch-chord airfoils were obtained by means of force measurements in the Langley 24-inch tunnel. In the 8-foot tunnel, for the 12-inch-chord airfoils the lift and moment data were obtained from pressure-distribution measurements and the drag data were obtained by means of wake surveys. The average variation of Reynolds number with Mach number for the airfoils as tested is shown in figure 1.

## RESULTS AND DISCUSSION

The changes which occur in airfoil characteristics such as drag and maximum lift coefficient with changes in the value of Reynolds number are directly connected with the action of the boundary layer on the flow over the airfoil. A discussion of the mechanics of these flow changes is contained in reference 1.

The variations of lift coefficient with angle of attack for the airfoils tested are compared in figure 2. Because the tests were made with different-size models of the same airfoil sections and the models were tested in different tunnels, variations in the data are to be expected as a result of individual model irregularities, failure to duplicate model alinement exactly, and slightly different wall effects. For these reasons, only the shape and character of the curves in figure 2 should be compared.

The most noticeable effects of difference in Reynolds number are slight changes in lift-curve slope and differences in the character of the break in the lift curve corresponding to the end of the low-drag region. These effects are more marked for the thicker airfoils.

The variation with Mach number of the lift-curve slope, taken in the design lift range, for the airfoils of different size is presented

in figure 3. The differences in slope are generally small although marked differences occur for the NACA 16-209 and 16-715 airfoils above a Mach number of 0.60.

If the moment coefficients of two airfoils are compared at a given value of lift coefficient, an indication of differences in load distribution is obtained. When this procedure is applied to data for two geometrically similar airfoils tested under different conditions of scale, an indication of fundamental-flow changes is obtained. The variation of pitching-moment coefficient with lift coefficient for several airfoils is therefore presented in figure 4. Analysis of these data indicates that the fundamental-flow changes, which may be due to scale effects or model irregularities, are small. The most noticeable differences occur at lift coefficients corresponding to the end of the region of low drag. These differences indicate that the lift coefficient at which transition occurs decreases as the Reynolds number is increased, as has been pointed out in reference 1. This effect is apparent for the thicker airfoils. The differences between the data for the 5- and 12-inch NACA 16-509 and 16-515 airfoils suggest individual model irregularities.

Because boundary-layer changes are involved, it is to be expected that with changes in Reynolds number the drag characteristics will be affected to a greater degree than the lift and moment characteristics. The variations of drag coefficient with lift coefficient for four airfoils, the NACA 16-209, 16-215, 16-709, and 16-715, at two values of Mach number are shown in figure 5.

In figure 6, curves of the variations of skin-friction drag coefficient with Reynolds number for a flat plate are presented. These curves are based on the laminar and turbulent laws for skin-friction drag (reference 2) and show how the drag coefficient decreases as the Reynolds number is increased. For the combined drag coefficient of both surfaces, the laminar law is

$$c_d = \frac{2.654}{\sqrt{R}}$$

and the turbulent law is

$$c_d = \frac{0.148}{R^{1/5}}$$

The points plotted in figure 6 are the values of minimum drag coefficient taken from figure 5. These data are generally within the limits of the laminar and turbulent curves. Reference 1 shows that rough

airfoil surfaces give drag coefficients well above the turbulent skin-friction curve. The relative position of the data for a given airfoil between the laminar and turbulent curves depends on scale effects and factors such as pressure gradients and surface roughness which affect boundary-layer transition.

Included in figure 6 is the variation of minimum drag coefficient for the NACA 16-209 airfoil as reported in reference 3. These data were obtained in one tunnel under conditions of low turbulence. The similarity between the trends of the drag variation with Reynolds number shown by the data taken from reference 3 and those reported herein indicates that the rather large difference in the drag as obtained in the Langley 8-foot high-speed tunnel and the Langley 24-inch high-speed tunnel is actually a scale effect and is not caused by differences in tunnel test techniques or model surface condition.

The differences in slope of the variation of drag coefficient with Reynolds number for the 5-inch-chord airfoils as compared with the NACA 16-209 data from reference 3 are ascribed to compressibility effects which result in the steepening of the pressure-recovery gradients over the airfoils. These effects are expected to be more pronounced for thick airfoils as is illustrated by the relatively slight variation of drag coefficient with Reynolds number for the NACA 16-215 and 16-715 airfoils. The adverse effects of increased recovery gradients in critical Reynolds number ranges are further illustrated by the increases in value of drag coefficient as the thickness and camber are increased.

In considering the application of these data to propeller design, it should be pointed out that changes in drag coefficient of the order of those found in figure 6 will have only a small effect on propeller performance at design conditions because at these conditions the lift-drag ratio is high and, since the elemental efficiency (see, for example, reference 4) is

$$\eta' = \frac{\tan \phi_o}{\tan (\phi + \gamma)}$$

the changes in efficiency will be of small order.

Wind-tunnel models are carefully prepared and maintained; whereas in actual operation manufacturing irregularities and surface roughness will probably produce values of drag coefficient closer to those obtained on the 5-inch-chord models. Therefore, although the 5-inch-chord data do not represent true conditions of scale, they may be safely used to estimate propeller performance. For example, the differences in efficiency computed by the relation just given based upon the differences in drag coefficient for the 5- and 12-inch-chord airfoils will be of the

order of 0.6 percent if it is assumed that for a typical propeller the representative sections over the important area of the blade have thickness ratios of 0.09 or less and are cambered to give a design lift coefficient of 0.5. This difference of efficiency will hold for a range of lift coefficient ±0.1 from design at values of Mach number up to 0.50. If thicker or lower cambered sections are used or if the blade is operated away from the design condition, differences greater than 1 percent may be expected. If, however, operational drag coefficients are higher than those presented for the 12-inch-chord airfoils, the differences in efficiency will be smaller. Moreover, use of the 5-inch-chord data gives a more conservative estimate of efficiency.

## CONCLUSION

Differences of less than 1 percent in propeller efficiency at or near the design condition will be involved in applying data from 5-inch-chord and 12-inch-chord airfoil tests to full-scale propeller design.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., August 21, 1947

## REFERENCES

1. Abbott, Ira H., Von Doenhoff, Albert E., and Stivers, Louis S., Jr.: Summary of Airfoil Data. NACA Rep. 824, 1945. (Formerly NACA ACR L5C05.)

2. Dodge, Russell A., and Thompson, Milton J.: Fluid Mechanics. First ed., McGraw-Hill Book Co., Inc., 1937, pp. 322-325.

3. Jacobs, Eastman N.: Preliminary Report on Laminar-Flow Airfoils and New Methods Adopted for Airfoil and Boundary-Layer Investigations. NACA ACR, June 1939.

4. Weick, Fred E.: Aircraft Propeller Design. McGraw-Hill Book Co., Inc., 1930, p. 68.

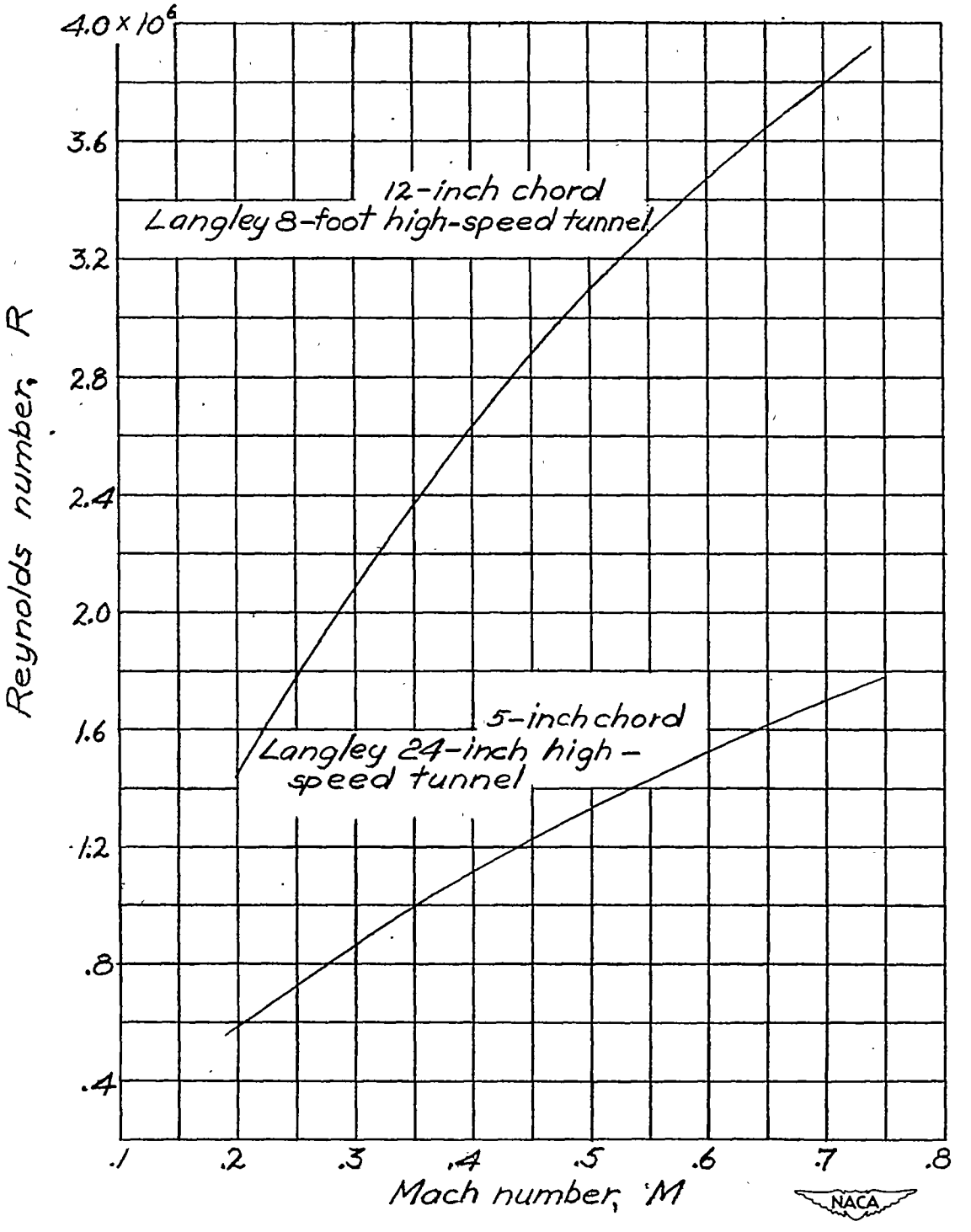



Figure 1.- Variation of average Reynolds number with Mach number.

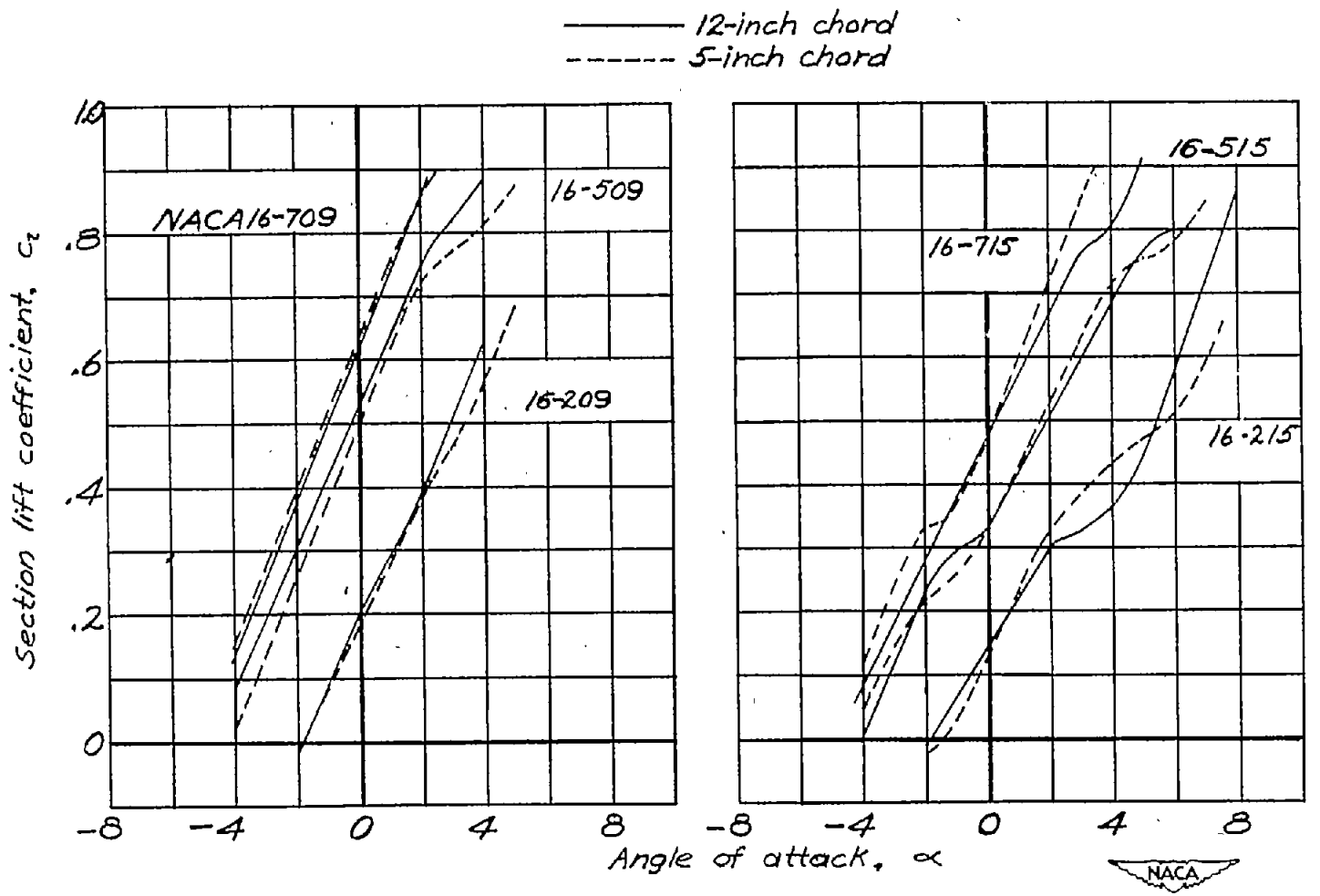



Figure 2.- Variation of lift coefficient with angle of attack for six NACA 16-series airfoils of two different chord lengths at $M = 0.60$.

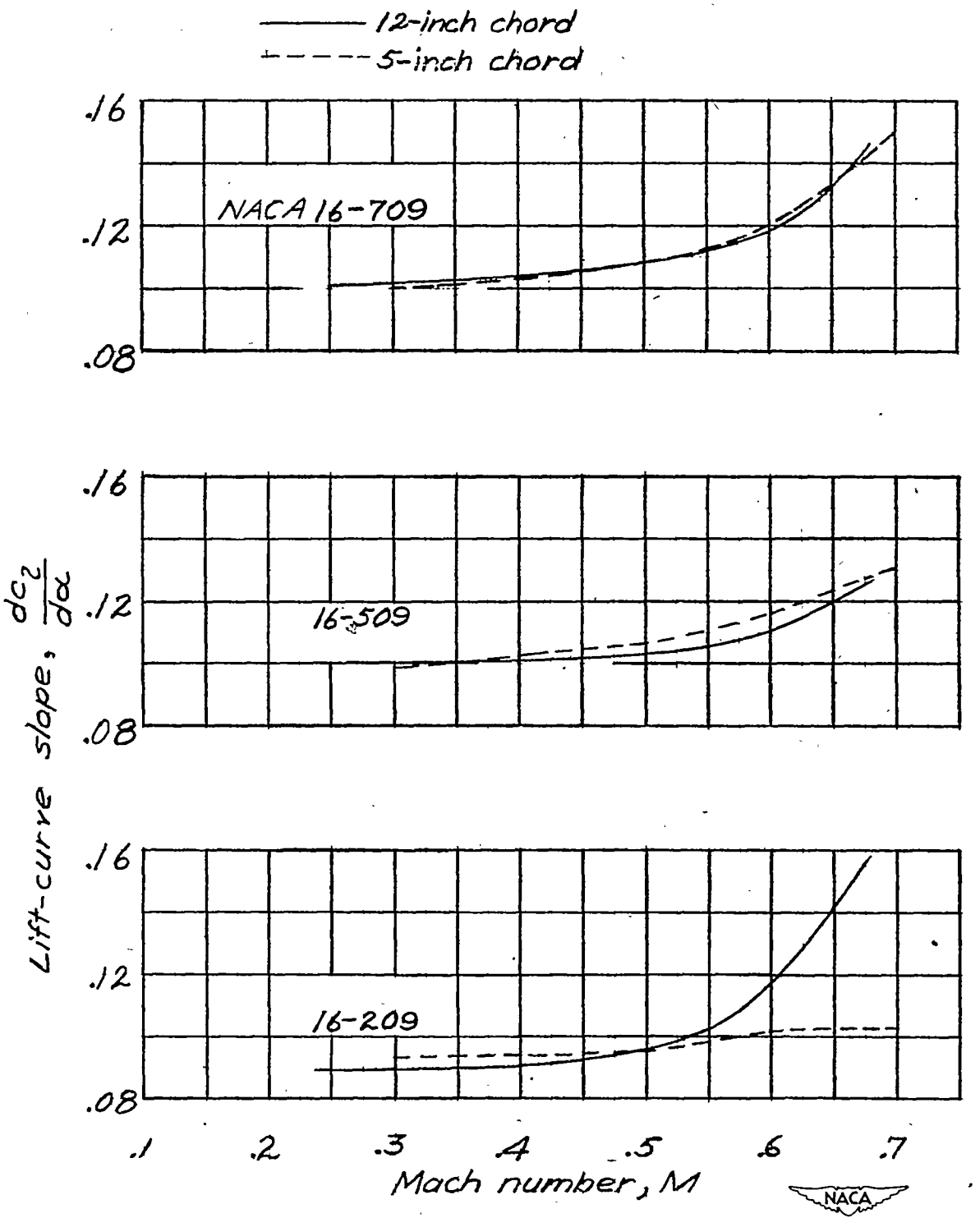



Figure 3.- Variation of lift-curve slope with Mach number for six NACA 16-series airfoils of two different chord lengths.

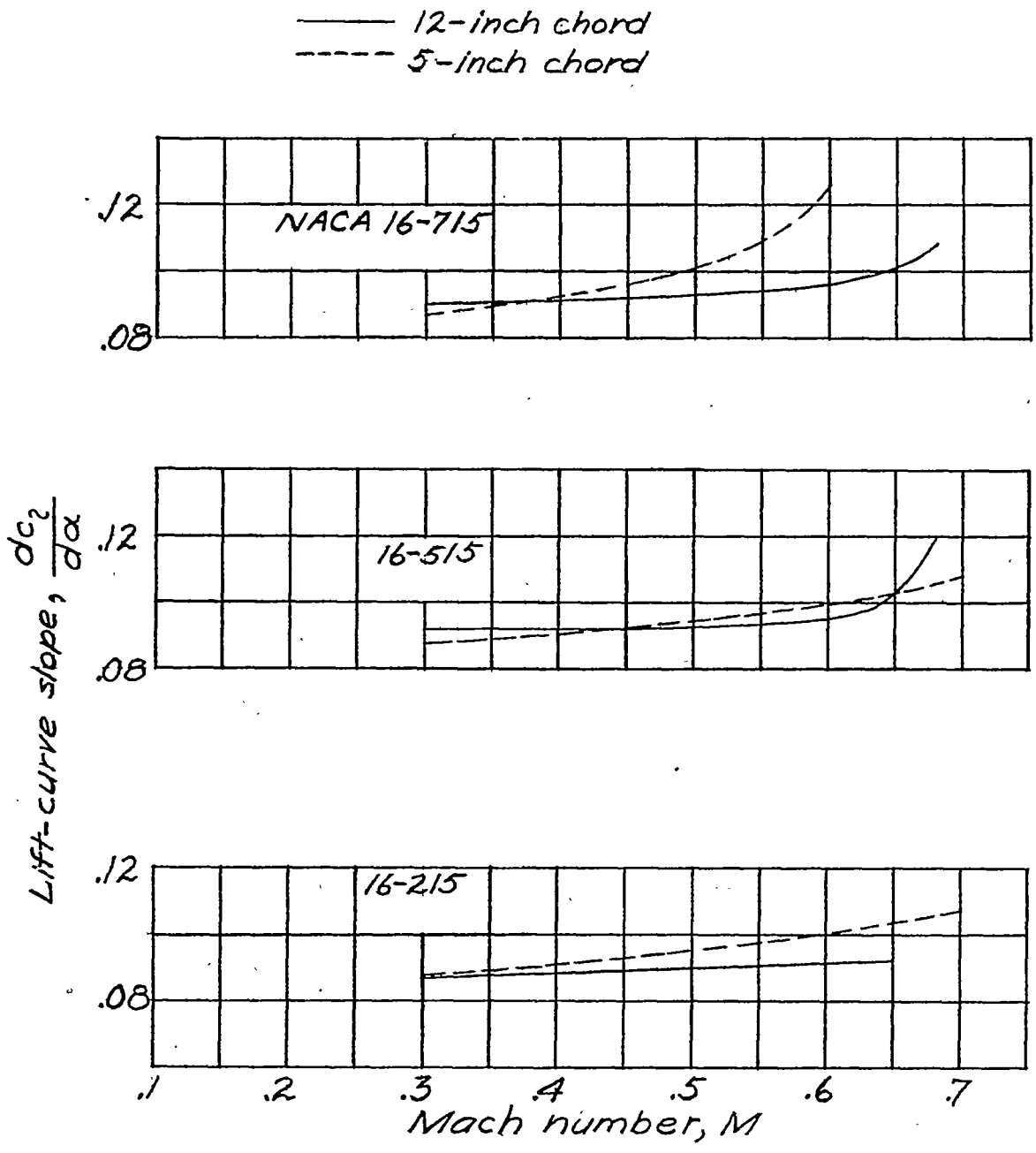



Figure 3.- Concluded.

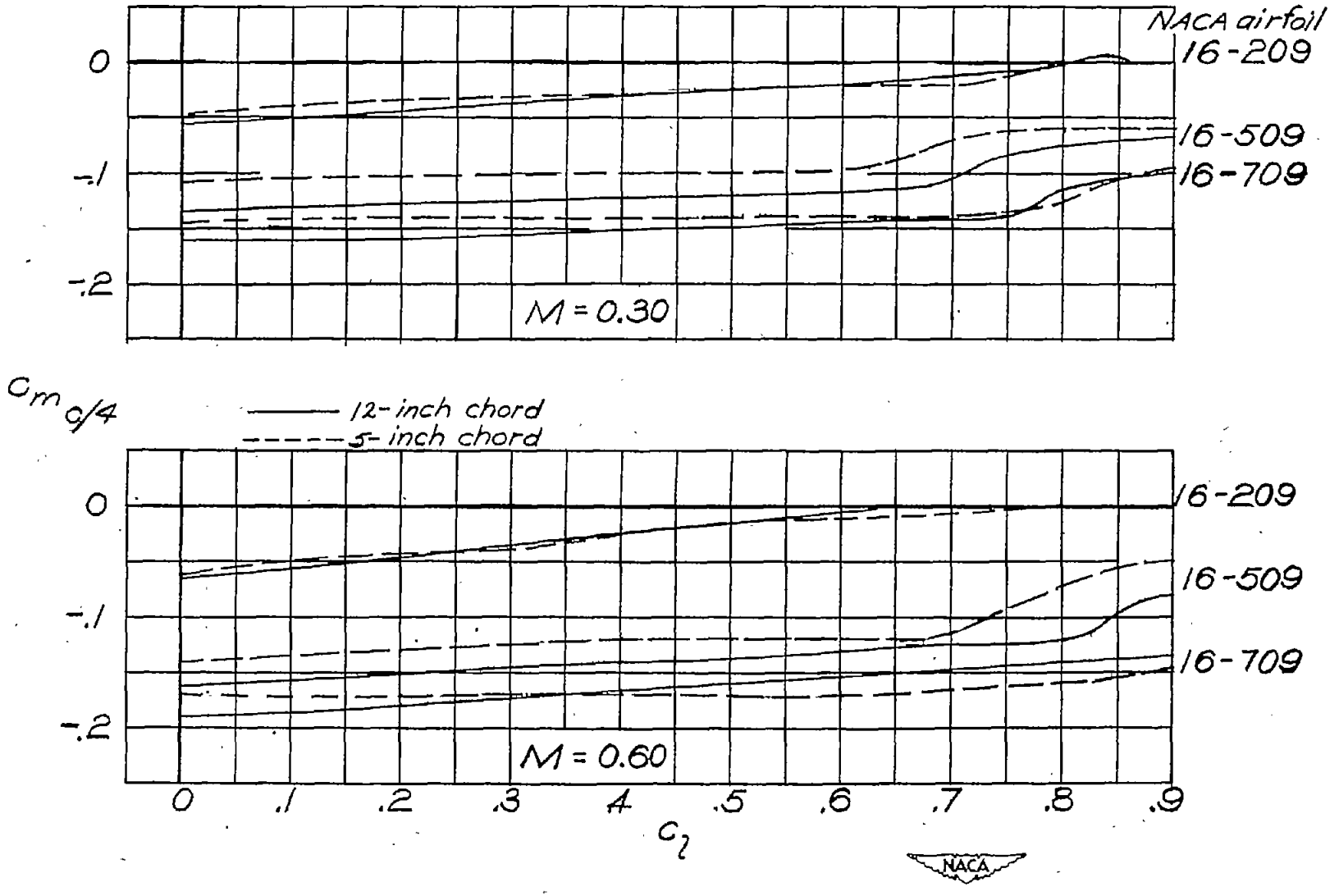
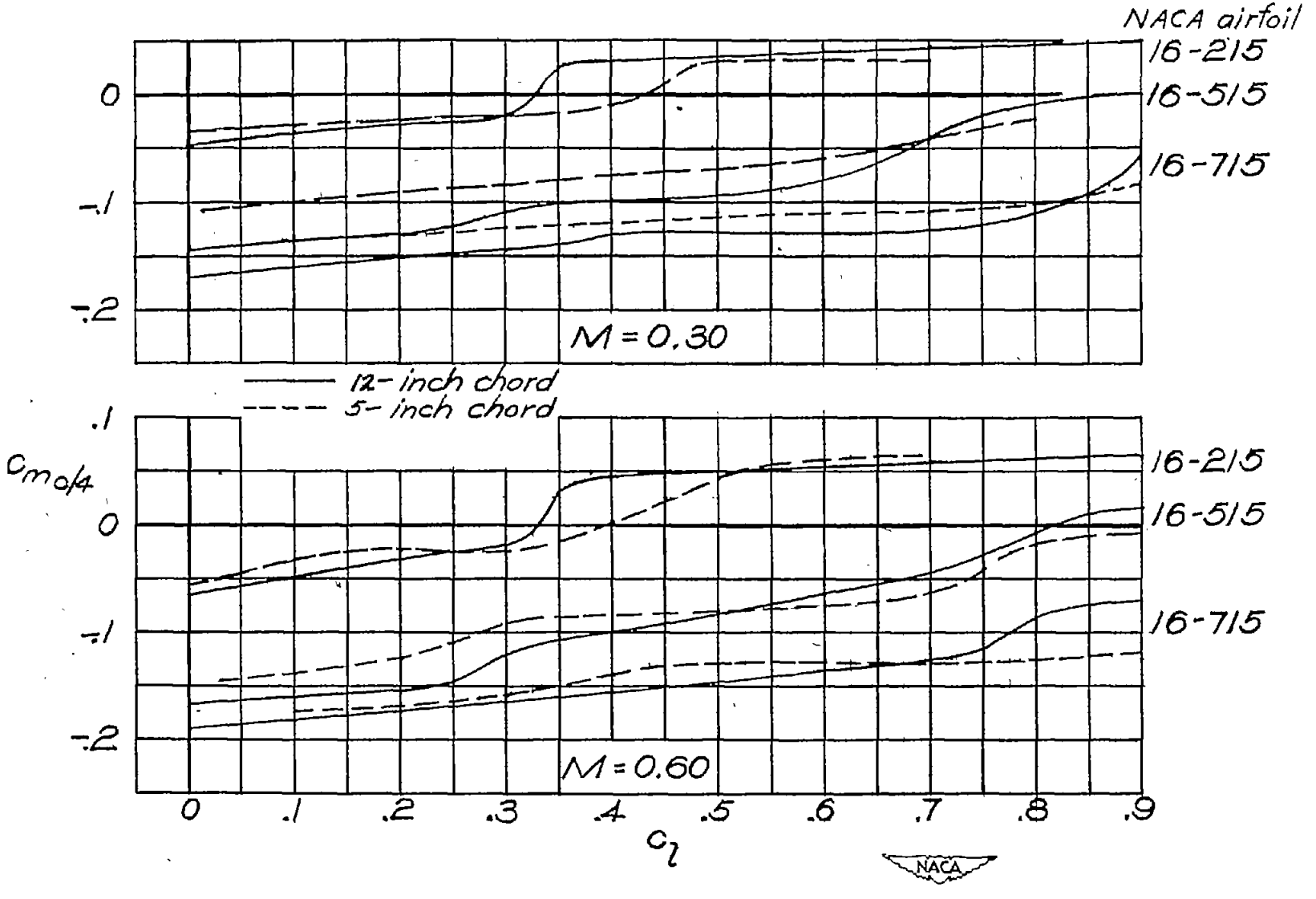



Figure 4.- Variation of moment coefficient with lift coefficient for six NACA 16-series airfoils of two different chord lengths.

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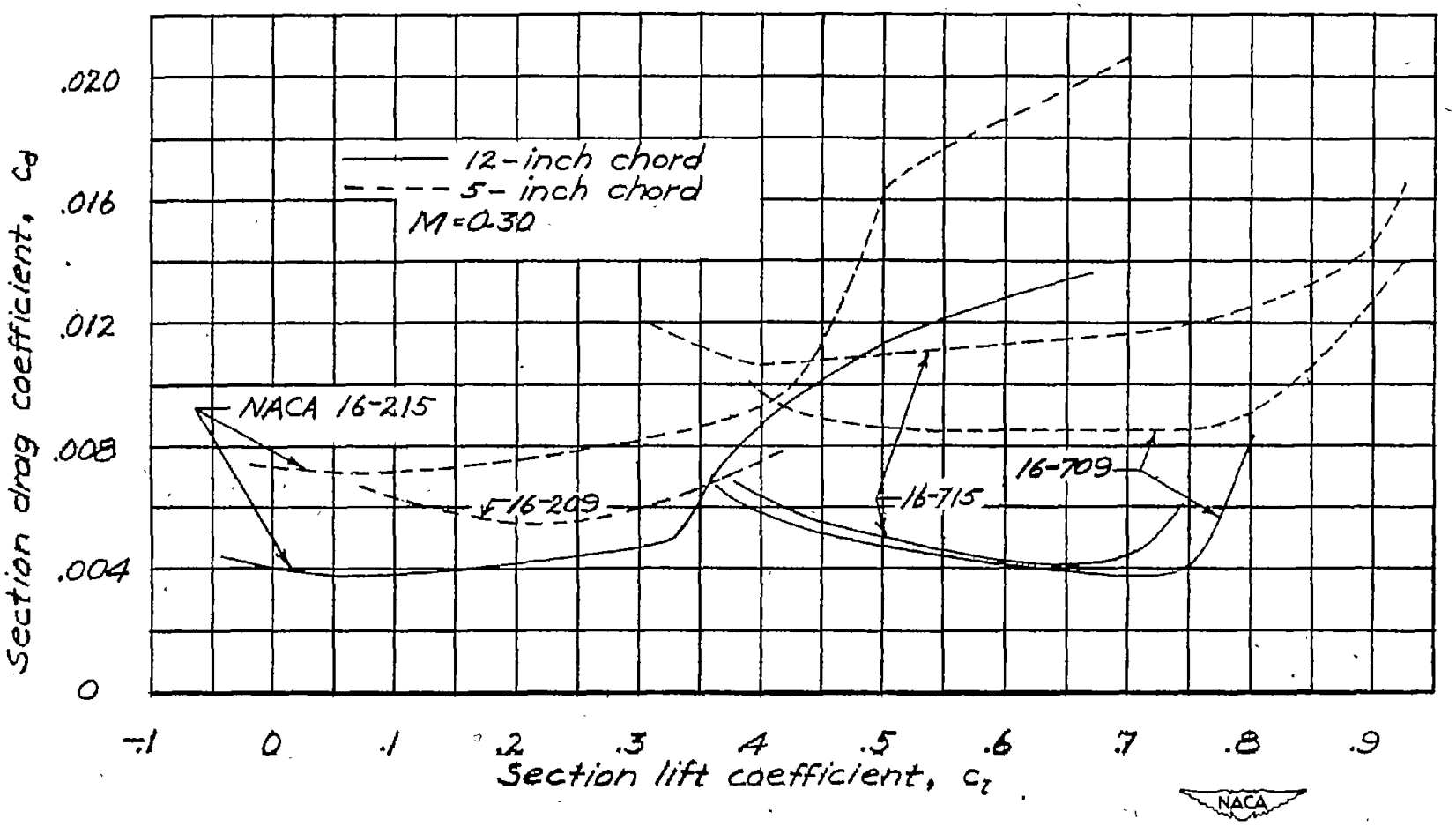


Figure 5.- Variation of drag coefficient with lift coefficient for four NACA 16-series airfoils of two different chord lengths.