13 NOV 1947

ACR No. 3I27

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED
September 1943 as
Advance Confidential Report 3I27

EFFECTS OF MEAN-LINE LOADING ON THE AERODYNAMIC CHARACTERISTICS OF SOME LOW-DRAG AIRFOILS

By Milton Davidson and Harold R. Turner, Jr.

Langley Memorial Aeronautical Laboratory
Langley Field, Va.

NACA

WASHINGTON

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE CONFIDENTIAL REPORT

EFFECTS OF MEAN-LINE LOADING ON THE AERODYNAMIC CHARACTERISTICS OF SOME LOW-DRAG AIRFOILS

By Milton Davidson and Harold R. Turner, Jr.

SUMMARY

The effect of variations in the type of mean line on the section characteristics of several representative NACA low-drag airfoils was investigated. The test results are compared with theoretical predictions and indicate trends that facilitate the choice of mean line in the absence of tests.

INTRODUCTION

The wing designer, with a variety of mean lines at his disposal, is confronted with the problem of choosing the proper mean line for a particular airfoil application. As an aid in the proper selection of mean lines, tests have been made in the NACA two-dimensional low-turbulence pressure tunnel of some NACA low-drag airfoils to observe the effects of varying the mean line of airfoils of the same family. The rolative advantages to be gained by the use of loading of one type in preference to another are discussed, and experimental test data and theoretically calculated values for the airfoils tested are given to indicate the limitations of the theory.

TEST METHODS[1]

In order to obtain a representative test group of airfoils, members of the NACA 63-series, NACA 65-series, and NACA 66-series

[1]At the time this paper was originally published, some of the corrections required for correcting the test data to free-air conditions had not been determined. The measured values of section lift coefficient c_l (figs. 1 to 11, figs. 13 and 15) should be corrected by the following equation

$$c_{l(\text{corrected})} = 0.965c_l + 0.01$$

The measured section angles of zero lift (fig. 12) will therefore be slightly different after the aforementioned correction is applied to the lift data.

families were selected. Airfoils with identical basic thickness forms were cambered (see reference 1) for the same design lift with the uniform-load mean line, that is, with $a = 1.0$, and with mean lines other than $a = 1.0$. Airfoils of the NACA 65-series were chosen to give a camber and a thickness variation.

All the airfoils, constructed as described in reference 1, were 24-inch-chord models and were tested in the smooth condition at Reynolds numbers of approximately 6×10^6 and 9×10^6; the models of thickness equal to or greater than 18 percent of the chord (0.18c) were also tested with a standard roughness applied to the leading edge (see reference 2) at a Reynolds number of approximately 6×10^6. Lift and drag values were obtained from tunnel-wall and wake-survey pressure measurements, and pitching-moment values were obtained from a balance (reference 1).

Average tunnel constants for these tests are

Reynolds number, R	Tunnel tank pressure (atm)	Dynamic pressure (lb/sq ft)	Mach number
6×10^6	3	89	0.137
6	4	64	.103
9	4	148	.153

RESULTS

Routine-test results giving section characteristics for airfoils tested in a smooth condition are presented in figures 1 to 7. The results are given in standard chart form, with two airfoils to each chart, for the following airfoils:

NACA 63,4-420, $a = 1.0$

NACA 63,4-420, $a = 0.3$

NACA 65_2-415, $a = 1.0$

NACA 65_2-415, $a = 0.5$

NACA 65_3-418, $a = 1.0$

NACA 65_3-418, a = 0.5

NACA 65_4-421, a = 1.0

NACA 65_4-421, a = 0.5

NACA 65,3-418, a = 1.0

NACA 65,3-418, a = 0.8

NACA 65,3-618, a = 1.0

NACA 65_3-618, a = 0.5

NACA 66,2-216, a = 1.0

NACA 66,2-216, a = 0.6

Charts of the airfoils with a standard roughness are given in figures 8 to 11; the lift and drag characteristics are presented in these charts for all of the afore-mentioned airfoils, 0.18c thick or thicker, with the exception of the NACA 65,3-418, a = 1.0 and the NACA 65,3-418, a = 0.8 airfoils. The characteristics for the corresponding smooth airfoil with a = 1.0 are also shown on each chart for comparison.

Measured values and theoretical mean-line values of angle of zero lift, design section lift coefficient, and section pitching-moment coefficient are given in figures 12 to 14, respectively. The theoretical mean-line values have been computed by using the values and methods of references 1 and 3.

Figure 15 shows the variation of design section lift coefficient and section pitching-moment coefficient with airfoil thickness for several airfoils of the NACA 65-series. The results given were obtained from tunnel measurements; from mean-line (thin-airfoil-theory) calculations; from integration of the combined theoretical pressure distributions due to basic form thickness and to camber

$S = \left(\frac{v}{V} \pm \frac{\Delta v}{V}\right)^2$ (see reference 1); and from a Theodorsen calculation (see reference 4) on the NACA 65_3-418, a = 1.0 airfoil. The symbols in the formula for S are defined as

S pressure coefficient

v velocity on surface of basic thickness form

V free-stream velocity

Δu velocity increment due to mean-line load distribution

DISCUSSION

Section Characteristics Applicable to Wing Design

Aerodynamically, wing design usually consists of the selection of suitable root and tip airfoil sections. The selection of suitable root and tip sections involves the proper choice of mean line; hence, the aerodynamicist must evaluate available mean-line data. The advantages of choosing one mean line in preference to another for a particular application can best be shown by the effects of different mean lines on the airfoil section characteristics. The most important of these characteristics are

α_{l_0} angle of zero lift

a_0 slope of section lift curve, per degree

$c_{l_{opt}}$ optimum lift coefficient, or section lift coefficient selected as middle of low-drag range

$c_{l_{max}}$ maximum section lift coefficient

c_l-range angular range corresponding to difference between angle of attack at $c_{l_{max}}$ and at $c_l = 0$

$c_{d_{o_{min}}}$ minimum section profile-drag coefficient

c_{d_o}-range extent of minimum section profile-drag coefficient

$c_{m_{c/4}}$ section pitching-moment coefficient about section quarter-chord point

V_c section critical speed

Selection of Mean Lines

Reference 1, which presents mean lines with values of a ranging from 0.3 to 1.0, recommends that a value of a be selected which is equal to or greater than the extent of the falling pressure for the associated basic thickness form. A large variety of loadings may be obtained by combinations of the various mean lines; however, the present paper is concerned with only the values of a as recommended in reference 1.

When the loading of an airfoil is changed, the inherent characteristics of the basic thickness form may be retained and yet the airfoil section characteristics may be greatly varied. For example, by employing one type of camber in preference to another, a higher section critical speed, a higher maximum section lift coefficient, and a higher section pitching-moment coefficient may be obtained without any change in section minimum profile-drag coefficient.

The trend of section characteristics can be shown partly by theory and partly by generalizations from test results. Thin-airfoil theory indicates that a higher critical speed, a greater section pitching-moment coefficient, and a lower value of section angle of zero lift are obtained as the mean line progresses in the direction from $a = 0.3$ to $a = 1.0$; however, indications of what happens to the maximum section lift coefficient must be obtained from test results.

Test results giving the section characteristics of airfoils with a uniform-load mean line and airfoils with loadings other than $a = 1.0$ are presented in figures 1 to 11. The charts for the airfoils in the smooth condition (figs. 1 to 7) indicate a higher $c_{l_{max}}$, a greater a_o, and a narrower c_l-range for the airfoils with $a = 1.0$ than with $a < 1.0$. The plots of c_d against c_l show no significant difference in $c_{d_{o_{min}}}$ although, at the higher values of c_l, the drag is considerably less for the airfoil with $a = 1.0$ than with other mean-line loadings. It is noted that the c_{d_o}-range for the airfoils with $a < 1.0$ shifts toward higher lift coefficients as compared to the airfoil with the $a = 1.0$ loading, and also the $c_{l_{opt}}$ is greater in almost every instance. The section pitching-moment coefficient, as is expected, is greater (more negative) for the airfoil with the $a = 1.0$ loading.

With regard to roughness, airfoils with $a = 1.0$ appear to be more conservative than airfoils with $a < 1.0$. The charts of the airfoils with roughness (figs. 8 to 11) show that the $a = 1.0$ airfoils have higher values of $c_{l_{max}}$ and lower values of c_d throughout the c_l-range than the $a < 1.0$ airfoils.

Comparison of measured values and theoretical mean-line values are shown as an aid in predicting airfoil section characteristics from mean-line data based on thin-airfoil theory. Because thin-airfoil theory does not take into account airfoil-thickness and boundary-layer considerations, mean-line data and measured results might be expected to diverge considerably. A comparison of measured values and theoretical mean-line values (figs. 12 to 15) shows that, for the $a < 1.0$ airfoils, the theoretical angles of zero lift and the theoretical pitching-moment coefficients are in fair agreement with those measured; the measured design section lift coefficients, however, are usually higher than the theoretical values as indicated in the airfoil designation numbers. Although, for the airfoils with $a = 1.0$, the theoretical and measured design lift coefficients are in fair agreement, the measured angles of zero lift and the measured pitching-moment coefficients are considerably less than those indicated by theory. The deviation of values of measured pitching-moment coefficient from the theoretical values results because in experiment a uniform load was not maintained over the airfoil to the trailing edge. This fact suggests that a reducing factor might be applied in order that the theoretical values of pitching-moment coefficient might conform more closely to the measured values.

With increasing airfoil thickness, there is an accompanying increase in section design lift and section pitching-moment coefficient. (See fig. 15.) Although thin-airfoil theory obviously gives no evidence of this increase, it is apparent from integrated theoretical pressure-distribution calculations and is substantiated by test results.

CONCLUSION

The general effects of variation in the type of mean line on the section characteristics of several representative low-drag airfoils are shown. The consistency of results indicates that these general trends are suitable for use in the selection of mean lines for application to airfoils for which test results are not available.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va.

REFERENCES

1. Jacobs, Eastman N., Abbott, Ira H., and Davidson, Milton: Preliminary Low-Drag-Airfoil and Flap Data from Tests at Large Reynolds Numbers and Low Turbulence, and Supplement. NACA A.C.R., March 1942.

2. Jacobs, Eastman N., Abbott, Ira H., and Davidson, Milton: Investigation of Extreme Leading-Edge Roughness on Thick Low-Drag Airfoils to Indicate those Critical to Separation. NACA C.B., June 1942.

3. Jacobs, E. N., and Abbott, I. H.: Angles of Zero Lift for Some NACA Low-Drag Airfoils. NACA C.B., Feb. 1942.

4. Theodorsen, T., and Garrick, I. E.: General Potential Theory of Arbitrary Wing Sections. Rep. No. 452, NACA, 1933.

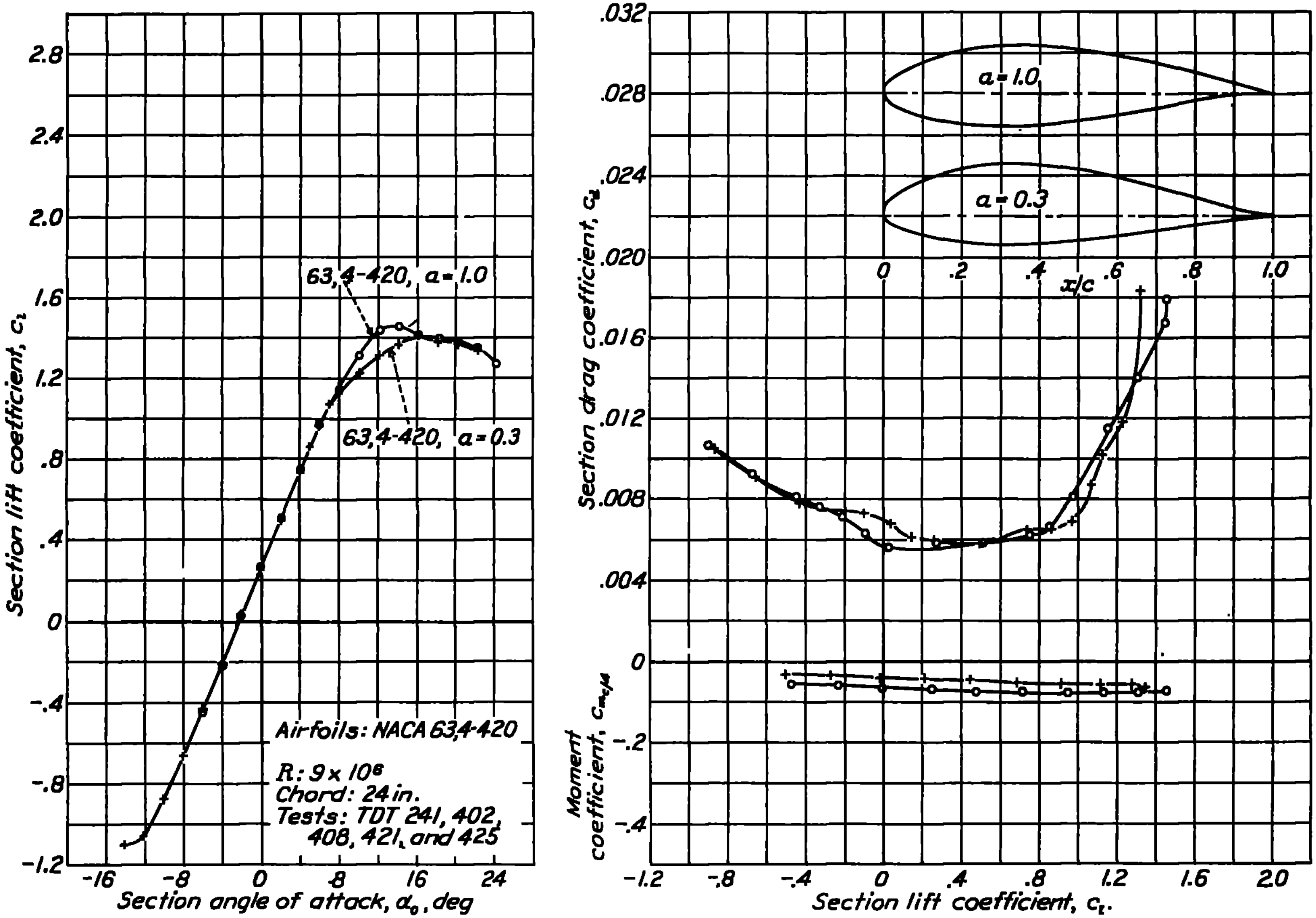

Figure 1.- Section characteristics of two NACA 63,4-420 airfoils.

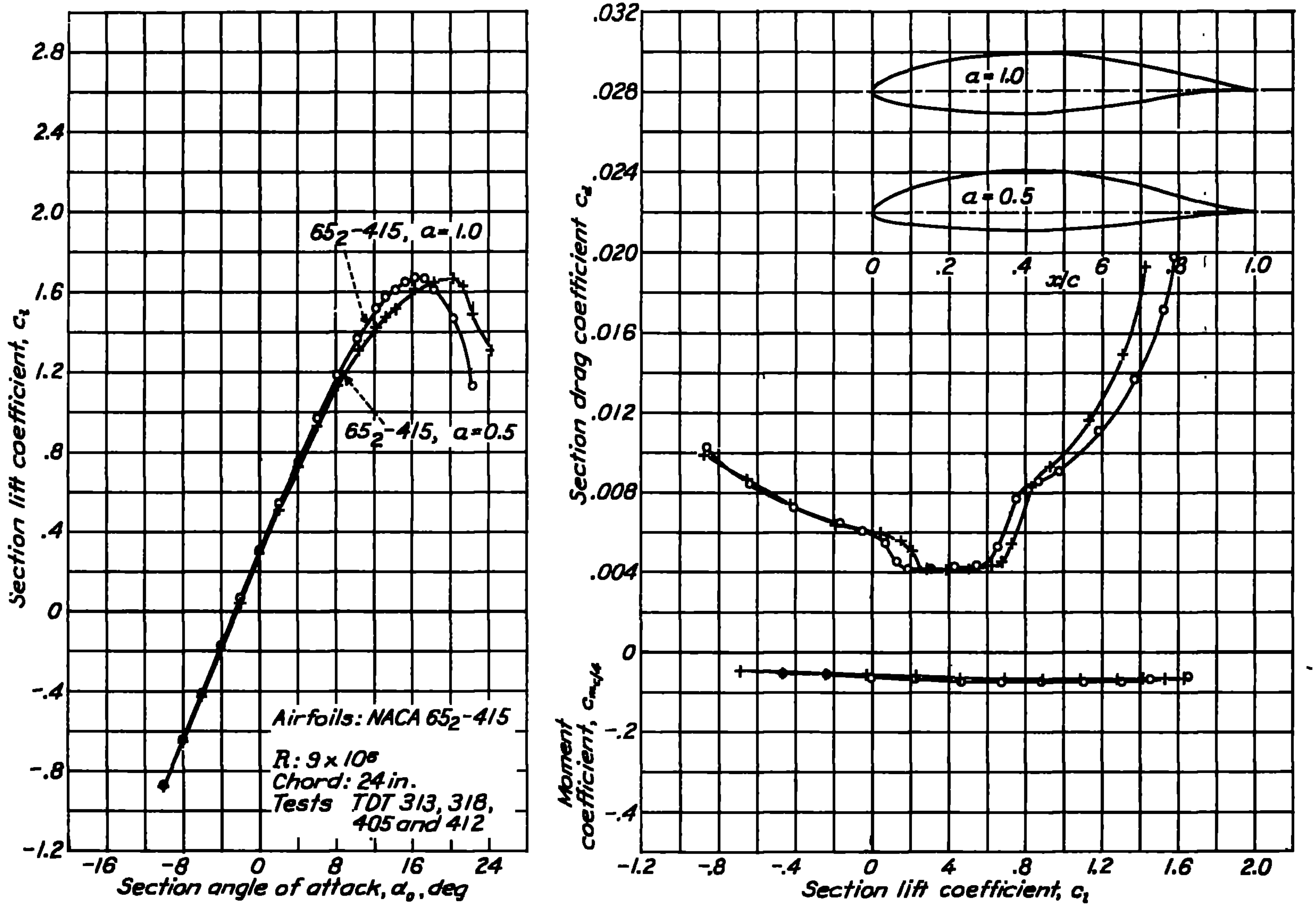

Figure 2.- Section characteristics of two NACA 65_2-415 airfoils.

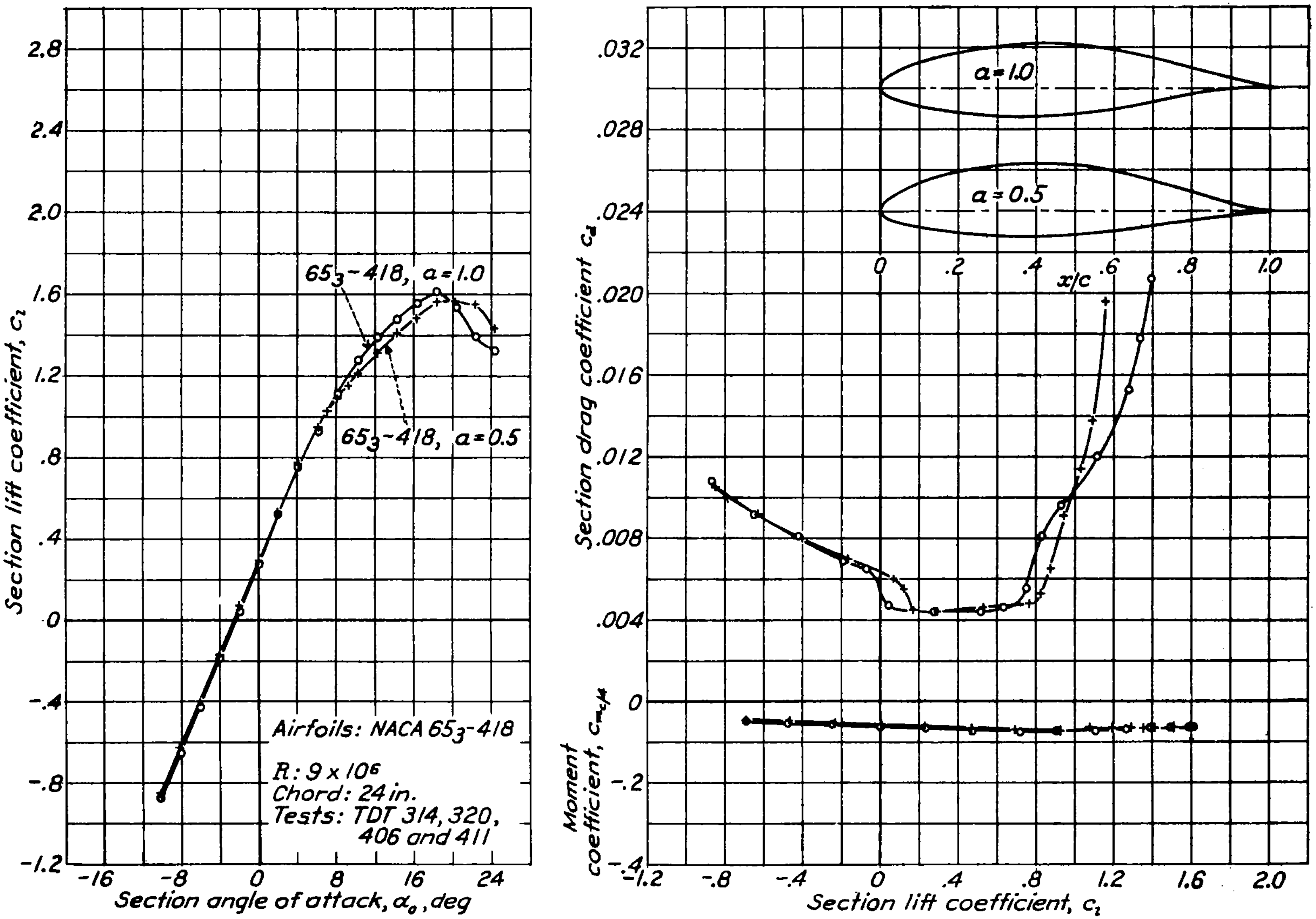

Figure 3.- Section characteristics of two NACA 65_3-418 airfoils.

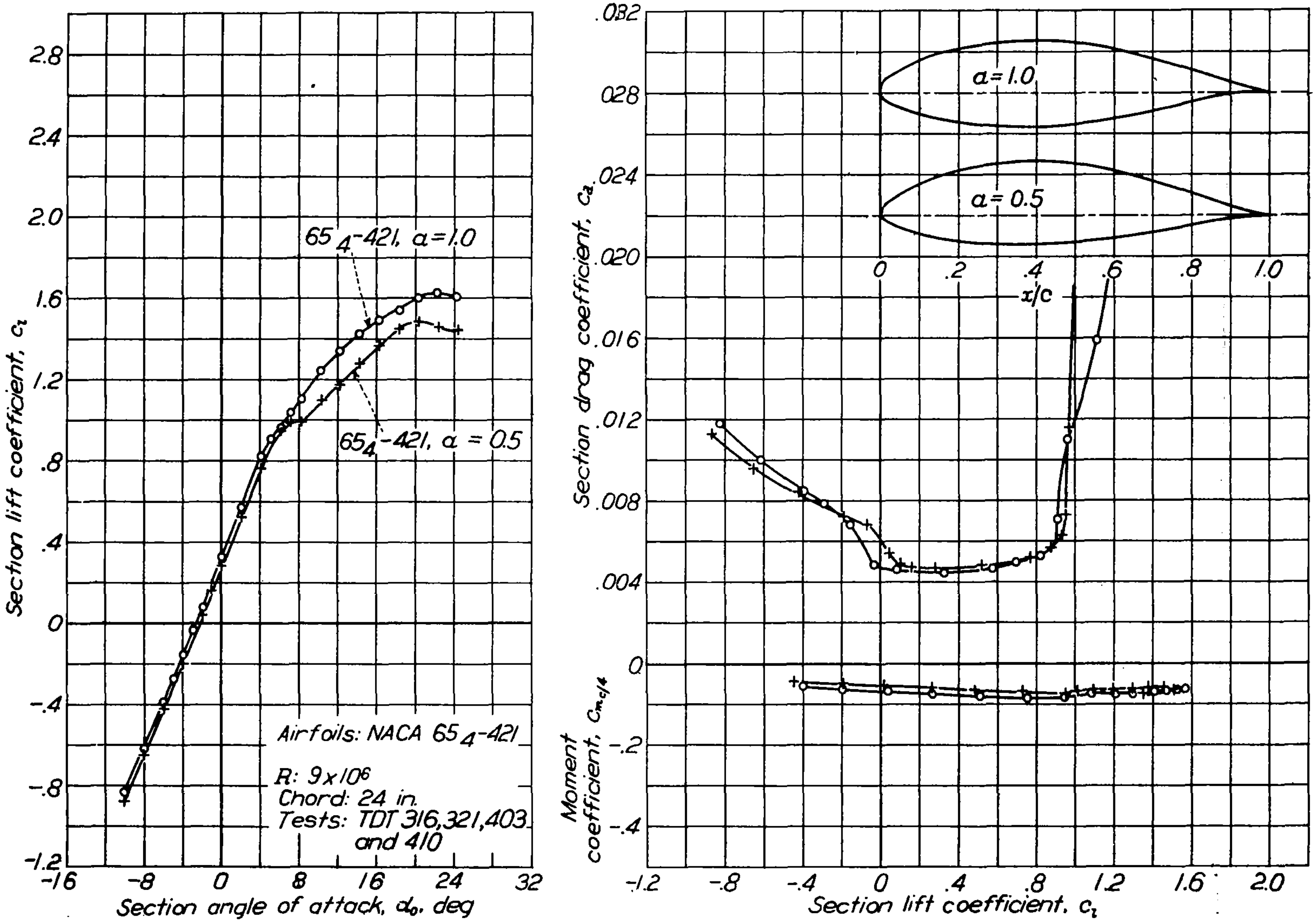

Figure 4.- Section characteristics of two NACA 65_4-421 airfoils.

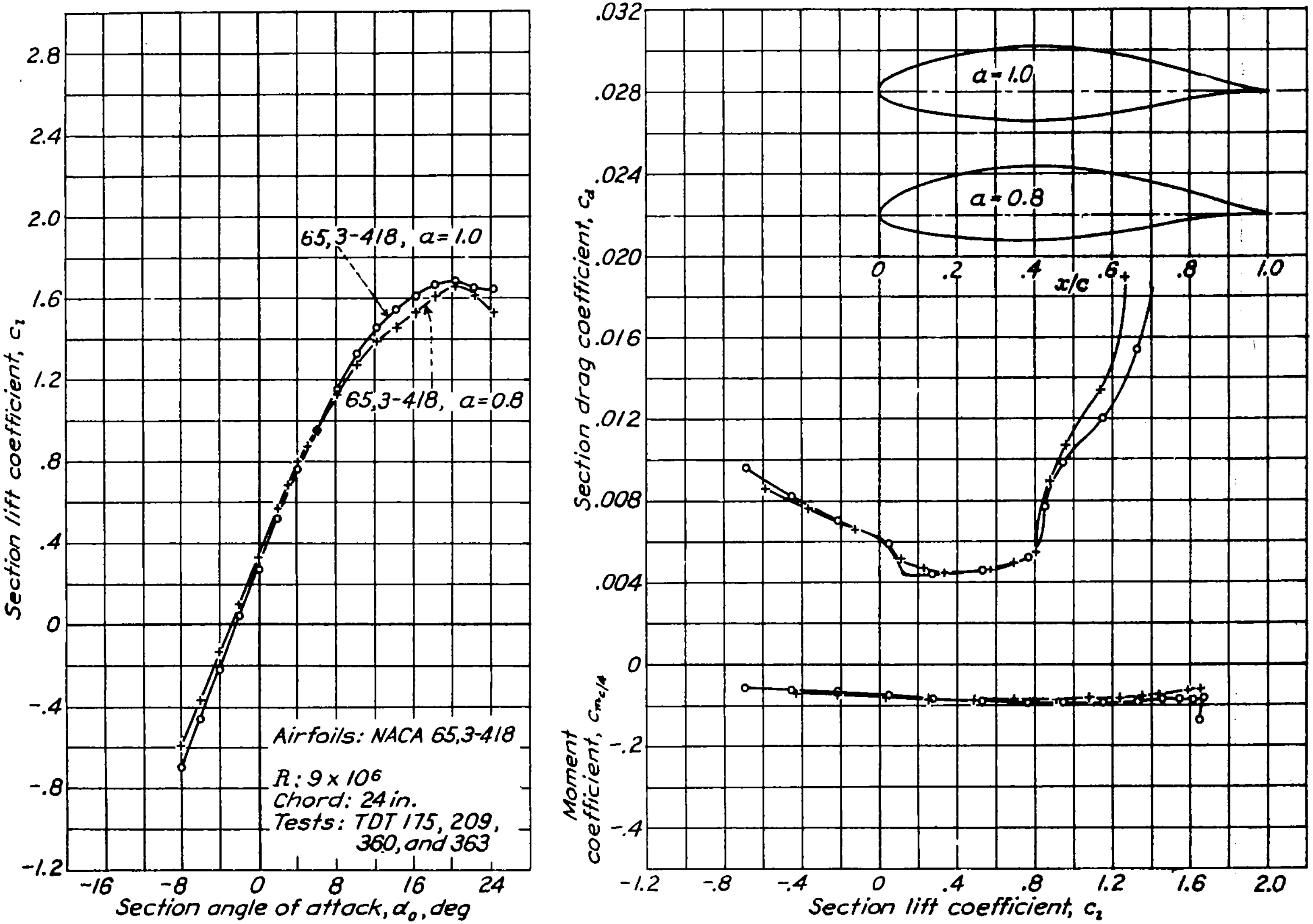

Figure 5.- Section characteristics of two NACA 65,3-418 airfoils.

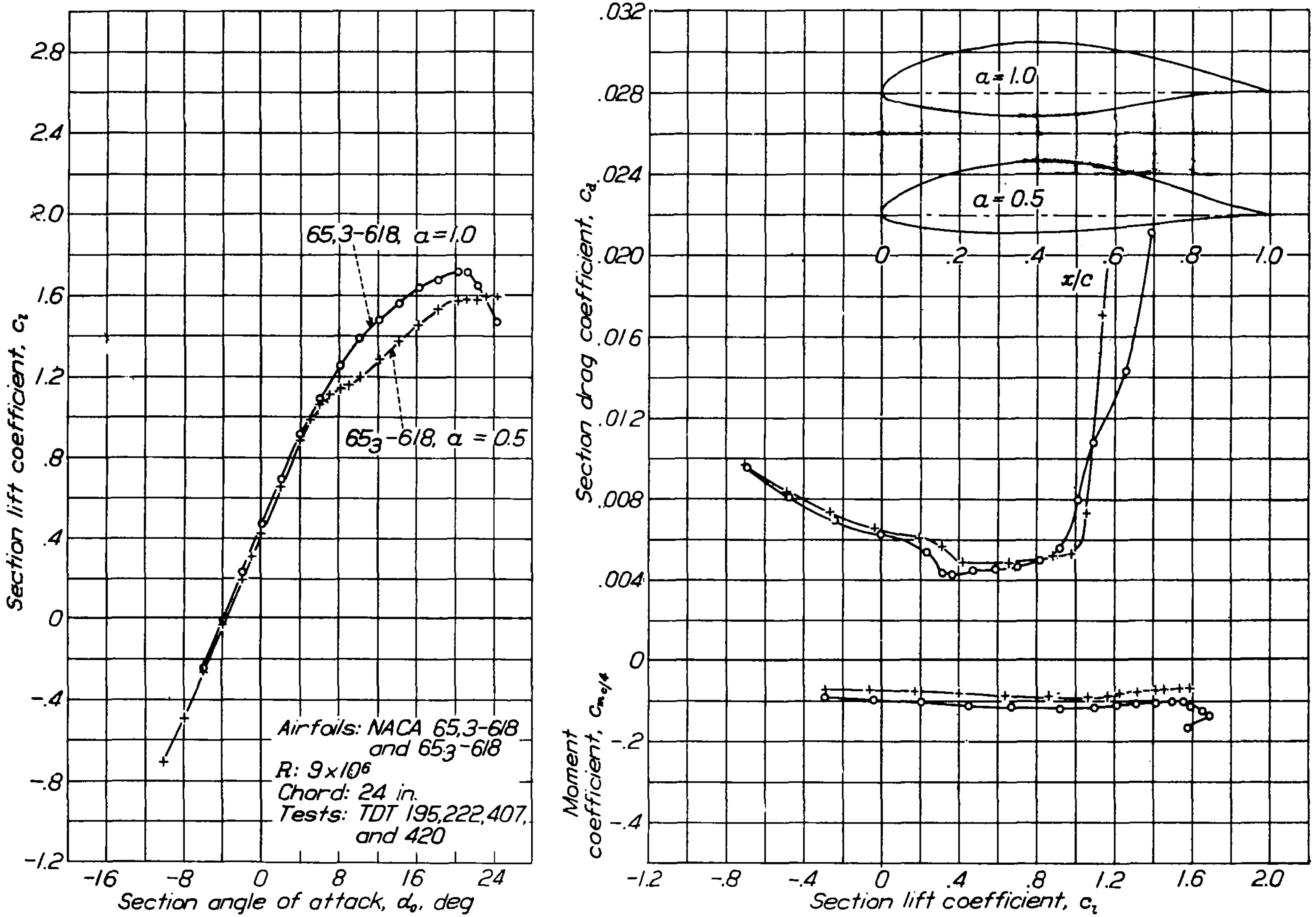

Figure 6.- Section characteristics of an NACA 65,3-618, a = 1.0 and an NACA 65_3-618, a = 0.5 airfoil.

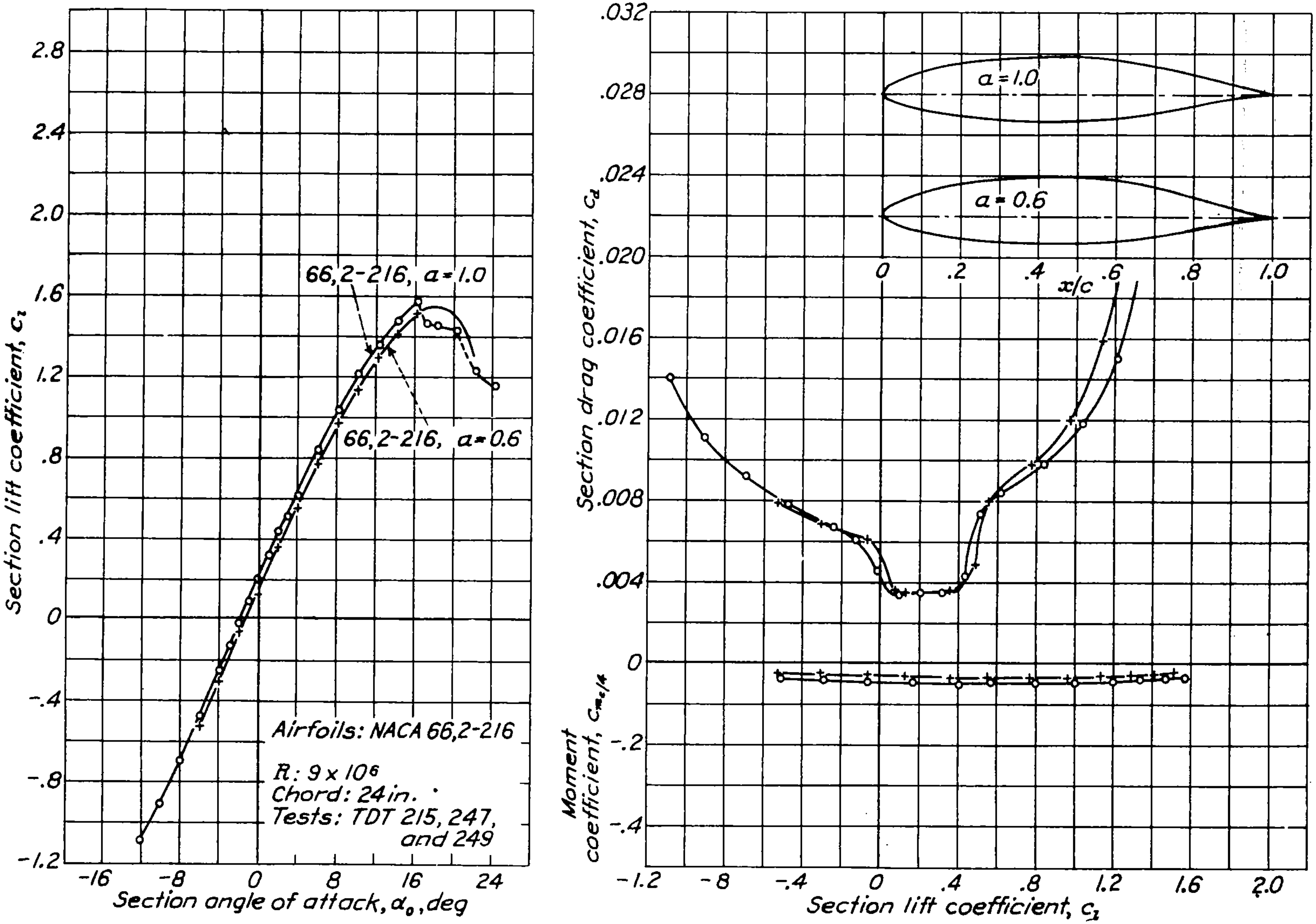

Figure 7.- Section characteristics of two NACA 66,2-216 airfoils.

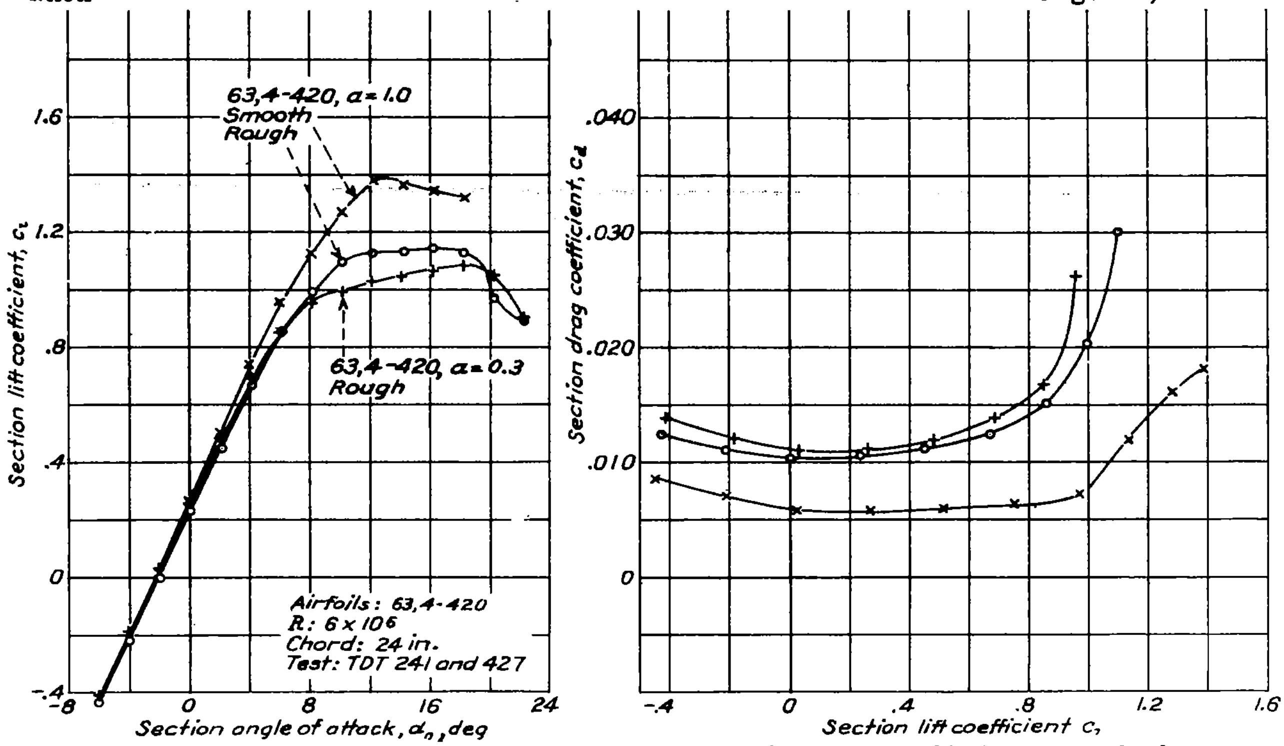

Figure 8.- Lift and drag characteristics of two NACA 63,4-420 airfoils with a standard roughness applied to the leading edges.

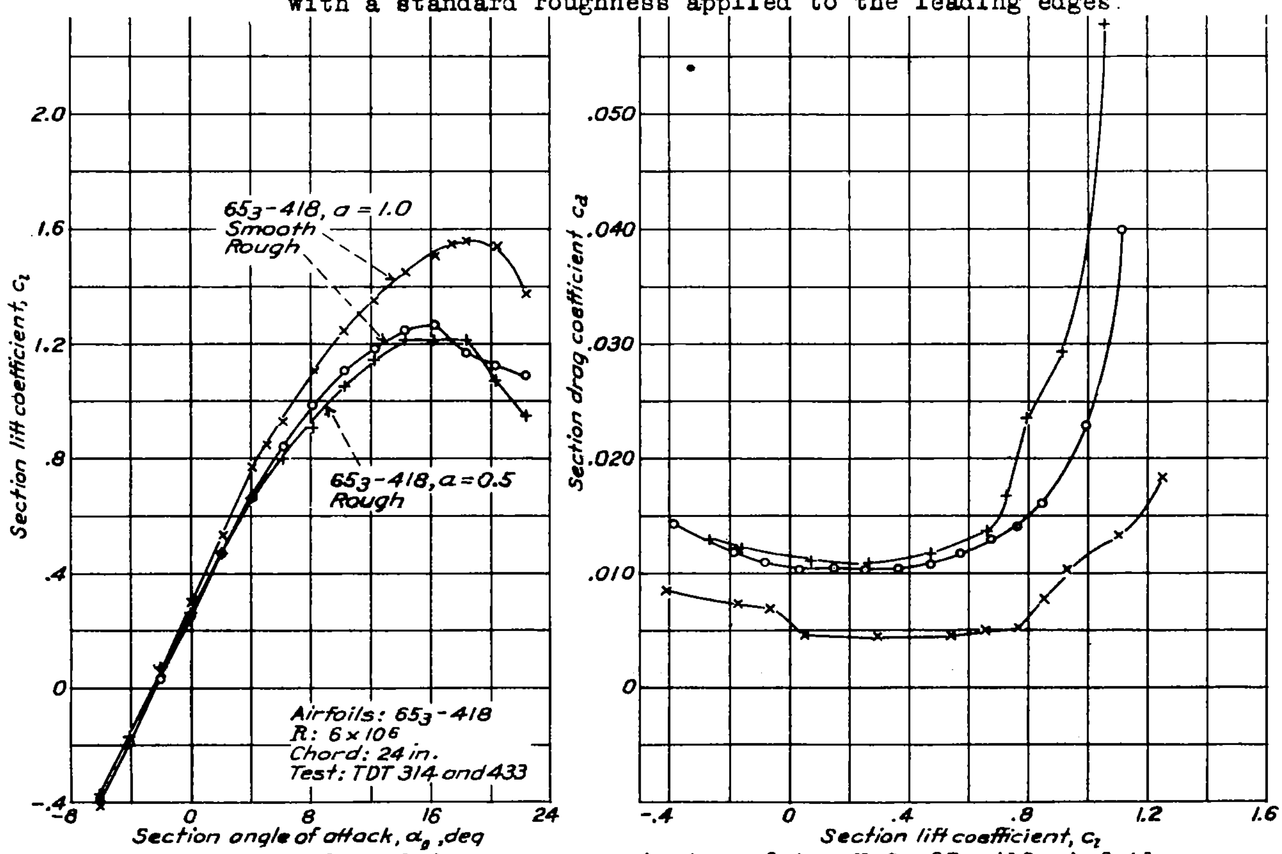

Figure 9.- Lift and drag characteristics of two NACA 65_3-418 airfoils with a standard roughness applied to the leading edges.

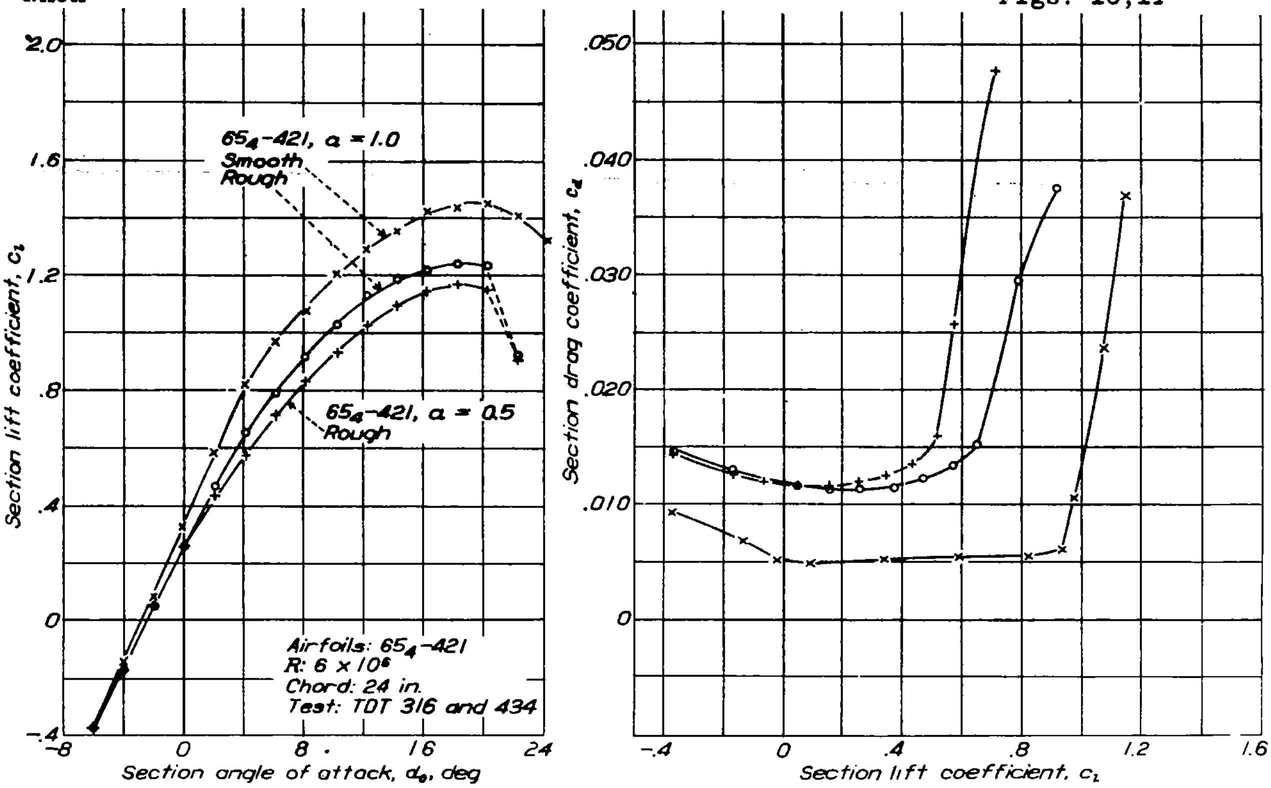

Figure 10.- Lift and drag characteristics of two NACA 65_4-421 airfoils with a standard roughness applied to the leading edges.

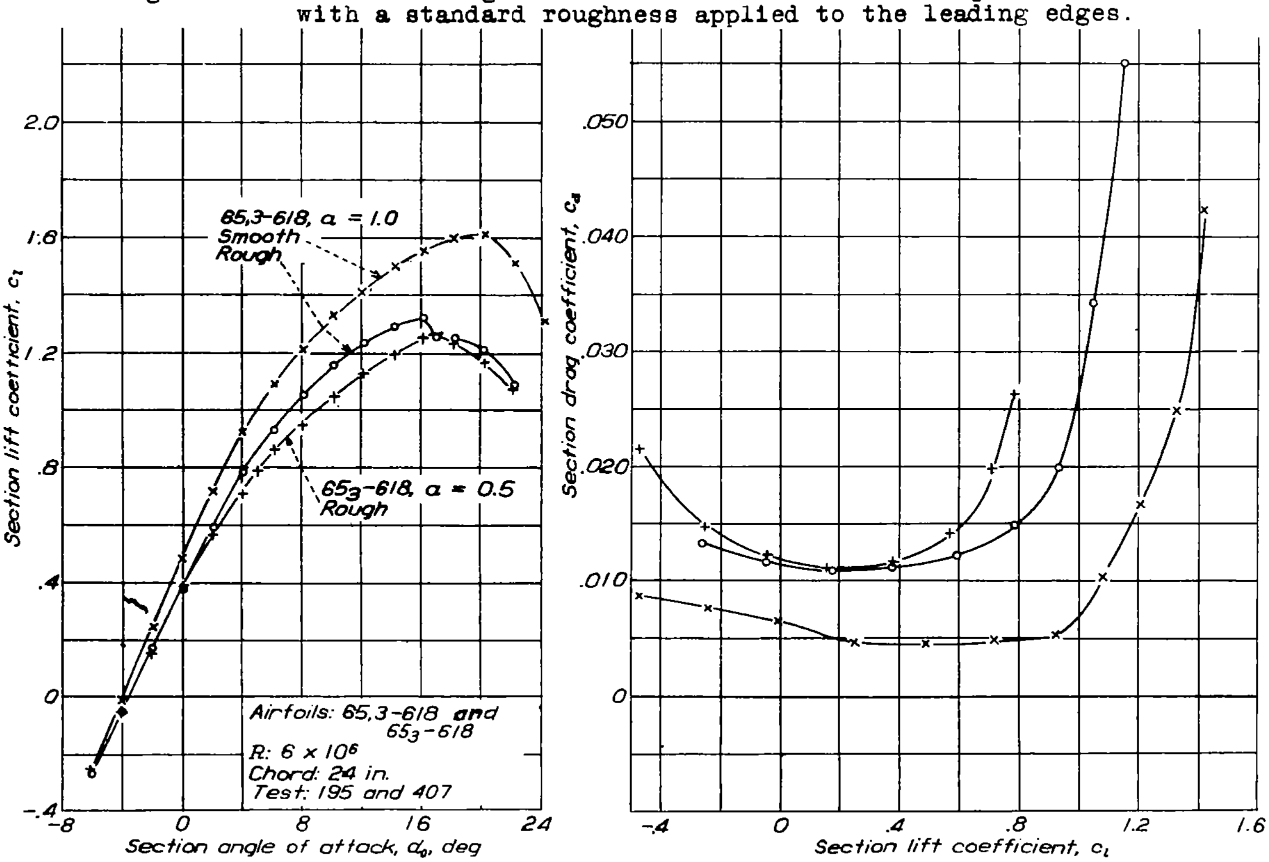

Figure 11.- Lift and drag characteristics of an NACA 65,3-618, a = 1.0 and an NACA 65_3-618, a = 0.5 airfoil with a standard roughness applied to the leading edge.

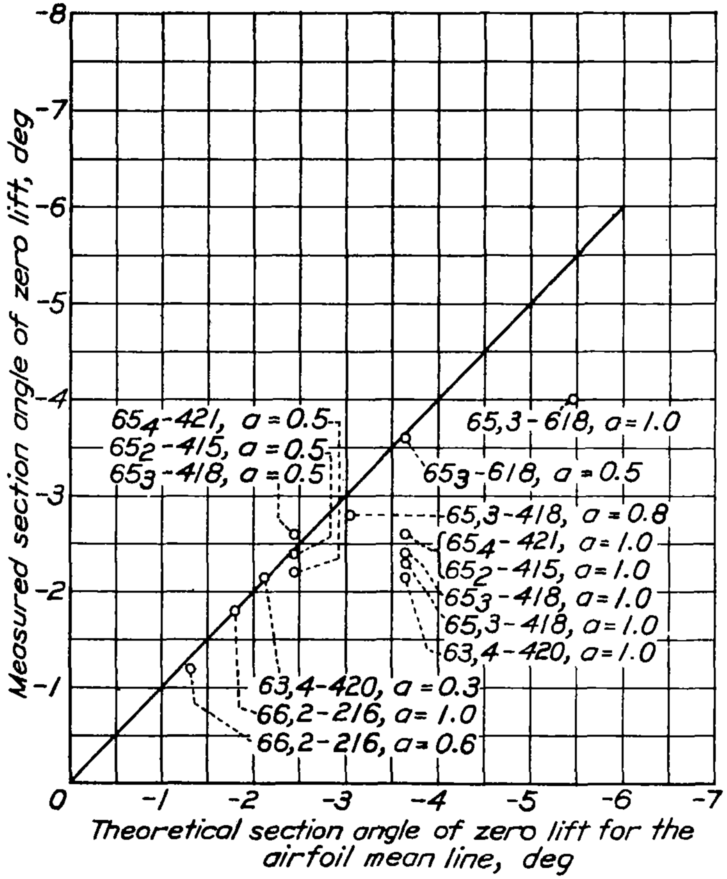

Figure 12.- Comparison of theoretical and measured section angles of zero lift for some NACA low-drag airfoils.

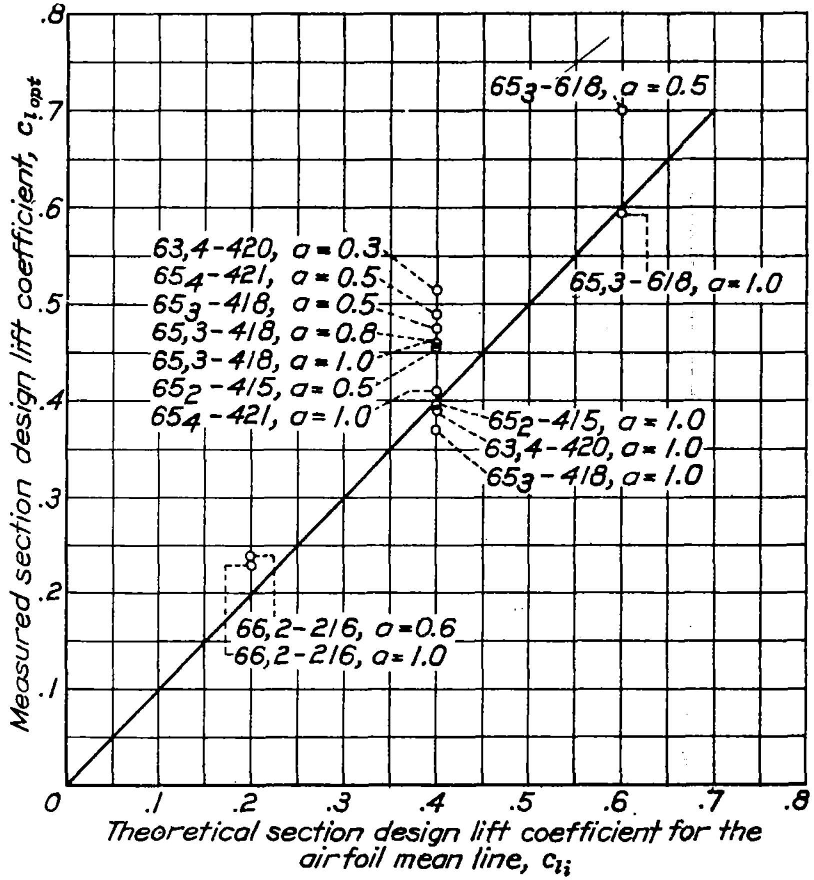

Figure 13.- Comparison of theoretical and measured section design lift coefficients for some NACA low-drag airfoils.

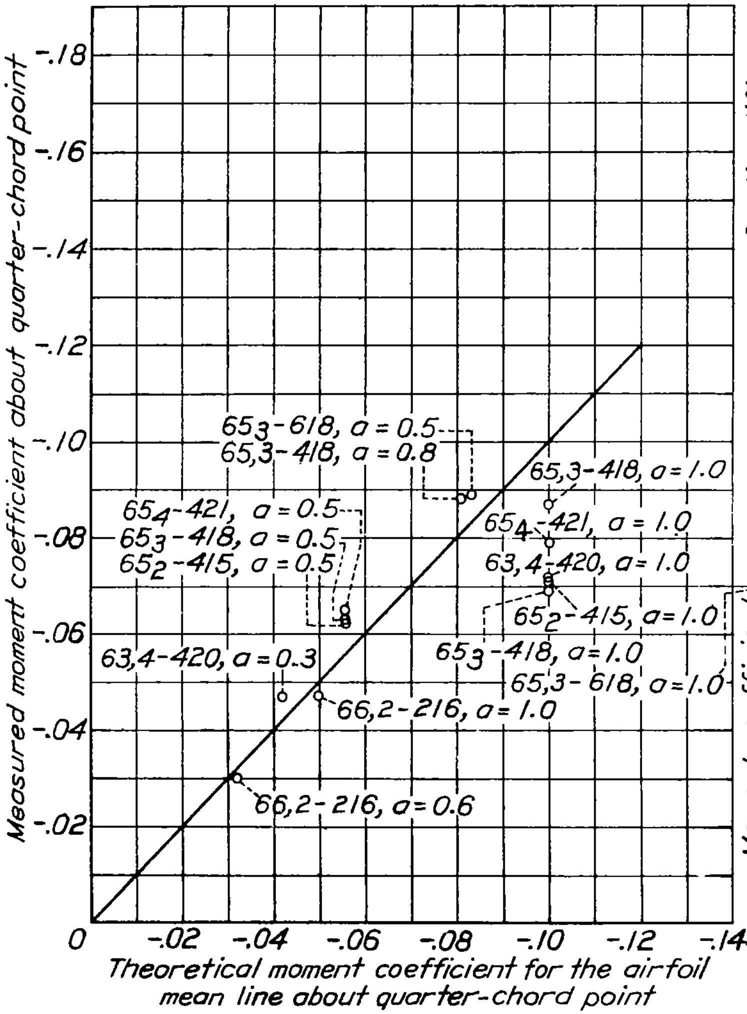

Figure 14.- Comparison of theoretical and measured moment coefficients for some NACA low-drag airfoils.

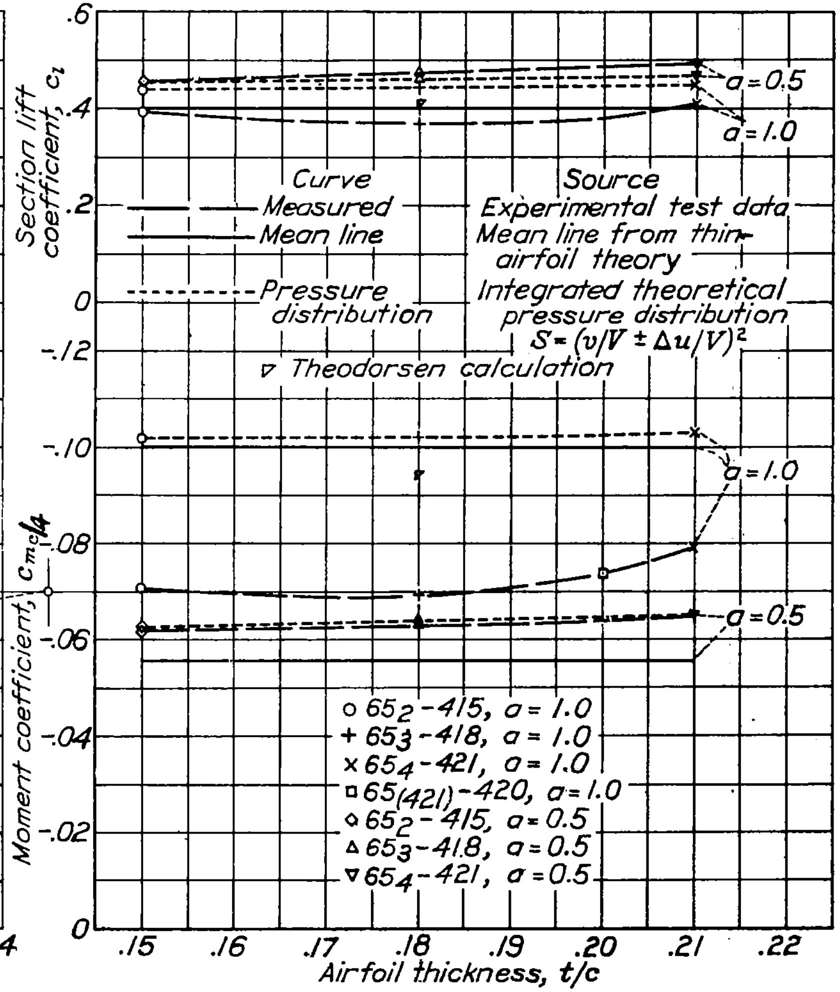

Figure 15.- Variation of moment coefficient $c_{m_{c/4}}$ and section lift coefficient c_l with airfoil thickness for some NACA low-drag airfoils.