REPORT No. 537

TESTS IN THE VARIABLE-DENSITY WIND TUNNEL OF RELATED AIRFOILS HAVING THE MAXIMUM CAMBER UNUSUALLY FAR FORWARD

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SUMMARY

A family of related airfoils having the position of maximum camber unusually far forward was investigated in the variable-density tunnel as an extension of the study recently completed of a large number of related airfoils. The new airfoils gave improved characteristics over those previously investigated, especially in regard to the pitching moment. Some of the new sections are markedly superior to well-known and commonly used sections and should replace them in applications requiring a slightly cambered section of moderate thickness, having a small pitching-moment coefficient.

INTRODUCTION

The investigation of a large family of related airfoils, reported in reference 1, indicated that the effects of camber in relation to maximum lift coefficients were more pronounced with airfoils having the maximum camber forward or aft of the usual positions (0.3*c* to 0.5*c*). The scope of the investigation, however, was not extended to include airfoils having extreme camber positions because the mean-line shapes originally employed could not be satisfactorily extended. A consideration of a program to include these extreme positions led to the elimination of the after positions because of the adverse pitching moments to be expected.

The investigation reported herein deals with a family of related airfoils having mean-line forms derived to extend the camber position from normal to extreme forward positions. These airfoils are divided into two groups, each group containing five airfoils of the same thickness (0.12*c*) and covering a range of maximum camber positions from 0.05*c* to 0.25*c*. One group is based on a simple mean line (mean line without reversal of curvature) and the other on a reflexed mean line. Instead of investigating each mean-line shape through a range of camber ratios as in the previous investigation of related airfoils, only one camber ratio is used for each type, the value of each being selected to give an optimum lift coefficient of 0.3.

DESCRIPTION OF AIRFOILS

The airfoils described herein are designated by the following numbers preceding the number 12, which designates the thickness:

210, 220, 230, 240, 250,
211, 221, 231, 241, 251

Following the designation system previously employed for the N. A. C. A. family airfoils, the first digit of the airfoil number is used to designate the relative magnitude of the camber. The various mean-line shapes are designated by the remaining two digits as follows:

Type \ Position of maximum camber	0.05c	0.10c	0.15c	0.20c	0.25c
Simple	10	20	30	40	50
Reflex	11	21	31	41	51

The ordinates of the airfoils were obtained by the method described in reference 1, which consists briefly in disposing the desired thickness form about a given mean line. The thickness form used is the same as that used for the 12-percent thick airfoils of the earlier investigation. The airfoil profiles are shown in figure 1.

Each mean line is defined by two equations derived so as to produce a shape having a progressively decreasing curvature from the leading edge aft. The curvature decreases to zero at a point slightly behind the maximum camber position and, for the simple mean lines, remains zero from this point to the trailing edge. The following expressions taken to represent the simple mean lines are chosen to satisfy these conditions:

$$\text{nose: } (x=0 \text{ to } x=m) \qquad \frac{d^2y}{dx^2}=k_1\,(x-m)$$

$$\text{tail: } (x=m \text{ to } x=1) \qquad \frac{d^2y}{dx^2}=0$$

The mean-line equations are derived from these expressions. The constants of integration are determined by the following conditions:

$$x=0 \qquad y=0$$

$$x=m \qquad y_N=y_T$$

$$\left(\frac{dy}{dx}\right)_N=\left(\frac{dy}{dx}\right)_T$$

$$x=1 \qquad y=0$$

where the subscripts $_N$ and $_T$ refer to the fore and aft equations, respectively. The solutions of the equations then become:

$$\text{nose: } y=\frac{1}{6}k_1[x^3-3mx^2+m^2\,(3-m)x]$$

$$\text{tail: } y=\frac{1}{6}k_1m^3\,(1-x)$$

The values of m were determined to give five positions of maximum camber, namely, 0.05*c*, 0.10*c*, 0.15*c*, 0.20*c*, and 0.25*c*. Finally, values of k_1 were calculated to give a theoretical lift coefficient of 0.3 ($C_{L_I}=0.3$) at the "ideal" angle of attack (reference 1). Table I presents the values of m and k_1 for convenient reference.

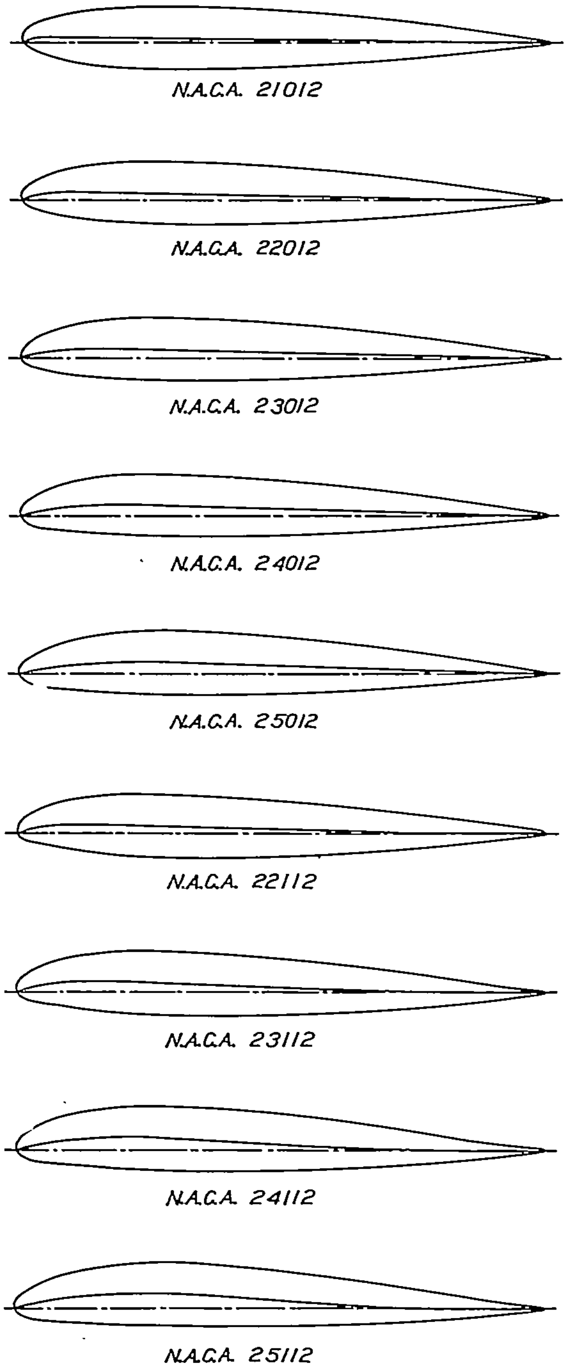


FIGURE 1.—Airfoil profiles.

TABLE I

Mean-line designation	Position of camber p	m	k_1	k_2/k_1
210	0.05	0.0580	361.4	----------
220	.10	.1260	51.64	----------
230	.15	.2025	15.957	----------
240	.20	.2900	6.643	----------
250	.25	.3910	3.230	----------
211	.05	(1)	(1)	(1)
221	.10	.1300	51.99	7.64
231	.15	.2170	15.793	67.70
241	.20	.3180	6.520	303.0
251	.25	.4410	3.191	1355

[1] The data for this airfoil are not included because the airfoil tested was subsequently found to differ from the intended airfoil through an error in deriving the ordinates.

The equations for the reflexed mean lines are derived from the following expressions again taken to give progressively decreasing curvature and to give zero curvature where the two parts join. The tail part, however, is represented by an expression giving a curved mean line permitting of adjustment to give zero pitching moment.

$$\text{nose: } (x=0 \text{ to } x=m) \quad \frac{d^2y}{dx^2}=k_1\,(x-m)$$

$$\text{tail: } (x=m \text{ to } x=1) \quad \frac{d^2y}{dx^2}=k_2\,(x-m)$$

Determining the constants of integration by the same conditions as for the simple mean lines, the solutions of these equations are:

$$\text{nose: } y=\frac{1}{6}k_1\left[(x-m)^3-\frac{k_2}{k_1}(1-m)^3x-m^3x+m^3\right]$$

$$\text{tail: } y=\frac{1}{6}k_1\left[\frac{k_2}{k_1}(x-m)^3-\frac{k_2}{k_1}(1-m)^3x-m^3x+m^3\right]$$

The ratio $\frac{k_2}{k_1}$ is expressed in terms of the position of maximum camber p and the juncture point m.

$$\frac{k_2}{k_1}=\frac{3\,(m-p)^2-m^3}{(1-m)^3}$$

For each of five values of p (0.05c, 0.10c, 0.15c, 0.20c, and 0.25c), m was determined to give $C_{m_{c/4}}=0$ and, finally, k_1 was calculated to give $C_{L_I}=0.3$. Values of $\frac{k_2}{k_1}$, m, and k_1, are given in table I.

The models, which are made of duralumin, are rectangular and have a chord of 5 inches and a span of 30 inches. They are constructed from the computed ordinates by the method described in reference 2.

TESTS AND RESULTS

Routine measurements of the lift, drag, and pitching moment about the quarter-chord point were made at a Reynolds Number of approximately 3,000,000 (tank pressure, approximately 20 atmospheres). A description of the variable-density tunnel, in which the tests were made, and of the method of testing is given in reference 2.

The discussion of precision in reference 1 points out an error in the velocity measurements due to a change in the apparent density of the manometer fluid with a change in tank pressure from atmospheric. This source of error has since been eliminated by correcting the manometer settings used in fixing the tunnel air speed.

The data are presented in standard graphic form (figs. 2 to 10) as coefficients corrected after the method of reference 2 to give airfoil characteristics for infinite aspect ratio and aspect ratio 6. Included in these figures are tables of airfoil ordinates at standard stations and a plot of the profile.

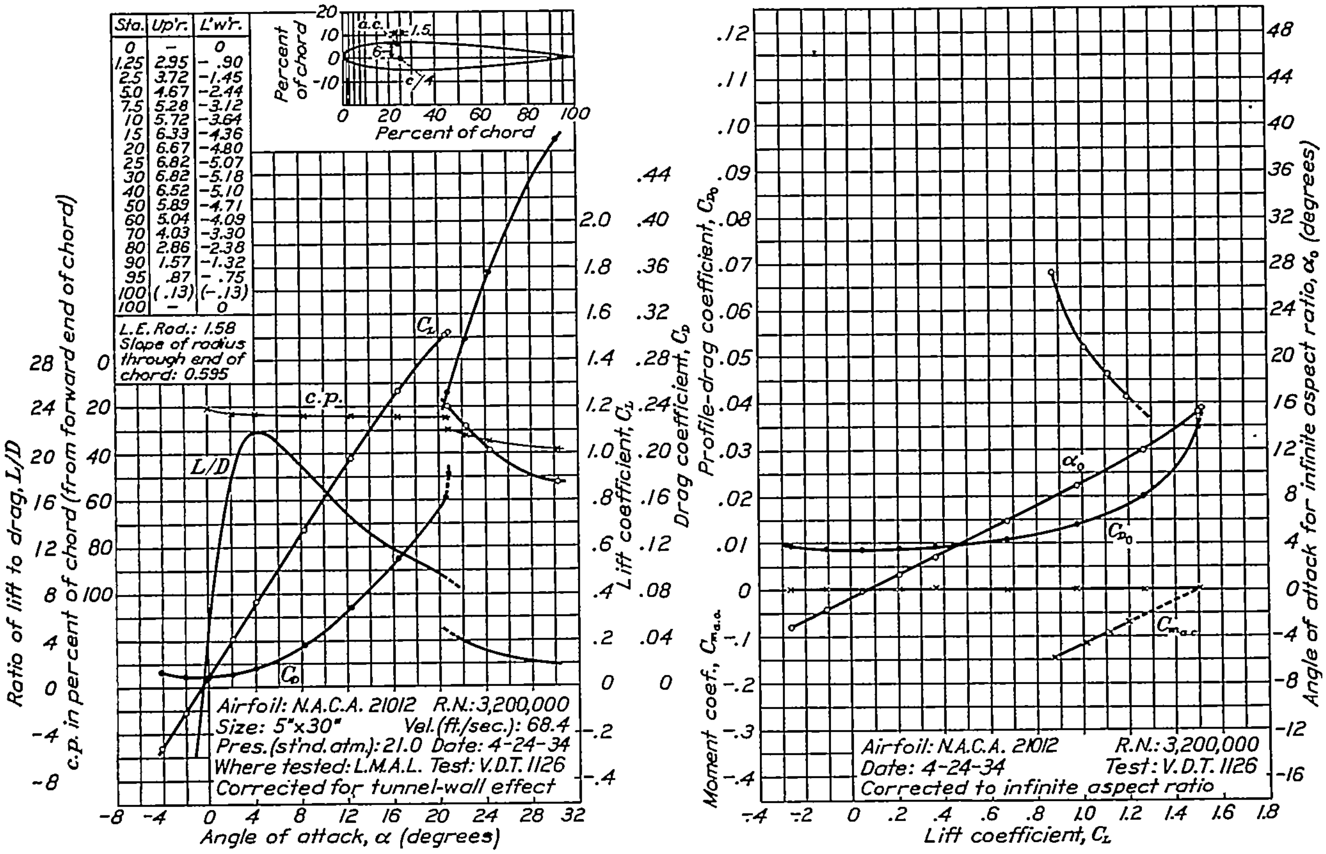


FIGURE 2.—N. A. C. A. 21012 airfoil.

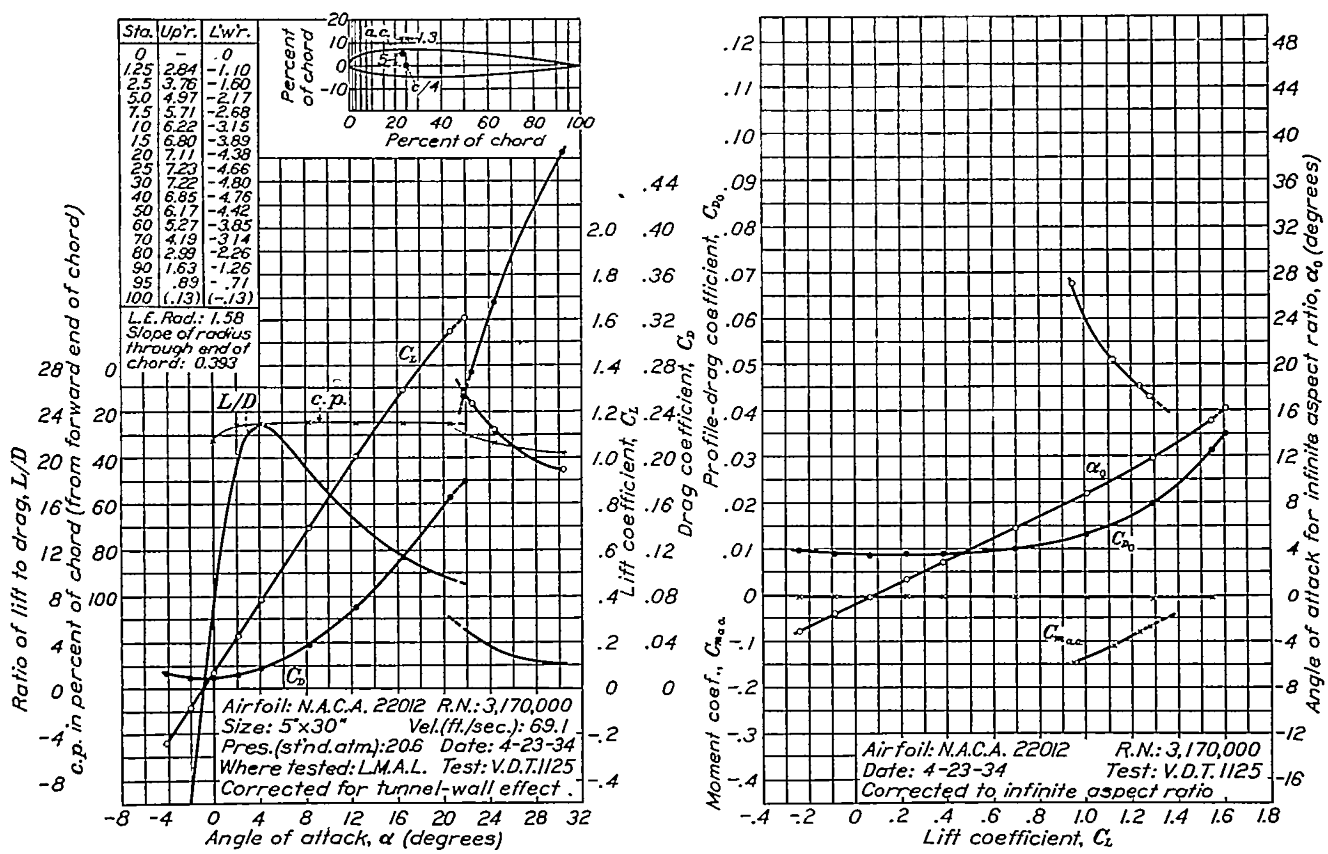


FIGURE 3.—N. A. C. A. 22012 airfoil.

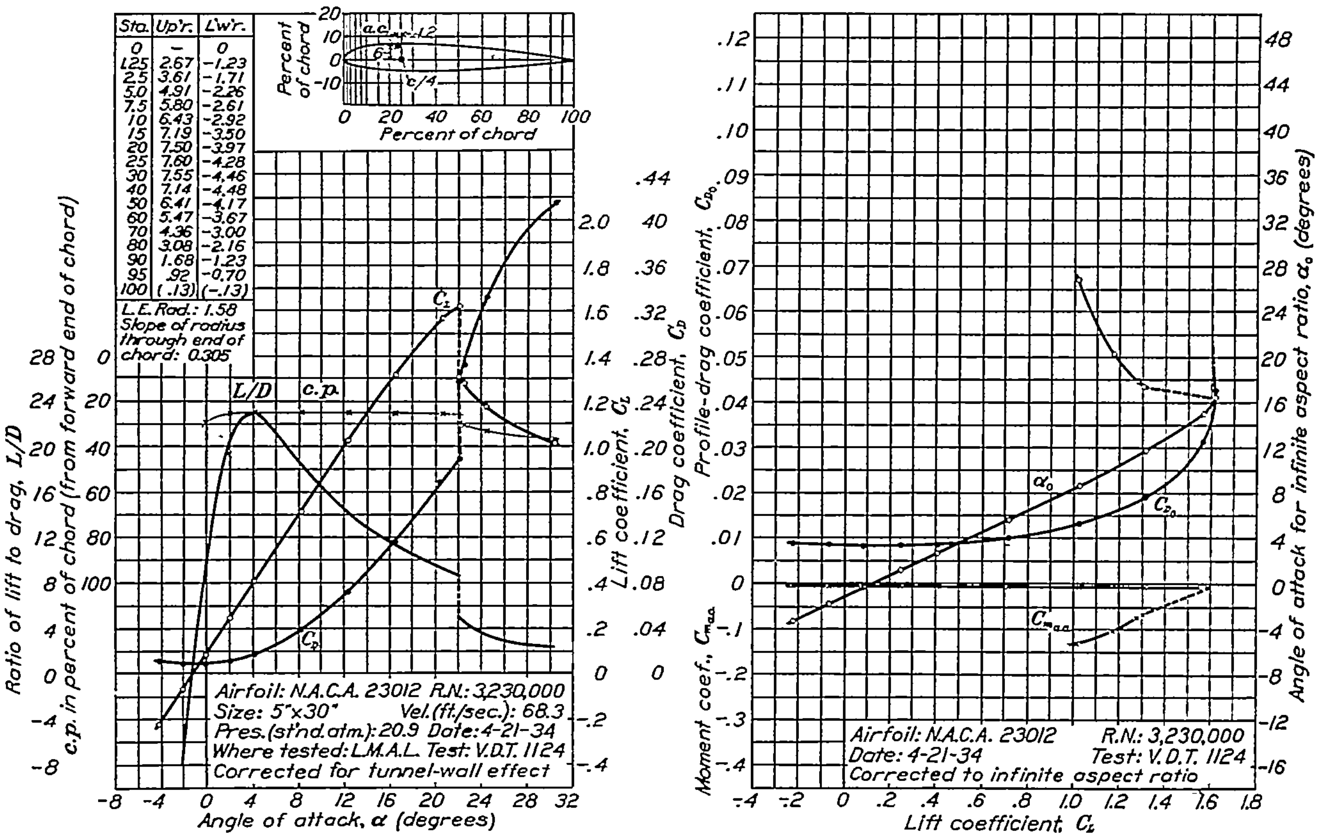


FIGURE 4.—N. A. C. A. 23012 airfoil.

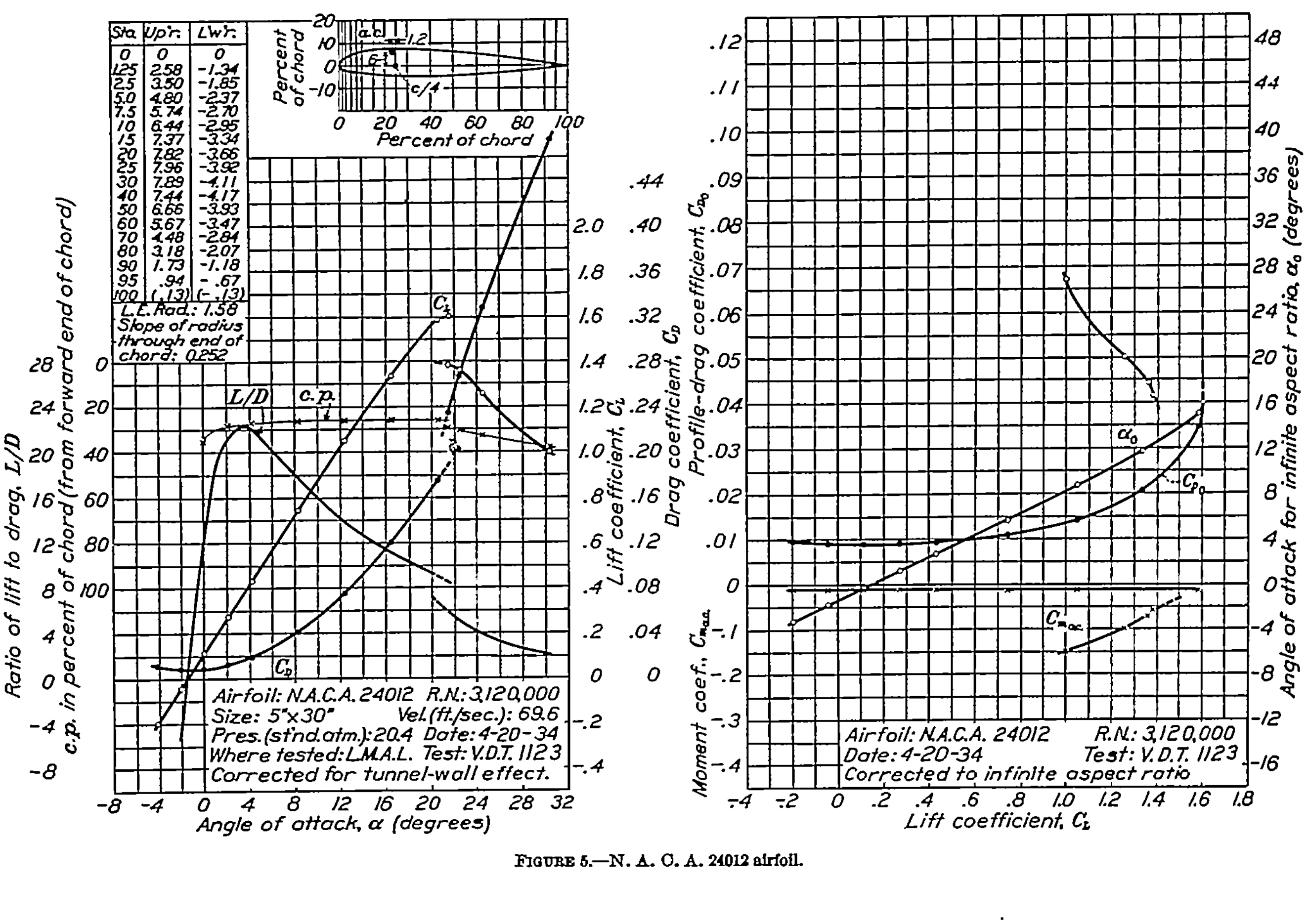
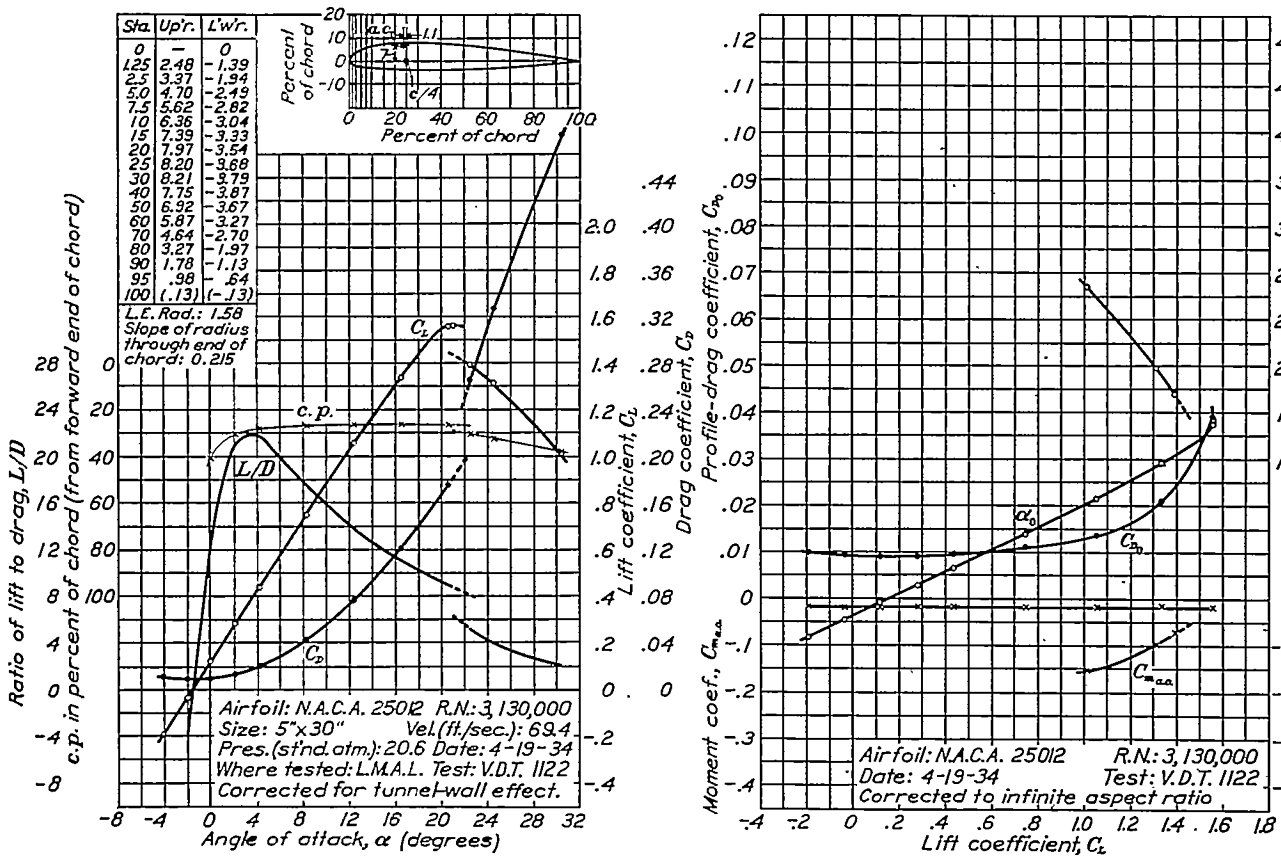
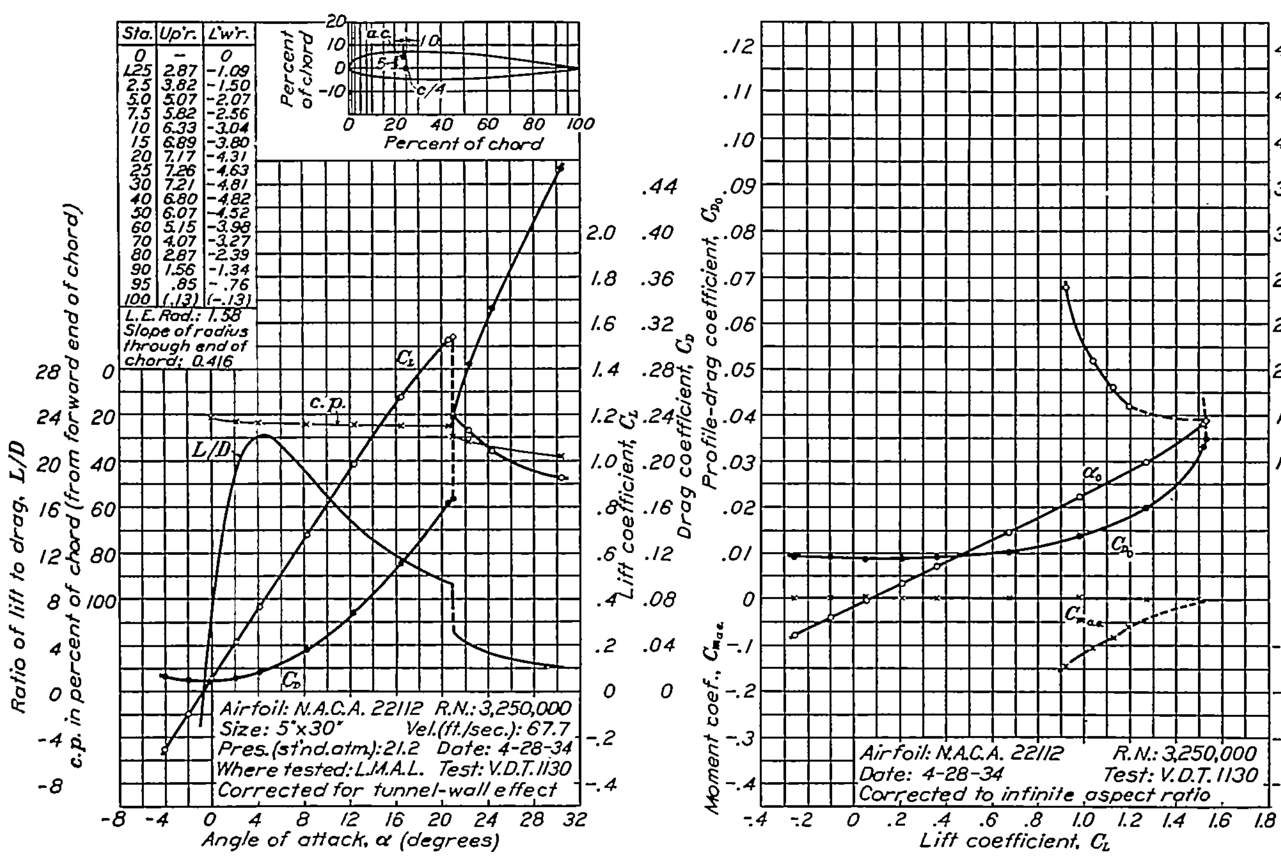


FIGURE 5.—N. A. C. A. 24012 airfoil.



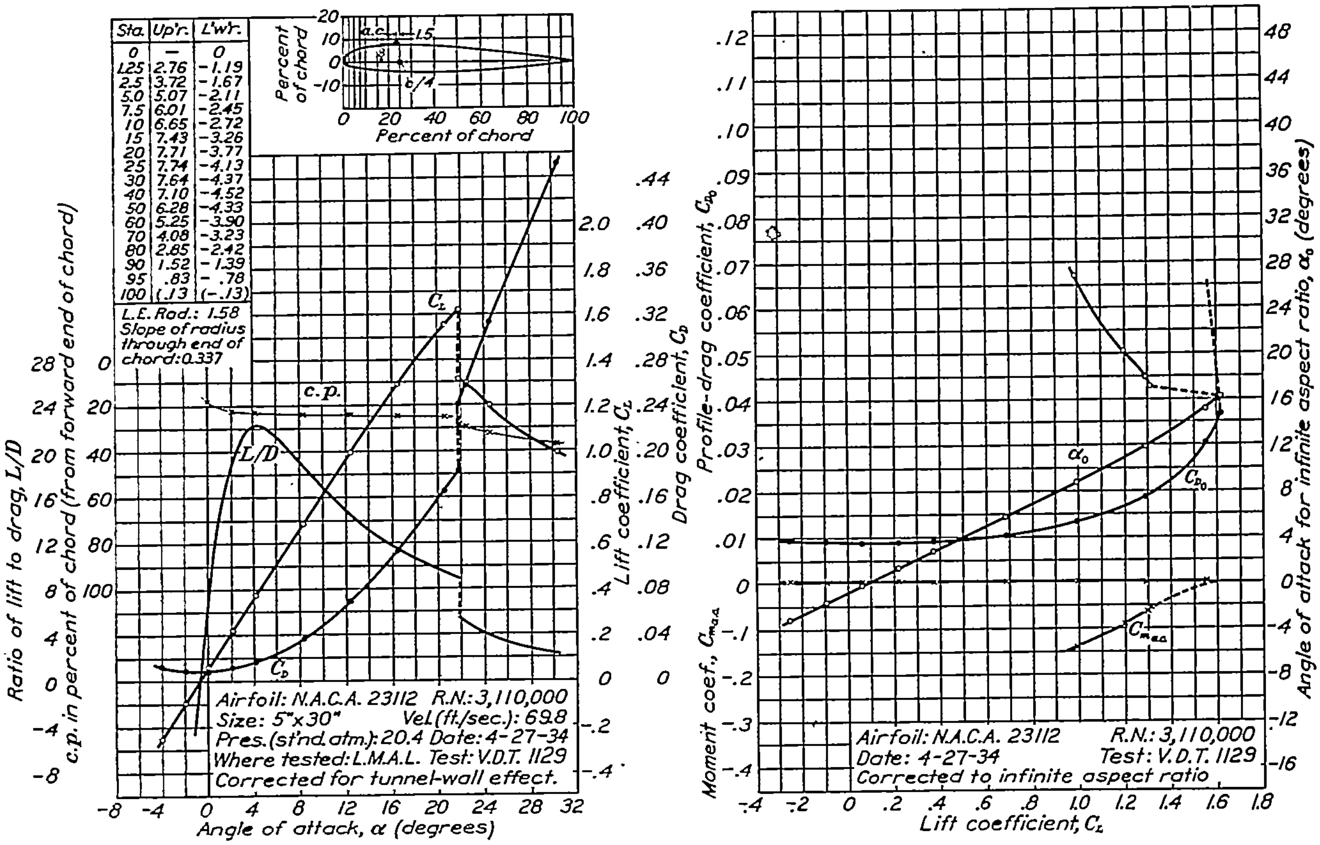
Sta.	Up'r.	L'w'r.
0	—	0
1.25	2.48	-1.39
2.5	3.37	-1.94
5.0	4.70	-2.49
7.5	5.62	-2.82
10	6.36	-3.04
15	7.39	-3.33
20	7.97	-3.54
25	8.20	-3.68
30	8.21	-3.79
40	7.75	-3.87
50	6.92	-3.67
60	5.87	-3.27
70	4.64	-2.70
80	3.27	-1.97
90	1.78	-1.13
95	.98	-.64
100	(.13)	(-.13)

FIGURE 6.—N. A. C. A. 25012 airfoil.



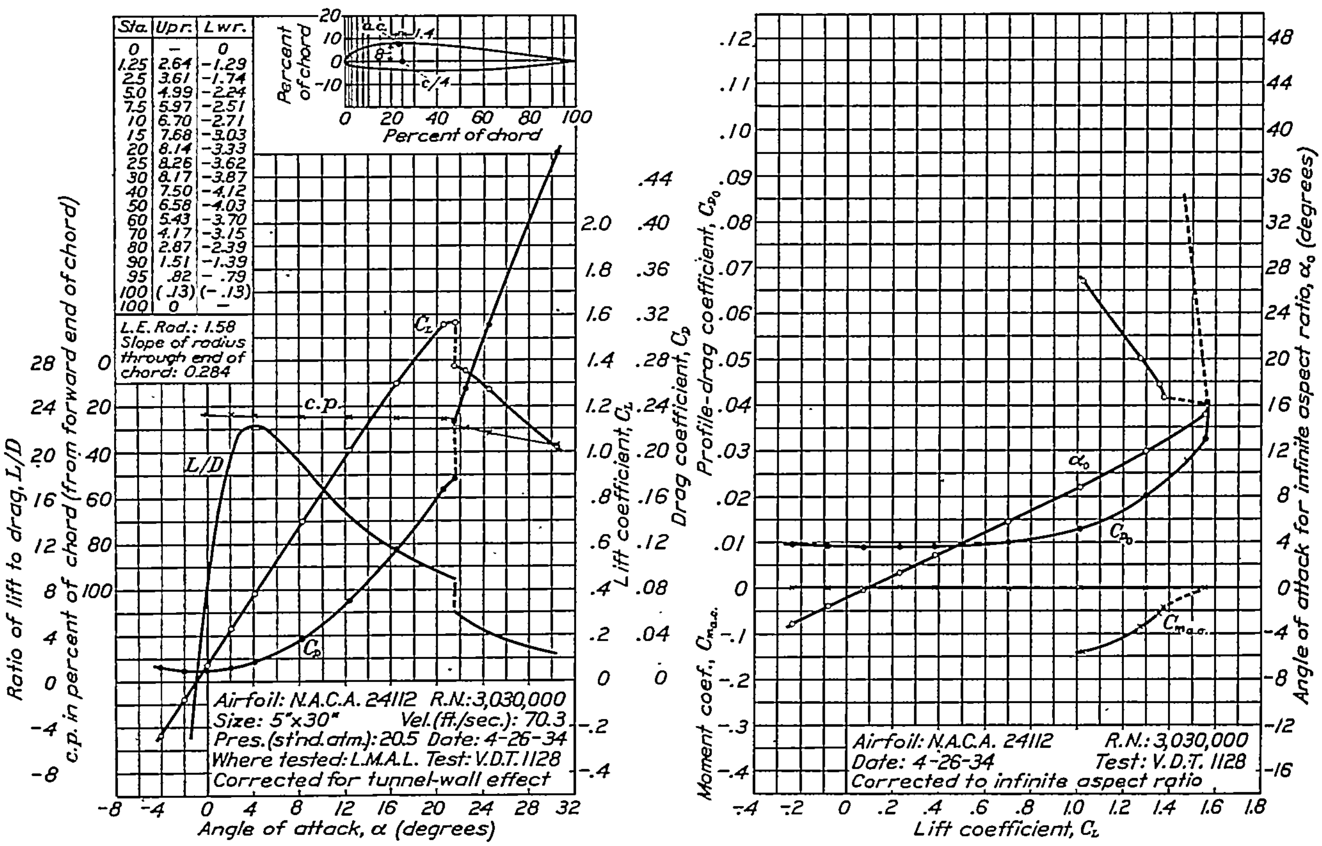
Sta.	Up'r.	L'w'r.
0	—	0
1.25	2.87	-1.09
2.5	3.82	-1.50
5.0	5.07	-2.07
7.5	5.82	-2.56
10	6.33	-3.04
15	6.89	-3.80
20	7.17	-4.31
25	7.26	-4.63
30	7.21	-4.81
40	6.80	-4.82
50	6.07	-4.52
60	5.15	-3.98
70	4.07	-3.27
80	2.87	-2.39
90	1.56	-1.34
95	.85	-.76
100	(.13)	(-.13)

FIGURE 7.—N. A. C. A. 2212 airfoil.



Sta.	Up'r.	L'wr.
0	—	0
1.25	2.76	-1.19
2.5	3.72	-1.67
5.0	5.07	-2.11
7.5	6.01	-2.45
10	6.65	-2.72
15	7.43	-3.26
20	7.71	-3.77
25	7.74	-4.13
30	7.64	-4.37
40	7.10	-4.52
50	6.28	-4.33
60	5.25	-3.90
70	4.08	-3.23
80	2.85	-2.42
90	1.52	-1.39
95	.83	- .78
100	(.13)	(-.13)

FIGURE 8.—N. A. C. A. 23112 airfoil.



Sta.	Upr.	Lwr.
0	—	0
1.25	2.64	-1.29
2.5	3.61	-1.74
5.0	4.99	-2.24
7.5	5.97	-2.51
10	6.70	-2.71
15	7.68	-3.03
20	8.14	-3.33
25	8.26	-3.62
30	8.17	-3.87
40	7.50	-4.12
50	6.58	-4.03
60	5.43	-3.70
70	4.17	-3.15
80	2.87	-2.39
90	1.51	-1.39
95	.82	- .79
100	(.13)	(-.13)
100	0	—

FIGURE 9.—N. A. C. A. 24112 airfoil.

In addition to the standard plots the important characteristics of these airfoils are presented in table II, including also the N. A. C. A. 0012 and the N. A. C. A. 2212 airfoils for comparison. These tabulated characteristics are corrected for turbulence and tip effects as discussed briefly in the succeeding paragraphs. The more accurate section characteristics thus obtained are designated by lower-case instead of capital letters, e. g., $c_{d_{0_{min}}}$ instead of $C_{D_{0_{min}}}$, etc.

Section characteristics derived from tests of airfoils having square tips are subject to small corrections made necessary by tip losses. Making the reasonable assumption that more accurate section characteristics can be obtained from tests on rounded-tip airfoils, corrections have been determined from comparative tests of several airfoils with and without rounded tips and the corrected characteristics are shown in table II.

The maximum-lift values given in the table may be considered as applicable to flight at the value of the Reynolds Number given as the "effective Reynolds Number." As discussed in reference 3, agreement with flight is to be expected when the results are thus applied on the basis of an effective Reynolds Number in order to allow for the effects of turbulence present in the wind tunnel. The tabulated drag coefficients have been corrected for the change in skin-friction drag corresponding to the change in Reynolds Number to an effective value. The data given in table II are therefore directly applicable at the effective Reynolds Number and, when supplemented by additional information to be published about the character of the scale effect as indicated by the scale-effect classification, will enable improved predictions of maximum lift coefficients at other values of the Reynolds Number.

DISCUSSION

The important independent variable, as mentioned in the introduction, is the camber position. The variation of the aerodynamic characteristics with camber position, discussed in the following paragraphs, is shown by cross plots (figs. 11 to 16) of the characteristics taken from the standard plots (figs. 2 to 10).

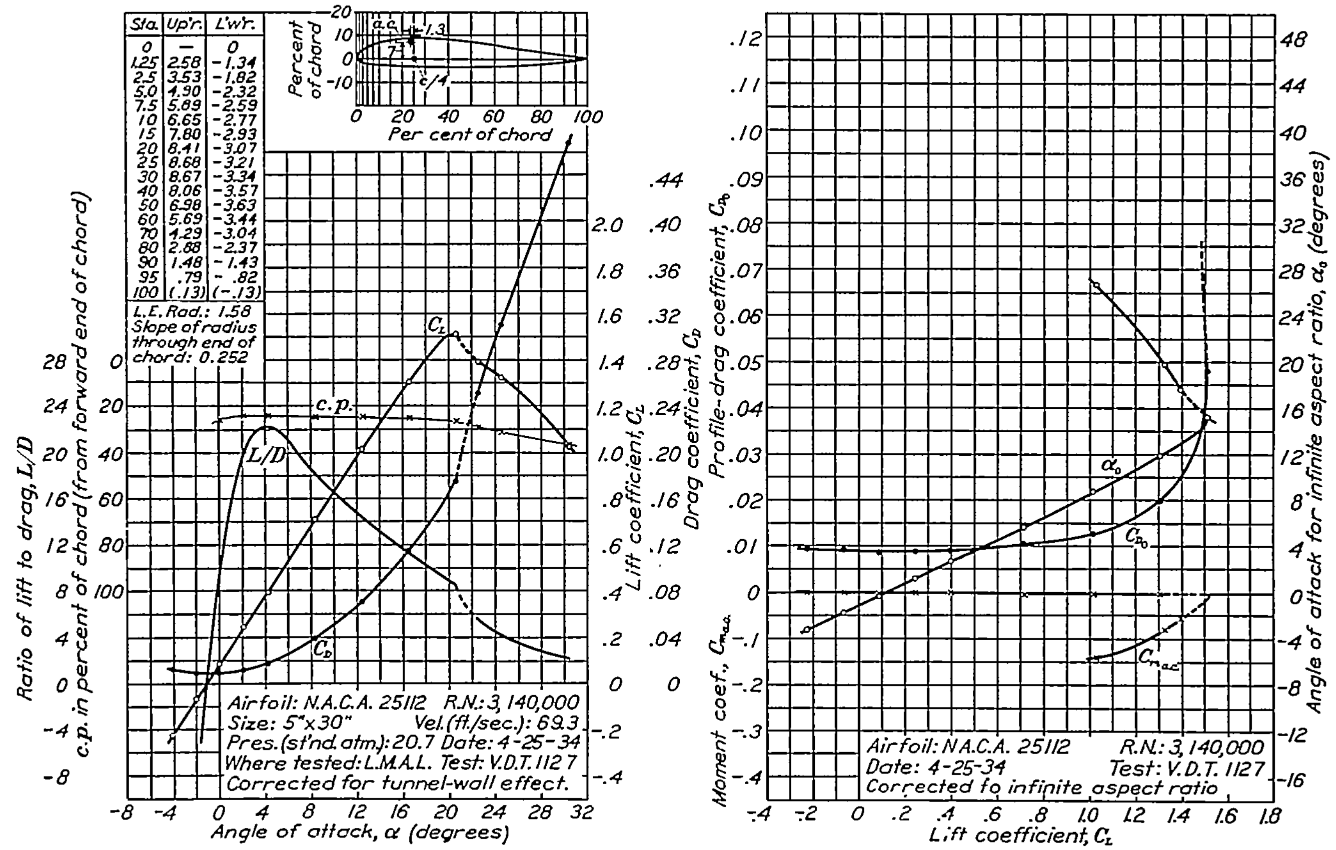


FIGURE 10.—N. A. C. A. 25112 airfoil.

The slope of the lift curve for each airfoil is less than the theoretical value for thin airfoils, 2π per radian, and is practically constant over the range of camber positions tested (fig. 11). The angle of zero lift is only slightly affected by change in camber position as shown in figure 12. Zero lift occurs at slightly greater negative angles than the theoretical values based on the mean line, the values of the experimental angles differing by approximately 0.2° from the theoretical values.

Previous tests have shown that reflexed mean-line airfoils produce a slightly higher minimum drag than simple mean-line airfoils. This conclusion is further confirmed by figure 13, which also shows a slight increase in drag as the camber position changes from

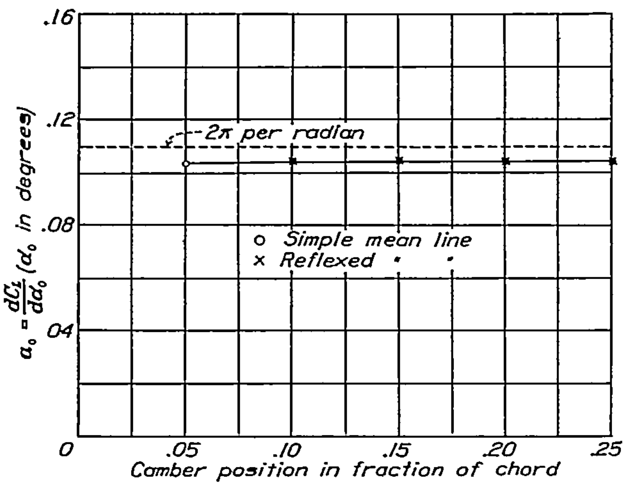


FIGURE 11.—Variation of lift-curve slope with camber position.

0.15*c* to 0.25*c*. The optimum lift (fig. 14) for both types is about the same but increases as the position of the camber moves aft in the range tested. These

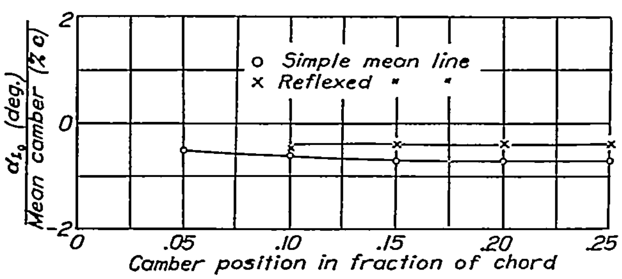


FIGURE 12.—Variation of angle of zero lift with camber position.

values may be compared with 0.3, the theoretically determined value of the lift coefficient at the "ideal" angle of attack for the mean line, i. e., the angle of

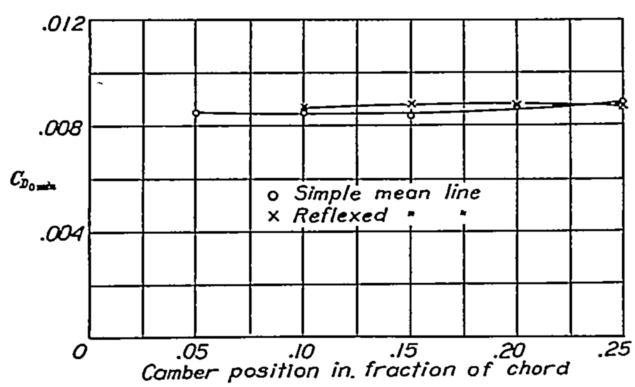


FIGURE 13.—Variation of minimum profile drag with camber position.

attack for which the thin-airfoil theory gives a finite velocity at the nose. The optimum lift coefficients for these airfoils are smaller than the theoretical value of the ideal lift coefficient ($C_{L_I}=0.3$).

The variation in maximum lift is shown in figure 15 and supports previous findings that reflex airfoils have a lower maximum lift. Moving the camber position

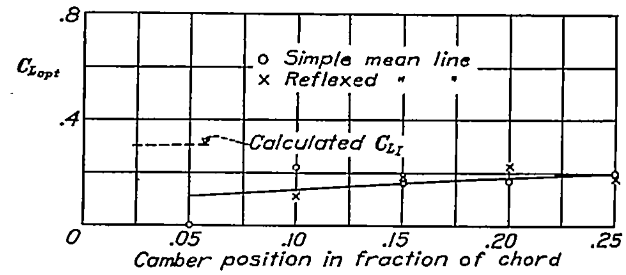


FIGURE 14.—Variation of optimum lift with camber position.

forward from 0.25*c* to 0.15*c* tends to increase slightly the maximum lift. With the maximum camber position forward of 0.15*c*, the maximum lift of the sim-

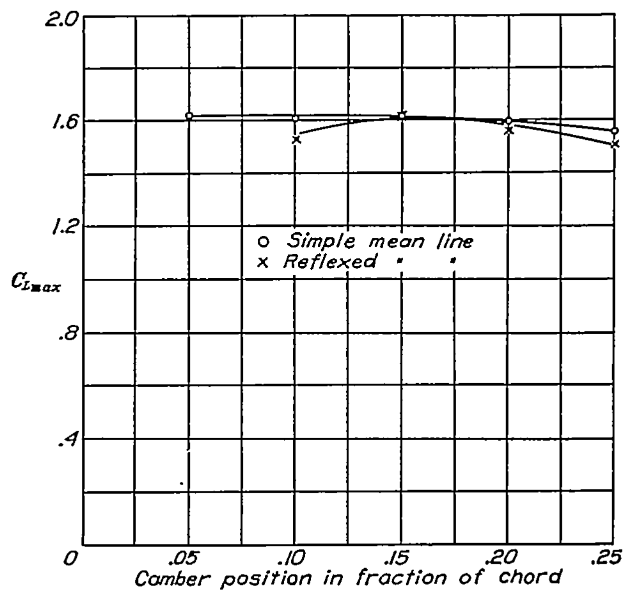


FIGURE 15.—Variation of maximum lift with camber position.

ple mean-line airfoils was unaffected but the reflexed mean-line airfoils showed a decreased maximum lift.

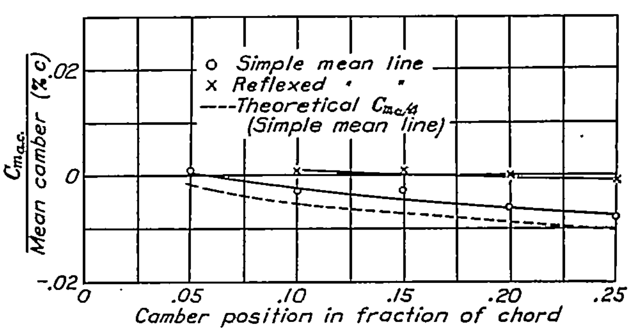


FIGURE 16.—Variation of pitching moment with camber position.

The measured pitching moment (fig. 16) for the reflexed airfoils remained practically zero with variation of position of maximum camber in accordance with design calculations. The simple mean-line airfoils gave exceptionally low pitching moments, somewhat lower than the theoretical values based on the mean line. Both the measured and theoretical curves for the simple mean-line airfoils are given in figure 16.

The analysis of these charts and the data of table II show that the reflexed airfoils, although comparing favorably with other reflexed airfoils, are surpassed by the simple mean-line airfoils. Furthermore, the airfoils covering a range of camber locations forward of normal positions possess improved characteristics.

A comparison of the N. A. C. A. 24012 with the N. A. C. A. 2212 indicates the differences that may be attributed to the difference between the mean-line forms. These airfoils having the same camber location but different mean-line forms possess approximately the same lift and drag characteristics. The angle of zero lift and the pitching moment, however, are quite different. Especially noteworthy is the very much lower pitching moment produced by the airfoils reported herein.

One of the promising airfoils of this group, the N. A. C. A. 23012 airfoil (previously referred to as "the N. A. C. A. A-312"), has been further investigated by tests in the full-scale tunnel and over a range of values of the Reynolds Number in the variable-density tunnel. These results (reference 3) confirm the conclusion that this airfoil has improved characteristics over well-known and commonly used airfoils of this class. It has a high maximum lift and a low pitching moment. Furthermore, the minimum drag is practically as low as that of the corresponding symmetrical airfoil, the N. A. C. A. 0012.

More generally, other sections of this group, such as the N. A. C. A. 21012 and 22012 having an even lower pitching moment than the 23012, should supply the need of many applications requiring a slightly cambered section of moderate thickness having a very low pitching moment.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *May 7, 1935.*

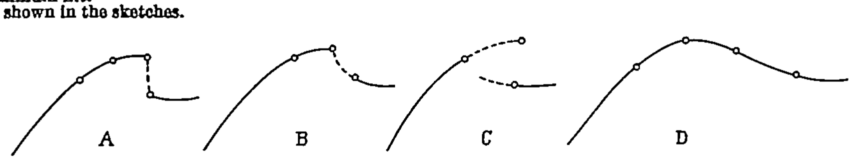
REFERENCES

1. 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. T. R. No. 460, N. A. C. A., 1933.
2. Jacobs, Eastman N., and Abbott, Ira, H.: The N. A. C. A. Variable-Density Wind Tunnel. T. R. No. 416, N. A. C. A., 1932.
3. Jacobs, Eastman N., and Clay, William C.: Characteristics of the N. A. C. A. 23012 Airfoil from Tests in the Full-Scale and Variable-Density Tunnels. T. R. No. 530, N. A. C. A., 1935.

TABLE II.—AIRFOIL DATA

Airfoil	Classification: Chord[1]	PD[2]	SE[3]	$C_{L_{max}}$[4]	Effective R. N., millions[5]	$C_{L_{max}}$	α_0 at $C_{L_{max}}$ (degrees)	Fundamental section characteristics: α_{l_0} (degrees)	a_0 (per deg.)	$c_{l_{opt}}$	$c_{d_{0_{min}}}$	$c_{m_{a.c.}}$	a. c. (percent c from c/4): Ahead	Above	Derived and additional characteristics that may be used for structural design: $\frac{C_{L_{max}}}{c_{d_{0_{min}}}}$	c. p. at $C_{L_{max}}$ (percent c): Computed	Actual	Wing characteristics A. R. 6 rounded tips: m_s (per rad.)	$C_{D_{min}}$	Thickness (percent c) at—: 0.15c	0.65c	Maximum	Camber (percent c)
N. A. C. A. 21012	A	C12	D2	C	8.37	(6) 1.67	15	−0.6	(6) 0.099	(6) 0.00	(6) 0.0070	(6) 0.001	(6) 2.0	(6) 3	(6) 239	(6) 23	25	4.32	0.0070	10.69	8.26	12	1.1
N. A. C. A. 22012	A	C12	D2	C	8.32	1.66	16	−.9	.100	.10	.0071	−.005	1.8	3	234	24	25	4.34	.0073	10.69	8.24	12	1.5
N. A. C. A. 23012	A	C12	D2	A	8.48	1.67	16	−1.2	.100	.08	.0069	−.005	1.7	3	242	24	26	4.34	.0070	10.69	8.25	12	1.8
N. A. C. A. 24012	A	C12	C3	C	8.26	1.65	16	−1.5	.100	.08	.0072	−.013	1.7	3	229	24	26	4.34	.0073	10.71	8.25	12	2.1
N. A. C. A. 25012	A	C12	C3	C	8.24	1.61	15	−1.6	.100	.10	.0075	−.019	1.6	3	215	25	27	4.34	.0077	10.72	8.28	12	2.3
N. A. C. A. 0012	A	C10	C0	A	8.53	1.58	17	.0	.097	.00	.0068	0	1.8	2	232	23	25	4.25	.0063	10.69	8.27	12	0
N. A. C. A. 2212	A	C12	C3	B	8.42	1.65	16	−1.8	.099	.12	.0072	−.029	1.4	2	229	25	27	4.32	.0073	10.69	8.25	12	2.0
N. A. C. A. 22112	A	C11	D2	B	8.55	1.58	15	−.8	.100	.06	.0072	.001	1.5	3	219	23	25	4.34	.0073	10.69	8.27	12	1.6
N. A. C. A. 23112	A	C11	D2	A	8.21	1.67	16	−.8	.100	.08	.0074	.002	2.0	4	226	23	25	4.34	.0075	10.69	8.28	12	2.1
N. A. C. A. 24112	A	C11	C3	A	8.00	1.61	16	−.9	.100	.10	.0074	0	1.9	4	218	23	25	4.34	.0075	10.71	8.26	12	2.4
N. A. C. A. 25112	A	C11	C3	B	8.24	1.56	15	−1.2	.100	.08	.0074	−.002	1.8	3	211	23	27	4.34	.0075	10.73	8.28	12	2.7

[1] Type of chord. A refers to a chord defined as a line joining the extremities of the meanline.
[2] Type of pressure distribution.
[3] Type of scale effect on maximum lift.
[4] Type of lift-curve peak as shown in the sketches.



NOTE.—The foregoing classifications are given here for convenient future reference. A detailed discussion will be published in a later report dealing with the application of airfoil characteristics to design problems.

[5] Turbulence factor is 2.64.
[6] These data have been corrected for tip effect.