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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 521

FULL-SCALE FORCE AND PRESSURE-DISTRIBUTION TESTS
ON A TAPERED U.S.A. 45 AIRFOIL

By John F. Parsons
Langley Memorial Aeronautical Laboratory

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By John F. Parsons

SUMMARY

This report presents the results of force and pressure-distribution tests on a 2:1 tapered U.S.A. 45 airfoil as determined in the full-scale wind tunnel. The airfoil has a constant-chord center section and rounded tips and is tapered in thickness from 18 percent at the root to 9 percent at the tip. Force tests were made throughout a Reynolds Number range of approximately 2,000,000 to 8,000,000 providing data on the scale effect in addition to the conventional characteristics. Pressure-distribution data were obtained from tests at a Reynolds Number of approximately 4,000,000. The aerodynamic characteristics given by the usual dimensionless coefficients are presented graphically.

INTRODUCTION

For a portion of an extensive wing-fuselage interference program being carried out in the N.A.C.A. full-scale wind tunnel, it was necessary to obtain pressure-distribution and force tests upon a tapered U.S.A. 45 airfoil. This particular airfoil section is a feature of the airplane used in the main investigation; otherwise a more commonly used section would have been chosen. The paucity of full-scale information on the aerodynamic characteristics of tapered airfoils warrants the presentation of these data as a report separate from the results of the wing-fuselage interference investigation.

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APPARATUS

Airfoil.- The airfoil, constructed primarily to conform with the requirements of a wing-fuselage interference investigation is of standard wood and fabric aircraft construction. Frise-type ailerons, each comprising 5.1 percent of the total area, were incorporated in the airfoil.

The airfoil (fig. 1) has a span of 45.75 feet, an aspect ratio of 6.20, and a mean chord of 7.38 feet; the area is 337.5 square feet. A constant-chord center section extends 10.7 percent of the semispan from the center line of the airfoil. The plan form, from the center section outboard, is determined by a basic trapezoid tapered 2:1; the rounded tips are formed within the trapezoid. An additional trapezoid, in a plane including the quarter-chord points and perpendicular to the basic plan-form trapezoid, determines the thickness taper outboard of the center section. A geometric similarity is maintained between the mean lines of the root and tip section profiles of the basic trapezoid and the mean line of the root section profile of a U.S.A. 45 airfoil. The desired profile thickness is obtained by varying the thickness of the original profile about its mean line. The thickness taper in percentage of the chord is from 18 percent at the root to 9 percent at the tip of the basic trapezoid. The ordinates of the root section of the airfoil are given in table I. Sections between the root and station 234.5 were formed by using straight-line elements between corresponding points on the root and tip sections of the basic trapezoid. All 25-percent-chord points on the upper surface of the airfoil between stations 234.5 lie on a straight line perpendicular to the plane of symmetry. From stations 234.5 outboard, the thickness at the 25-percent-chord points departs equally, top and bottom, from the basic-thickness trapezoid and the thickness ratios are identical with those of the corresponding sections of the basic trapezoids.

The airfoil was designed with the chords of all the sections parallel. A slight washout was, however, inadvertently built into the structure, accounting for a maximum deviation of section angle of less than 0.3° from the average angle of attack of the airfoil. A tolerance of ±1/16 inch in section profile was specified and errors in construction were found to be within these limits.

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For the purpose of pressure-distribution testing, 68 pairs of standard N.A.C.A. pressure orifices were installed, in special pressure-orifice ribs, at eight positions along the semispan. One orifice of each pair opened on the upper surface of the airfoil, the other, on the lower surface. These pairs of orifices were arranged along the chord in such a manner as to facilitate fairing of the pressure diagrams. The lateral, or spanwise, location of the pressure orifice rows is shown in figure 1.

Manometers.- A pair of multiple-tube recording manometers of the liquid type (fig. 2) were used to measure simultaneously the pressures at the orifices. Each manometer was composed of a circular bank of 100 glass tubes. One end of each tube was immersed in a closed reservoir containing carbon tetrachloride; the other end was connected to the pressure orifice through aluminum and rubber tubing. An initial pressure was imposed upon the carbon tetrachloride in the reservoir to raise the static level of the liquid to a height sufficient to enable the recording of both the positive and negative pressures of the order of magnitude encountered. Photostat paper was automatically drawn around the outer circumference of the bank of tubes and the exposure made by flashing a vertical neon lamp located at the center of the bank. It was thus possible with the two manometers to record simultaneously the pressure heads produced by the aerodynamic pressures at all the orifices. The aluminum tubing from each of the pressure orifices was collected inside the airfoil and was led, in the form of a strut, through the lower surface of the airfoil at the plane of symmetry to the two manometers located in the balance house below.

Tunnel.- The tests were conducted in the N.A.C.A. full-scale wind tunnel. A description of the tunnel, balances, and auxiliary apparatus is given in reference 1. Figure 3 shows the airfoil mounted on the balance for the force tests.

TESTS

The pressure-distribution tests were run at a Reynolds Number of approximately 4,000,000 based upon the mean chord of the airfoil (7.38 feet) as a characteristic length. Four exposures, i.e., four distinct series of pressure measurements, were made at each of nine angles throughout an angle-of-attack range of -4° to 24°. An average of

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these four readings, for each orifice, was used in plotting the pressure diagrams.

Lift, drag, and pitching-moment measurements comprised the force tests on the airfoil during which data were obtained throughout an angle-of-attack range of -8° to 26° at Reynolds Numbers varying from approximately 2,000,000 to 5,000,000. In addition, tests to determine the scale effect upon minimum drag, the angle of zero lift, slope of the lift curve, and the value of the pitching-moment coefficient at zero lift were made over a short range of angle of attack (-8.0° to 0.8°) in the neighborhood of minimum drag, at Reynolds Numbers up to 8,000,000. All tests were made with the airfoil at 0° yaw and roll and with the ailerons locked at 0° relative to the airfoil. The test procedure is detailed in reference 2.

RESULTS

The results of the tests, in the usual form of dimensionless coefficients, are presented graphically in figures 4 to 9. All test results have been corrected for the influence of the jet boundary, support interference, and for the effect of blocking as detailed in references 2 and 3. Average air-stream angle and dynamic-pressure corrections were applied to the force-test results; local air-stream angle and dynamic pressures at each orifice rib were considered in computing the pressure-distribution data.

<u>Force tests</u>.- Figure 4 presents the coefficients plotted against angle of attack for a Reynolds Number of approximately 5,000,000. The pitching-moment coefficients are referred to the axis about which the coefficient, based on the mean chord, is constant over a considerable range of angle of attack. The intersection of this axis with the plane of symmetry of the airfoil is termed the "aerodynamic center", giving rise to the designation of the pitching-moment coefficient as $C_{m_{ac}}$. The location of this axis is given, with reference to the root chord, in figure 4.

The variation of the airfoil characteristics over a large range of Reynolds Numbers is shown in figure 5.

Scale effect upon the effective profile-drag coeffi-

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cient C_{D_e} is shown in figure 6. The coefficient defined by $C_{D_e} = C_D - C_L{}^2/6.20\pi$ was chosen to facilitate a comparison with other airfoils. This arbitrary coefficient is based upon an elliptical wing loading and can be used correctly only on airfoils of aspect ratio 6.20. A comparison with airfoils of different aspect ratio may be effected with little error at low values of C_L.

Pressure distribution.- The normal-force and pitching-moment coefficients and the longitudinal and lateral locations of the center of pressure for the entire wing are plotted against the angle of attack to present the results of the pressure-distribution tests. In addition to the preceding plots, span-load diagrams are given.

The values of normal-force coefficient C_N and of longitudinal center-of-pressure location were determined for each section from the pressure diagrams, orifice pressure against section chord, as follows:

$$C_N = \frac{A}{q\ c}$$

$$\text{Longitudinal c.p. from quarter-chord point} = \frac{M_A}{A}$$

where A is the integrated area of the pressure diagram.

M_A, integrated moment of area of the pressure diagram about the quarter point of the section chord.

c, section chord.

q, dynamic pressure.

The relative normal loadings K, expressed in nondimensional form, at the various sections are plotted against the semispan in figure 7. When the chord varies along the semispan, the coefficient C_N does not represent the span loads; and it becomes necessary to use a coefficient K defined by

$$K = C_N \frac{\text{section chord}}{\text{semispan}}$$

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Values of the normal-force coefficient C_N, the pitching-moment coefficient about the quarter-chord point, the longitudinal center-of-pressure location in percent of the root chord from the leading edge of the root chord, and the lateral center-of-pressure location in percent of the semispan from the plane of symmetry for the whole wing, as derived from the pressure plots, are presented in figure 8 and were determined as follows:

$$C_N = \frac{A'}{q\frac{S}{2}} \qquad \text{Lateral c.p.} = \frac{M_{A'}}{A'} \times \frac{2}{b}$$

$$C_{m_{c/4}} = \frac{A''}{q\frac{S}{2}\bar{c}} \qquad \text{Longitudinal c.p.} = \frac{1}{4} - \frac{C_{m_{c/4}}}{C_N} \times \frac{\bar{c}}{c'}$$

where A' is the integrated area of the semispan load diagram.

$M_{A'}$, integrated moment of area of the semispan load diagram about the plane of symmetry.

A'', integrated area of the semispan moment diagram; the section pitching moments about the quarter-chord point were computed from section C_N and c.p. positions and plotted against the semispan.

S, total airfoil area.

b, airfoil span.

$\bar{c}$, mean chord of airfoil, $\frac{S}{b}$.

c', root chord of airfoil.

It is to be noted that the longitudinal center-of-pressure locations and the pitching-moment coefficients about the quarter-chord points have been determined considering only the normal forces; i.e., the chord forces on the airfoil have been neglected. The preceding data have been corrected for local air-stream angle and dynamic pressure as well as for wing washout and may be considered as applying to an unwarped airfoil in a steady rectilinear flow.

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A comparison between force and pressure-distribution tests at the same Reynolds Number is afforded in figure 9. For this comparison the results of the pressure-distribution test have been corrected to the conditions of the force test; i.e., the various sections have been considered as working under the same conditions as in the force test, with washout and at varying angles of attack. Again, as in the previous data, the values of longitudinal center-of-pressure location and pitching-moment coefficients are based solely upon the normal forces.

DISCUSSION

An inspection of figure 4 indicates no extreme variation from the normal trend of aerodynamic characteristics. It will be noticed that the lift curve deviates only slightly from a linear function of the angle of attack until a sharp break occurs at the stall, which, at a Reynolds Number of approximately 5,000,000, occurs at $\alpha = 16.2^\circ$ and a value of $C_{L_{max}} = 1.385$. The pitching-moment coefficient $C_{m_{ac}}$ remains constant at a value of -0.041 from slightly below the angle of zero lift (-3.9°) to the angle of stall. A normal center-of-pressure travel and a value of $(L/D)_{max}$ of 21.5 further characterizes this airfoil.

Scale effect upon the tapered U.S.A. 45 airfoil (fig. 5) exhibits the same tendencies as it does on the rectangular Clark Y airfoil of reference 2. A large variation in $C_{D_{min}}$, $C_{L_{max}}$, and $\alpha_{C_{L_{max}}}$ with scale, at low Reynolds Numbers is evident and a "flattening out," or asymptotic tendency, occurs at high Reynolds Numbers. The effect upon L/D, C_{m_o}, $\alpha_{C_L} = 0$, and $dC_L/d\alpha$ is small with these quantities reaching asymptotic values within the range of Reynolds Numbers investigated. The scale effect on $C_{D_{e_{min}}}$ is similar to that on $C_{D_{min}}$, a value of 0.0095 being attained at a Reynolds Number of approximately 5,000,000 (fig. 6).

The relative loading along the semispan for the untwisted airfoil in a uniform velocity field at a Reynolds Number of approximately 4,000,000 (fig. 7) for angles below the stall is light at the tips and approaches a lin-

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ear function of the span over the tapered portion of the airfoil. A sharp break in loading at the center section is evident and is, no doubt, due to the interrupted plan-form contour. This break might be obviated and an improvement in load obtained through an increase in the angle of attack of the center section relative to the remainder of the airfoil.

The normal-force coefficient for the entire airfoil C_N exhibits the same tendency (fig. 8) as does the lift coefficient. The stall is at $\alpha = 15.7^\circ$ and at a value of $C_N = 1.333$. The longitudinal center of pressure based on C_N alone has a normal travel and reaches a maximum forward position of 26.6 percent of the root chord. The pitching-moment coefficient about the quarter-chord point of the root chord $C_{m_{c/4}}$, based on C_N and the mean chord, increases from -0.042 at $\alpha = 0^\circ$ to -0.025 and then decreases abruptly at the stall to a constant value of -0.075 beyond the stall. The lateral center-of-pressure location is practically constant at approximately 43 percent of the semispan from the plane of symmetry, throughout the flight range, moving toward the tip just beyond the stall and then receding slowly.

The comparison of force and pressure-distribution tests, at a Reynolds Number of approximately 4,000,000 as given in figure 9, shows the two methods to be in excellent agreement, providing justification for the dependence upon full-scale pressure-distribution data.

Application of these data to flight conditions without correction is believed justifiable in view of the small degree of turbulence in the wind tunnel (reference 2). For the $C_{L_{max}}$ and $\alpha_{C_{L_{max}}}$ characteristics, which have not reached an asymptotic value in the range of Reynolds Numbers investigated, the range will probably be sufficient for most flight conditions. For any value of C_L below the stall, the scale effect upon the pitching-moment coefficient, about the root quarter-chord point, is slight above a Reynolds Number of 4,000,000. It is then reasonable to expect that the distribution of load at each section remains essentially constant at any one value of C_L for Reynolds Numbers greater than 4,000,000. From the foregoing, the application of the pressure-dis-

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tribution data obtained at a Reynolds Number of approximately 4,000,000 to a larger Reynolds Number seems permissible when the airfoil is in an unstalled attitude.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., February 20, 1935.

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1. DeFrance, Smith J.: The N.A.C.A. Full-Scale Wind Tunnel. T.R. No. 459, N.A.C.A., 1933.

2. Silverstein, Abe: Scale Effect on Clark Y. Airfoil Characteristics from N.A.C.A. Full-Scale Wind-Tunnel Tests. T.R. No. 502, N.A.C.A., 1934.

3. Theodorsen, Theodore, and Silverstein, Abe: Experimental Verification of the Theory of Wind-Tunnel Boundary Interference. T.R. No. 478, N.A.C.A., 1934.

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TABLE I

TAPERED U.S.A. 45 AIRFOIL

Specified Section Ordinates, Root Section

Root - Station 29.5		
Chord = 116 inches		
Thickness = 18 percent		
Station	Upper	Lower
0	1.63	1.63
1.25	4.71	-.04
2.50	6.20	-.67
5.00	8.63	-1.52
7.50	10.45	-2.05
10.00	11.70	-2.50
15.00	13.22	-3.20
20.00	14.11	-3.51
25.00	14.38	-3.62
30.00	14.24	-3.68
40.00	13.13	-3.61
50.00	11.08	-3.40
60.00	9.60	-3.00
70.00	7.47	-2.44
80.00	5.11	-1.73
90.00	2.59	-.92
95.00	1.27	-.45
100.00	0	0

Section ordinates in percent chord

Stations in percent chord from L.E.

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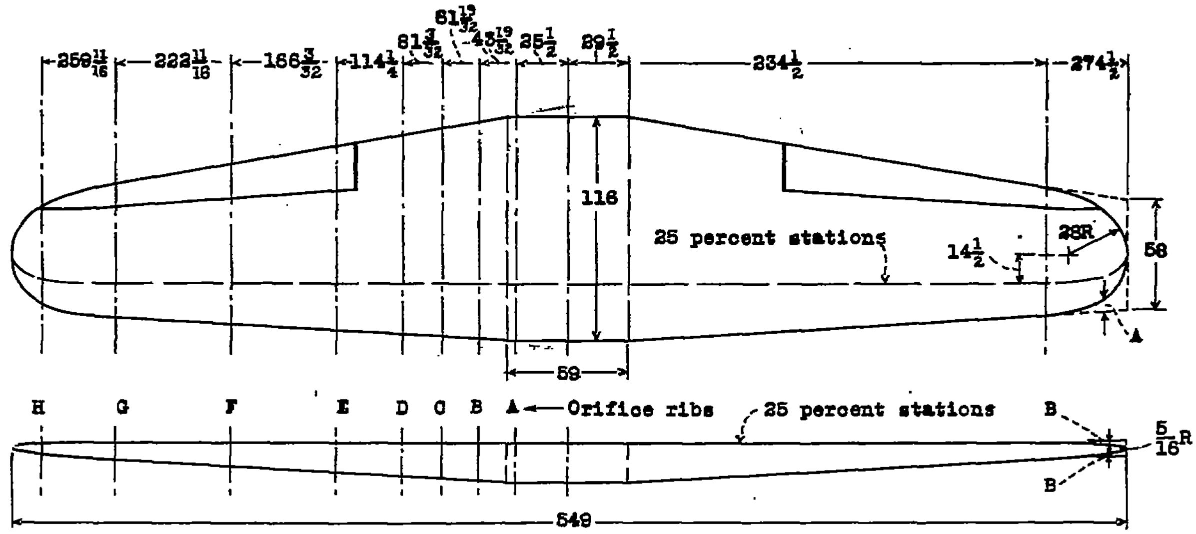

Station	Chord	A	B
234.5	67.47	0	0
244.5	63.70	0.52	0.05
254.5	56.40	2.88	.35
264.5	43.40	8.20	1.20
274.5	0	29.00	3.15

All dimensions are in inches

Figure 1.- Tapered U.S.A.45 airfoil. Plan form and orifice location.

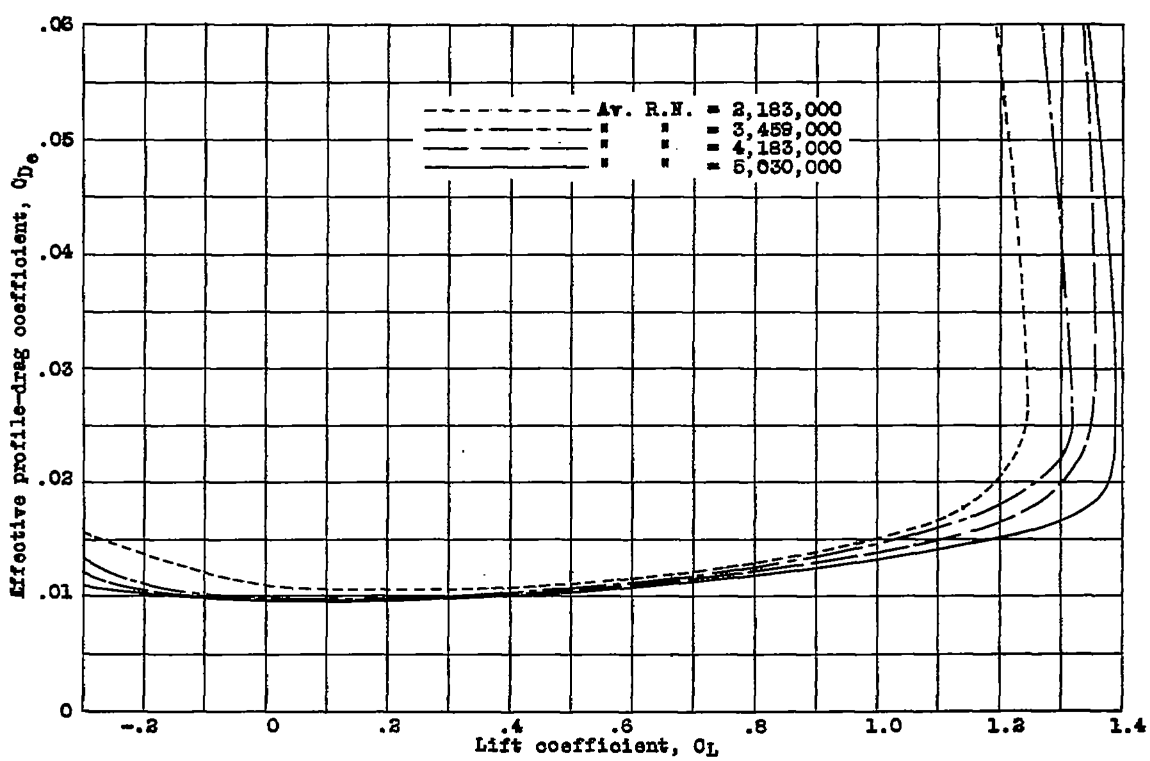

Figure 6.- Variation of effective-profile-drag coefficient with lift coefficient of the tapered U.S.A.45 airfoil. Size. 7.38'(mean chord) by 45.75'. Results corrected for tunnel effects. F.S.W.T.

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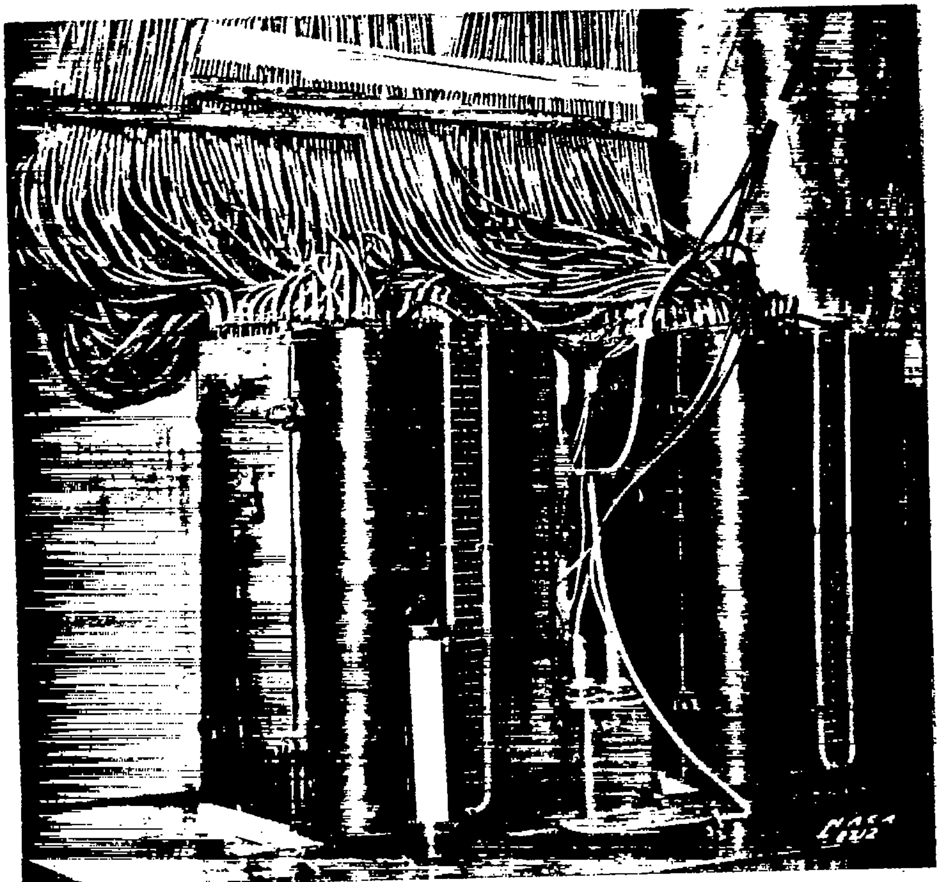

Figure 2.- Manometer installation for tapered U.S.A. 45 airfoil.

Figure 3.- The tapered U.S.A. 45 airfoil mounted on the tunnel balance.

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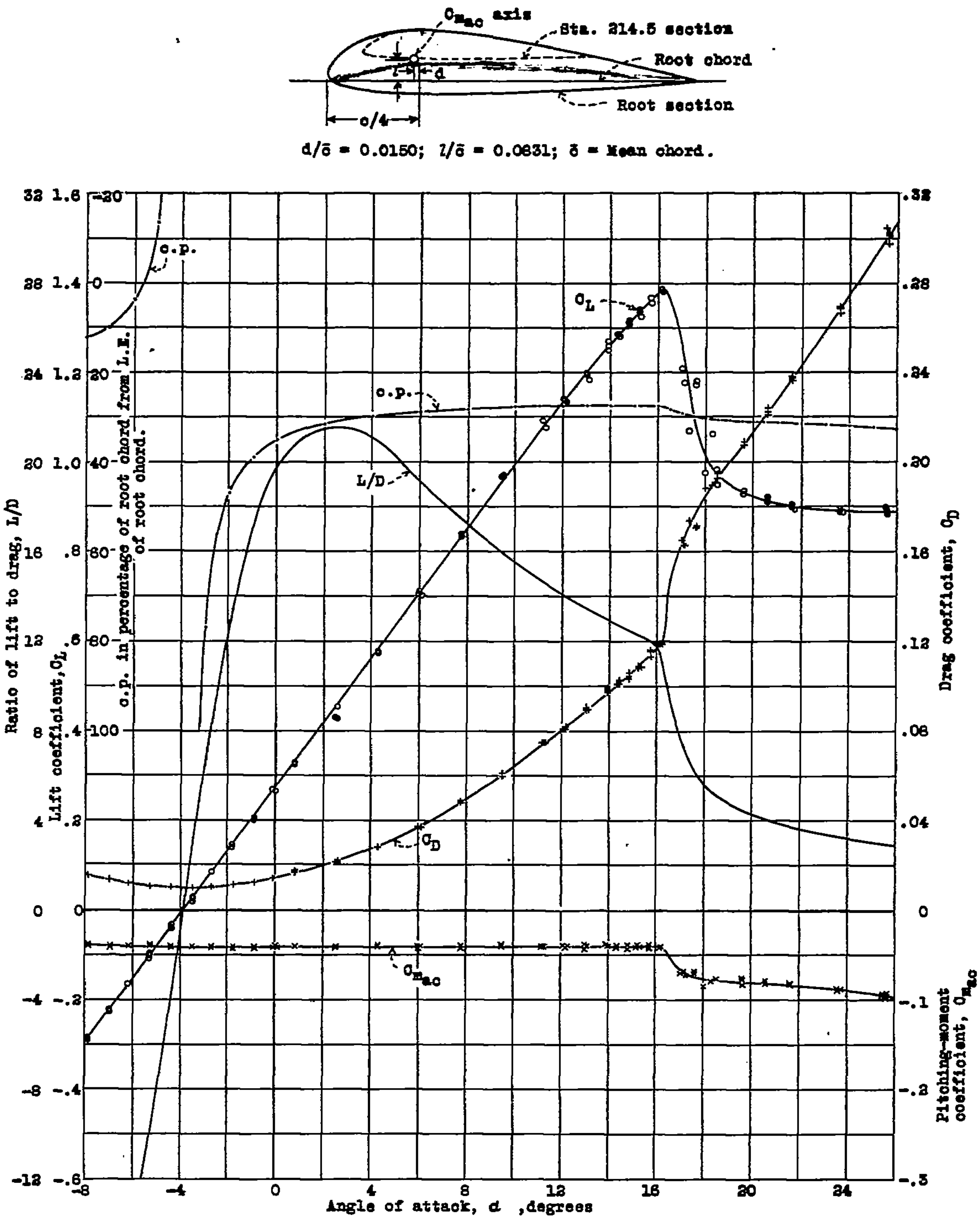

Figure 4.- Characteristics of the tapered U.S.A.45 airfoil as determined by force tests. Velocity: 112.3 ft./sec. Av. Reynolds Number:5,030,000. Size: 7.38'(mean chord) by 45.75' . Results corrected for tunnel effects. F.S.W.T.

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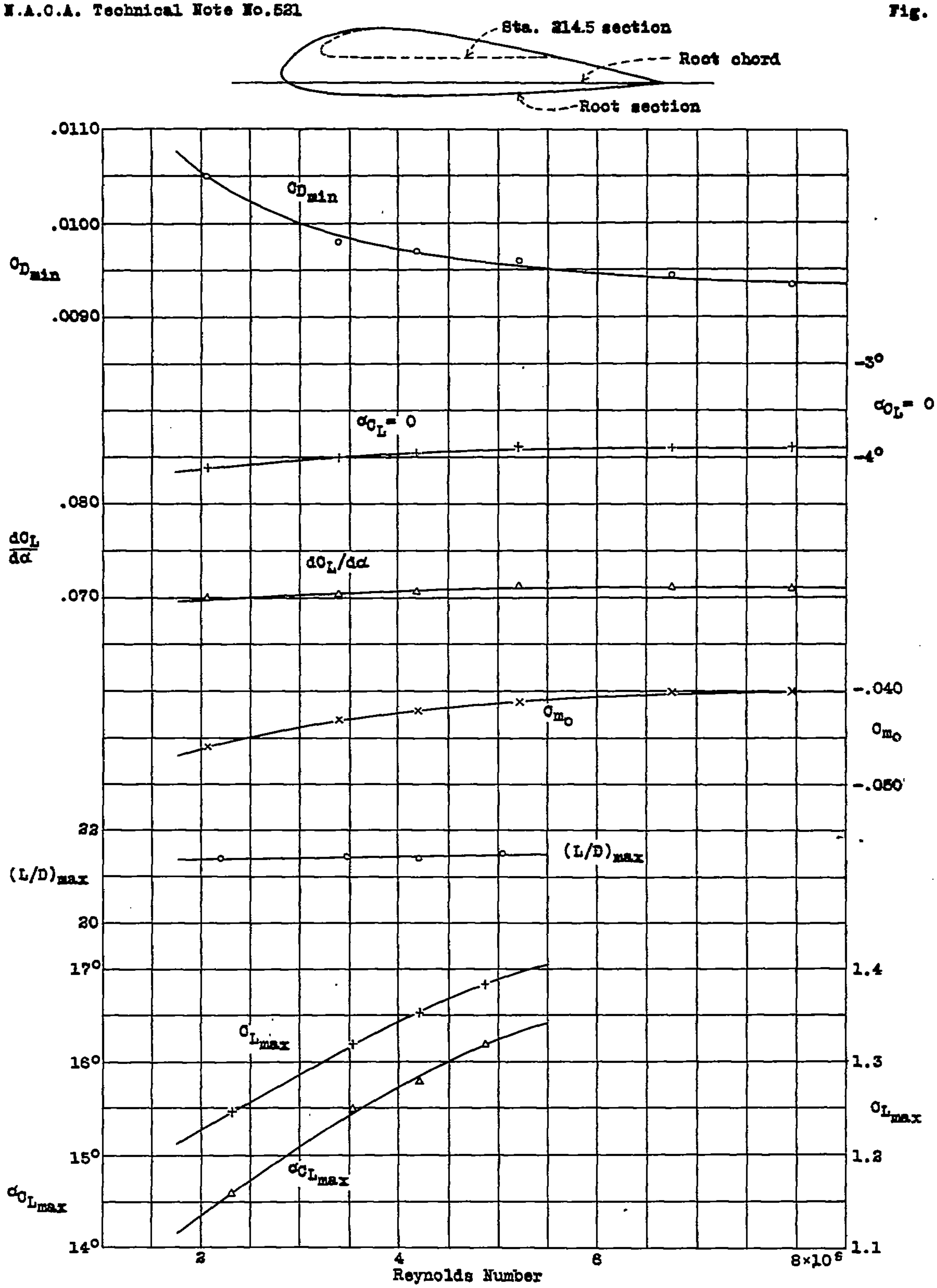

Figure 5.- Scale effect on tapered U.S.A.45 airfoil. Size: 7.38'(mean chord) by 45.75'. Results corrected for tunnel effects. F.S.W.T.

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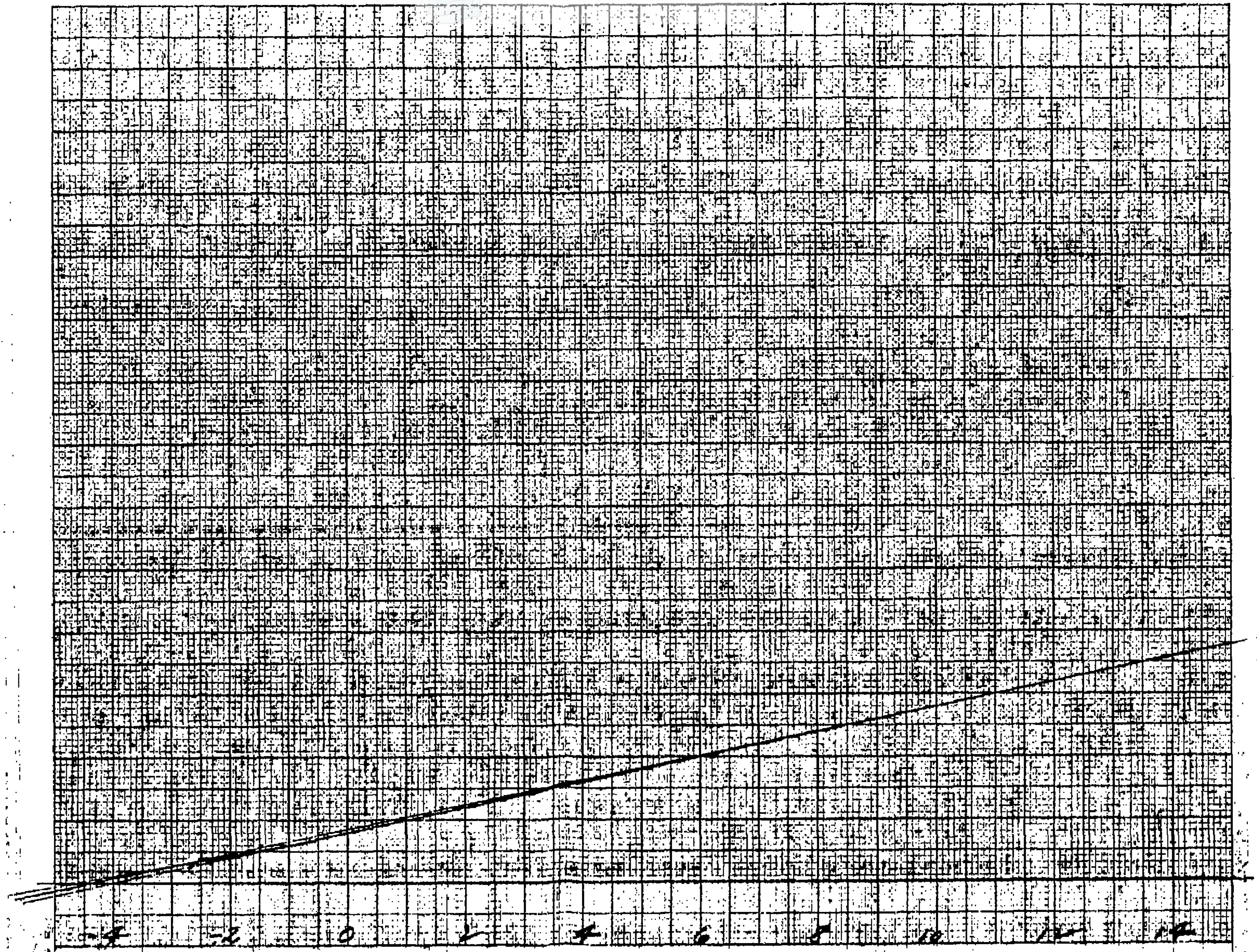

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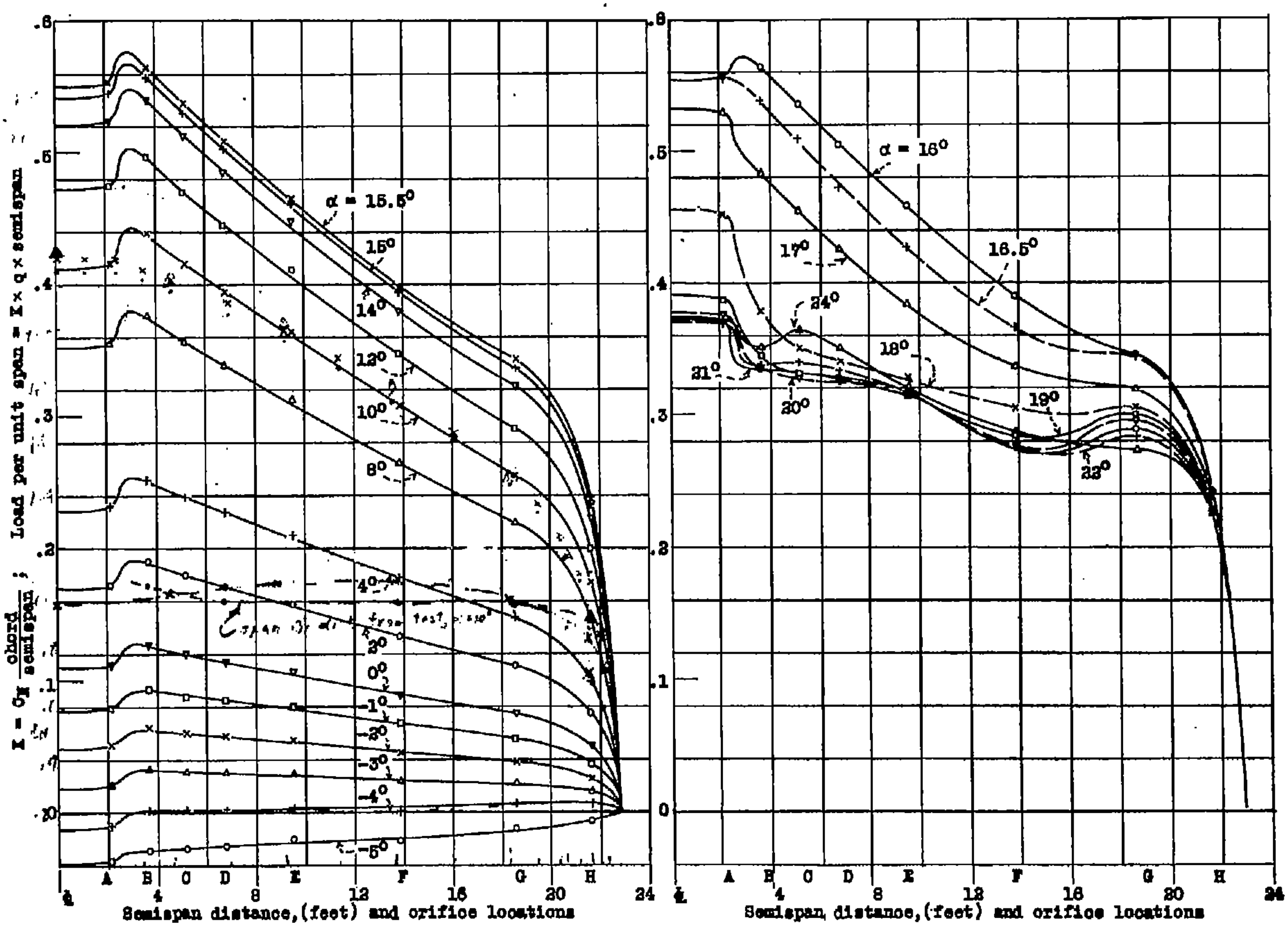

Figure 7.- The semispan load diagram of the U.S.A.45 tapered airfoil. Size: 7.38'(mean chord) by 45.75'. Average Reynolds Number:4,183,000. Results corrected for tunnel effects. F.S.W.T.

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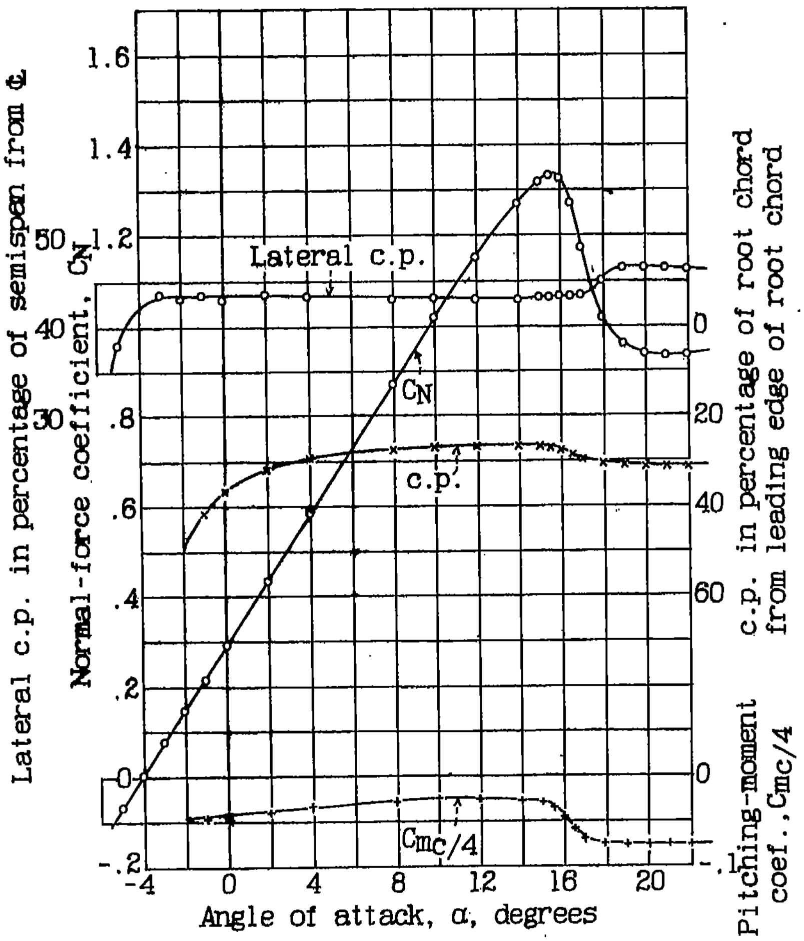

Figure 8.- The characteristics, as determined by pressure-distribution tests, of the tapered U.S.A. 45 airfoil.

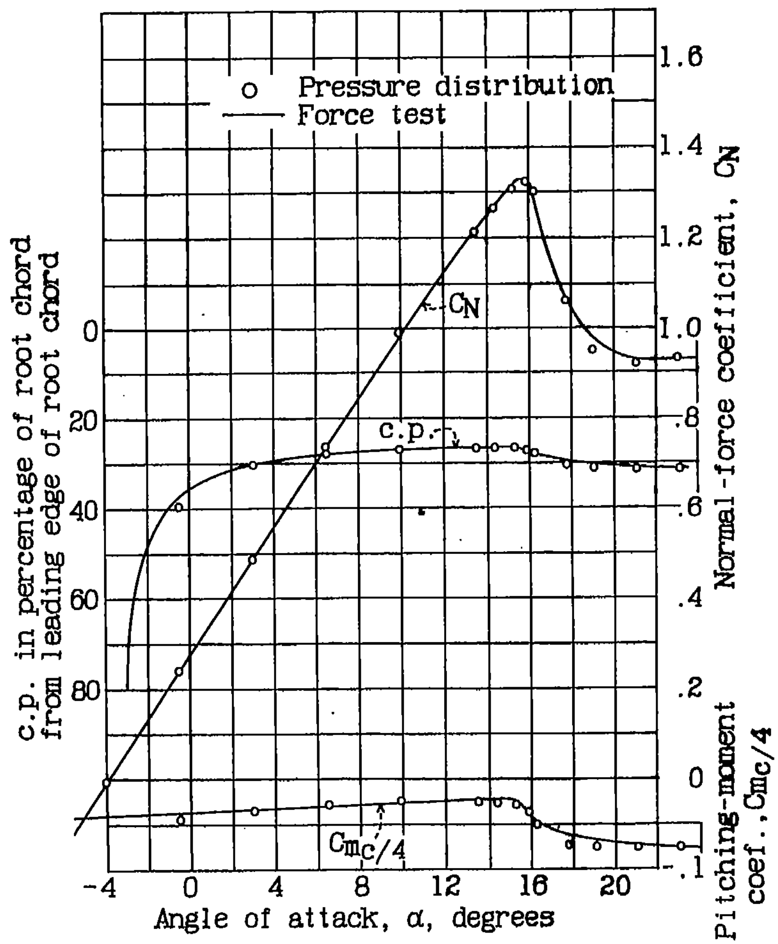

Figure 9.- Comparison of results of force and pressure-distribution tests of the tapered U.S.A. 45 airfoil

Av. Reynolds Number: 4,183,000. Size: 7.38' (mean chord) by 45.75'. Results corrected for tunnel effects. F.S.W.T.