REPORT No. 416

THE N. A. C. A. VARIABLE-DENSITY WIND TUNNEL

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SUMMARY

This report describes the redesigned variable-density wind tunnel of the National Advisory Committee for Aeronautics; it supersedes a previous report that described the original tunnel. The operation of the balance and the method of testing are explained and the method of correcting and presenting airfoil data is described. A summary of the formulas for predicting the characteristics of finite wings from the airfoil section data as they are usually presented is also given.

INTRODUCTION

The variable-density wind tunnel was constructed by the National Advisory Committee for Aeronautics to provide equipment for testing models wherein the error resulting from the comparatively low dynamic scales common to most other model tests could be eliminated. The necessity of recognizing this source of error and the practicability of eliminating it by the use of this type of wind tunnel have been demonstrated by investigations which have been made in the variable-density wind tunnel and in flight. A discussion of the theory of this type of wind tunnel is given in reference 1. The Reynolds Number $\left(\frac{\rho Vl}{\mu}\right)$ is a measure of the dynamic scale, and large values of the Reynolds Number are obtained in this tunnel by increasing the density (ρ) while the other factors remain sensibly constant.

The variable-density wind tunnel was proposed in 1921 (reference 2), and the construction of the tunnel was completed in March, 1923. A description of the tunnel as it then existed is given in reference 1. The closed-throat test section was 5 feet in diameter, and the tunnel was of wooden construction inclosed within a steel tank. A number of investigations were made in this tunnel, and the results showed the theory to be correct.

The tunnel was destroyed by fire in August, 1927, but the tank in which it was inclosed was not seriously damaged. The tunnel was rebuilt, using fireproof construction, and the balance was made more accessible by building the test section of the open-throat type. After the reconstruction of the tunnel was completed in April, 1928, the tunnel was employed for pressure-distribution investigations until the new balance was built. The balance was installed in January, 1929, and several investigations were made on airfoil and airship models.

Owing to several difficulties, some of which had existed in the earlier form of the tunnel, the open-throat tunnel was not considered satisfactory in the light of later developments in the art of wind-tunnel design. The difficulties, which included excessive vibration, unsteady velocity at the test section, a rather large pressure gradient along the axis of the test section, and excessive effects of extraneous air currents on the balance, were overcome by rebuilding parts of the tunnel. The whole interior structure was altered to give greater rigidity and the method of supporting the structure and the balance from the tank wall was improved. The test section was changed to the closed-throat type. A new exit cone having a smaller divergence angle and a new entrance cone having a better form were built. The synchronous-drive motor was replaced by a direct-current motor. These changes were completed in December, 1930. This report describes in some detail the mechanical features and the method of operation of the redesigned tunnel.

DESCRIPTION OF TUNNEL

The variable-density wind tunnel is similar to other tunnels except that it is inclosed within a tank to allow the use of compressed air as the working fluid. The novel features arise from the restricted space inside the tank, the exterior controls for the balance and other apparatus, and the large range of forces on the model.

Tank and arrangement.—The general arrangement is shown in Figures 1 and 2. Entrance to the tunnel, which is constructed inside the tank, is gained by means of an elliptical door in one end. The propeller drive shaft passes through a suitable stuffing box in the opposite end of the tank. Small glass windows are provided for reading the balances and observing the model. The tank, which is designed to withstand a working pressure of 21 atmospheres, is built of heavy steel plate lapped and riveted according to the usual practice in steam-boiler construction. A concrete foundation supports the tank, which, together with its contents, weighs about 100 tons.

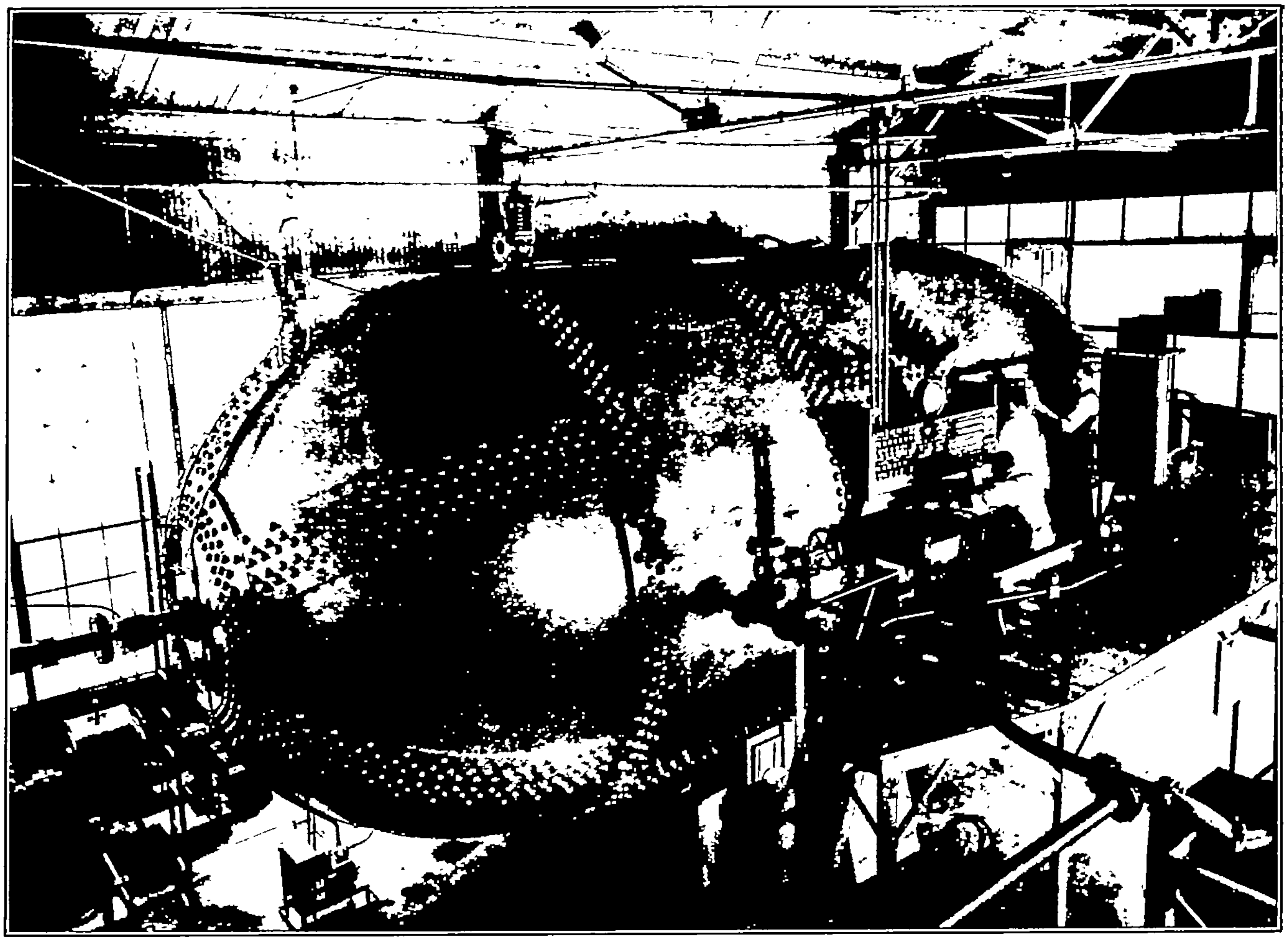

FIGURE 1.—General view of the variable-density wind tunne

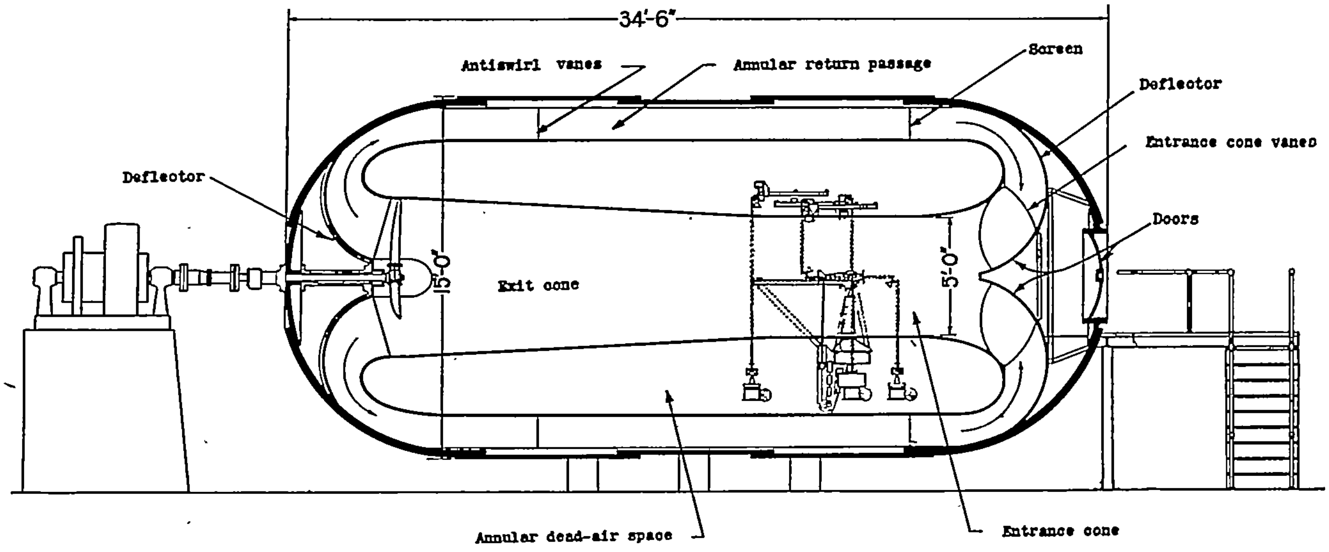

FIGURE 2.—Diagrammatic longitudinal section of the variable-density wind tunnel

Air passages and structure.—The tunnel consists essentially of a central air passage (fig. 2) consisting of the entrance cone, the test section, and the exit cone, and an annular return passage surrounding the central air passage but separated from it by a dead-air space containing the balance. In each circuit of the passages the air is twice turned through an angle of 180°, one turn being made in the entrance cone, which is designed to prevent the air from separating from the walls. The test section is 5 feet in diameter and 6 feet long, and it is made slightly divergent to reduce the horizontal static-pressure gradient. Four holes are cut in the wall of the test section downstream from the model position to maintain the pressure in the dead-air space very nearly the same as the static pressure in the test section, and accordingly to reduce the flow of air into the test section through the holes for the model-support struts. The included angle between the walls of the exit cone is a little less than 6°, and the portion tapered at this angle is 14 feet long. The return passage has a constant cross-sectional area about three times that of the test section. A screen, to provide a certain amount of damping and to equalize the flow, is located in the return passage at the position shown in Figure 2, and a safety screen not shown, is located in the exit cone in front of the propeller. Twisting of the air stream is prevented by 12 antiswirl vanes located immediately behind the propeller and extending for some distance into the return passage and by 6 vanes fastened to the deflector doors in the entrance cone.

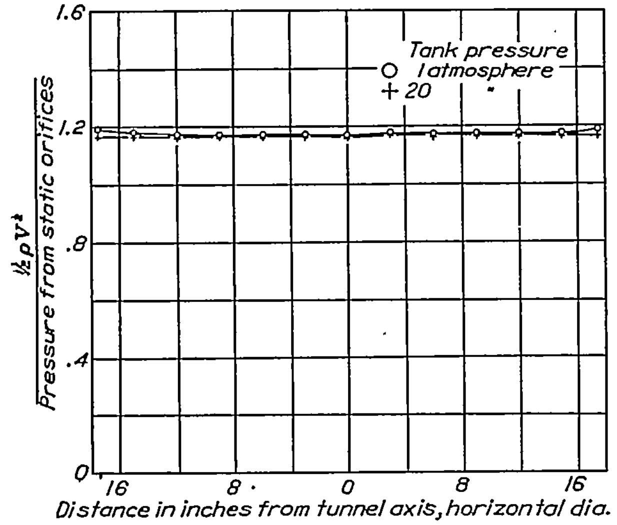

FIGURE 3.—Ratio of dynamic pressure at the model position to the pressure across the static-pressure orifices

Propeller, drive motor, and compressors.—The air is circulated by a 3-bladed metal propeller 6.5 feet in diameter which is driven by a shunt-wound direct-current motor. The current is provided by a 200-kilowatt motor generator set equipped with an automatic voltage regulator. Fine speed control is obtained by means of rheostats in the field circuit of the drive motor. The propeller shaft passes through a loosely packed stuffing box in the tank wall. Air leakage is reduced by oil which slowly leaks through the stuffing box and is returned to a reservoir by a small pump.

The air is compressed by a 2-stage primary compressor and a booster compressor which fill the tank with air at 20 atmospheres pressure in about 70 minutes. The booster compressor can also be used to evacuate the tank to pressures below atmospheric.

TUNNEL CHARACTERISTICS

Velocity and pressure distribution.—Figure 3 indicates the velocity distribution over a distance across the test section equal to the span of the largest model used in this tunnel. The velocity is slightly low at the tunnel axis, but the variation is within ±0.5 per cent. The variation in direction of the air flow as indicated by a yaw head passed across the test section is less than $\pm\frac{1}{4}°$. Figure 4 indicates the small static-pressure variation along the tunnel axis.

Energy ratio.—The energy ratio $\left(\text{E.R.}=\frac{\frac{1}{2}\rho A V^3}{\text{Power input}}\right)$ of the tunnel at atmospheric pressure without any screens in the air passages is about 2.3 if the power input is taken as the power supplied to the propeller by the drive motor. The energy ratio of the tunnel as it is actually operated at 20 atmospheres tank pressure with both screens in place is 1.09 if the power input is taken as the electrical power supplied to the drive motor.

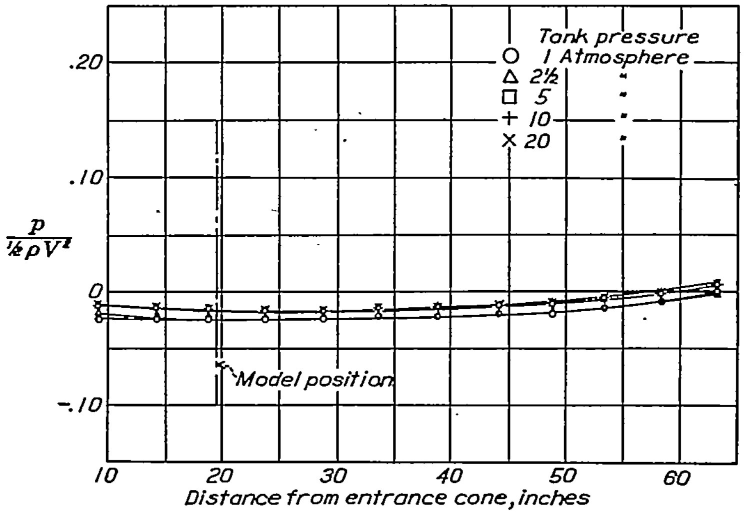

FIGURE 4.—Ratio of static to dynamic pressure on the axis of the variable-density wind tunnel. The static p is referred to the pressure from the static pressure orifices in the entrance cone

DESCRIPTION OF BALANCE

General.—The balance must measure the large range of forces resulting from the large variation of air densities at which tests are made, and it must be oper-

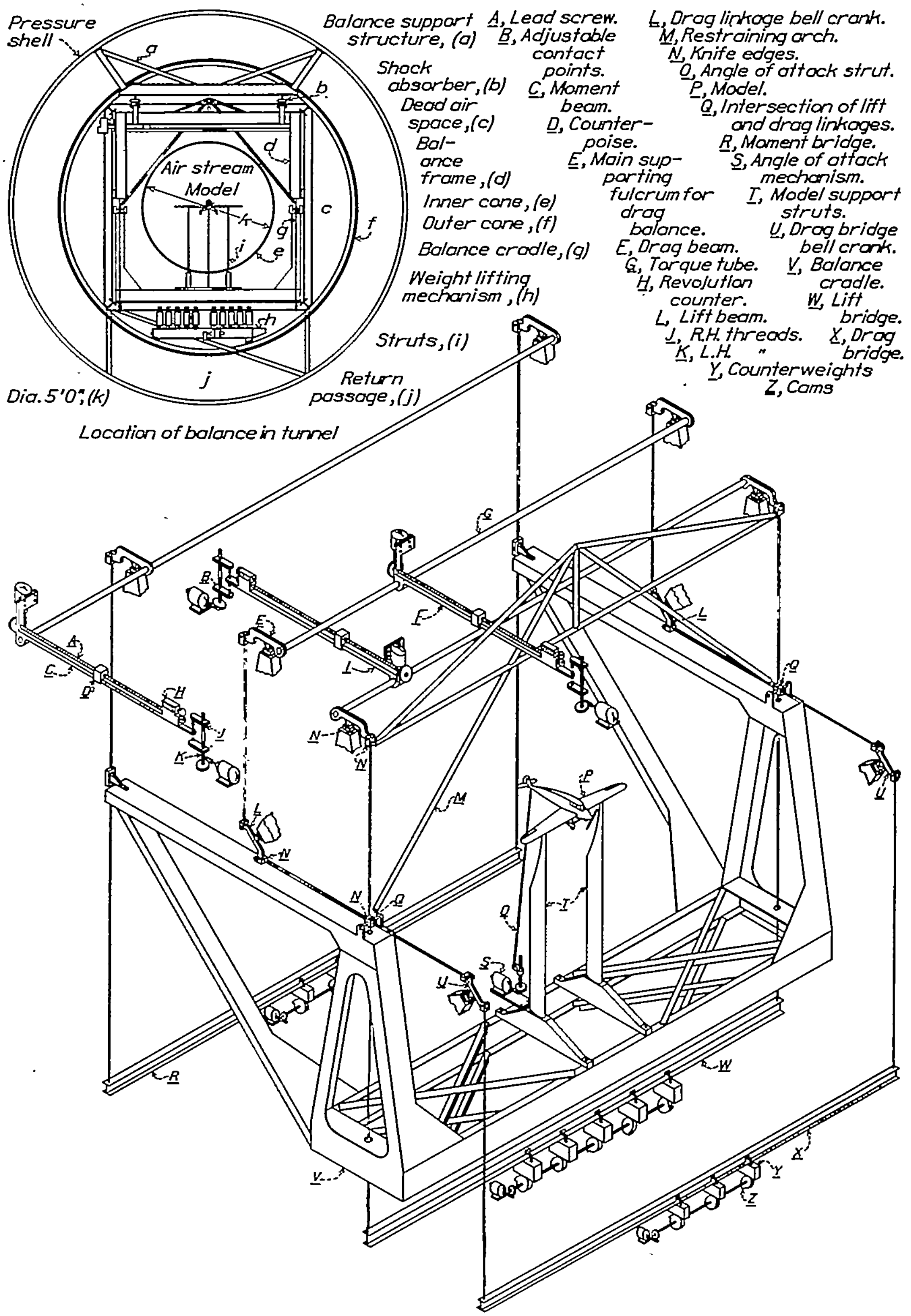

FIGURE 5.—Diagrammatic drawing of the balance of the variable-density wind tunnel

ated completely from outside the tank. The balance measures the lift and drag forces and the pitching moments by means of three beams balanced by moving weights. The essential parts of the balance are a rigid steel frame called the balance cradle, the balance beams, and the linkages necessary to transmit the forces to the balance beams from the cradle to which the model is rigidly fastened.

Linkages.—Figure 5 is a diagrammatic drawing of the balance showing the main parts. The balance cradle, which is a rigid structure extending across the tunnel under the test section, is suspended by rods from two of the balance beams, which in turn are externally supported through knife-edges. The rods thus serve to transmit vertical forces from the cradle to the beams and also to form parallelograms, of which the sides of the cradle are the lower horizontal members, on each side of the test section. The balance cradle would thus be free to move along the tunnel axis if it were not restrained in this movement by the drag linkages, which are attached to the balance cradle, as shown diagrammatically in Figure 6. Cross-tunnel movement and rotation of the balance cradle are prevented by the torque tubes and the restraining arch shown in Figure 5.

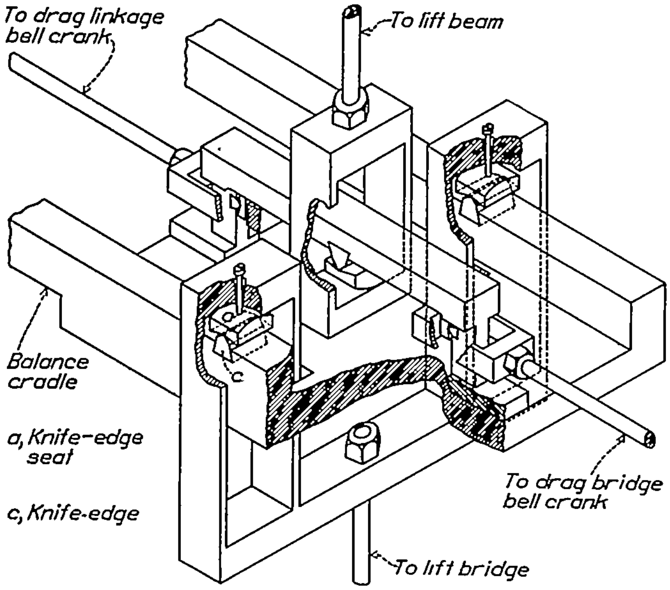

FIGURE 6.—Diagrammatic drawing of the intersection of the lift and drag linkages

The drag linkage transmits the horizontal or drag forces from the balance cradle to the drag beam through bell cranks, one of which is shown photographically in Figure 7. The horizontal members of this linkage lie in the plane of the tunnel axis. Therefore, if pitching moments are taken about a point on the axis of the tunnel in the plane of the forward vertical linkages, i. e., about a point on the line of intersections of the lift and drag linkages (fig. 6), neither the forces from the drag linkage nor the forces from the forward vertical linkage contribute to the pitching moment. The rear vertical linkage is therefore called the moment balance, and the model is usually mounted so that this balance measures directly the pitching moment. The forward vertical linkage is called the lift balance because it measures most of the lift, although the total lift is the sum of the forces measured by the lift and moment beams.

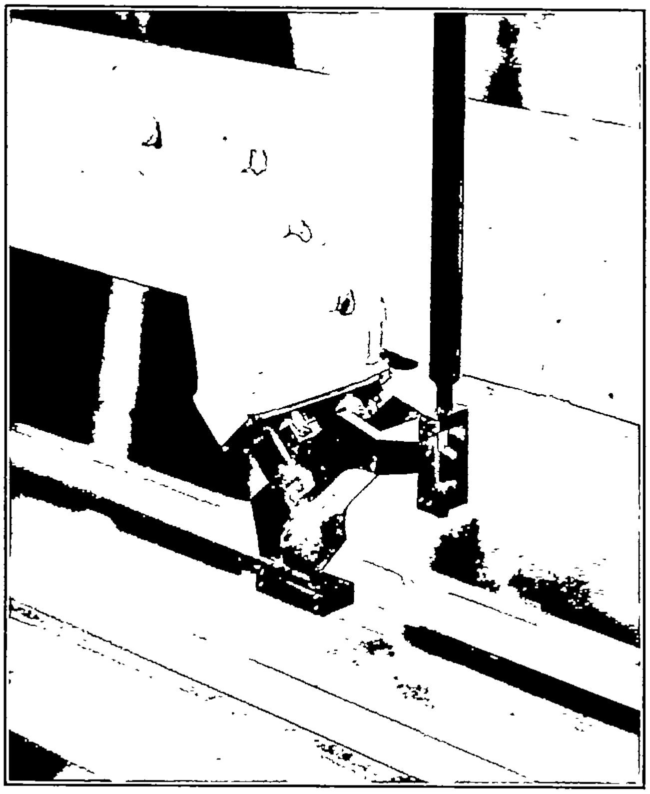

FIGURE 7.—Photograph of one of the drag-linkage bell cranks

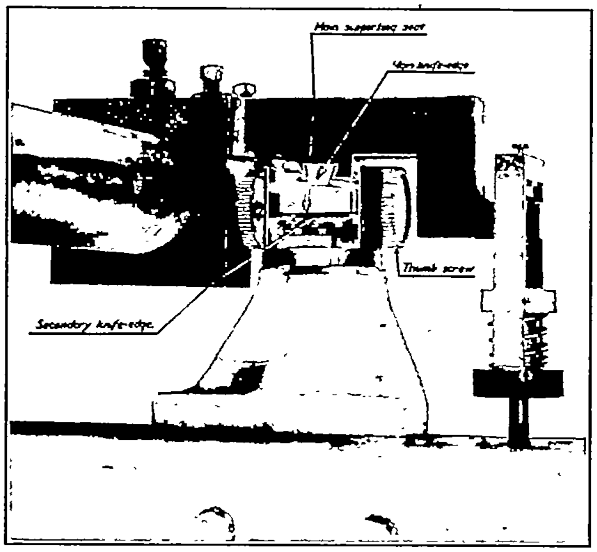

FIGURE 8.—Photograph of one of the main supporting fulcrums of the drag balance

Knife-edges.—All linkages are connected by means of knife-edges and seats carefully made of hardened high carbon steel. In all cases the knife-edges are fixed in the members in which the lever arms must be maintained exactly. The knife-edge seats are arranged so that they may align themselves with the knife-edges. In some parts of the balance it is necessary to fix accurately the position of the seat as well as that of the knife-edge. Seats of this type are called main supporting seats. A photograph of one is shown in Figure 8. They have a V-shaped groove in which the knife-edge rests. The bottom of the V is sharp and the included angle between the sides is 120°. The main supporting seats are carried by secondary knife-edges at rights angles to the main ones so that the seats are free to rock in such a way that the bearing is equalized along the main knife-edge. The positions of these seats are adjustable along the secondary knife-edge in the direction of the tunnel axis by means of the thumbscrews shown in Figure 8, and the whole unit, including the secondary knife-edge and thumbscrew assembly is free to rotate about a vertical axis to align the seat with the main knife-edge. The less important seats, such as those shown in Figure 6, also have a V-shaped groove in which the knife-edge rests, but the angle between the sides is 150° and a bottom radius is provided to lessen the friction. This type of seat is not fastened rigidly to the member that carries it but rests on a curved base, so that the seat can take up positions such that the knife-edge will bear evenly on the seat throughout its length.

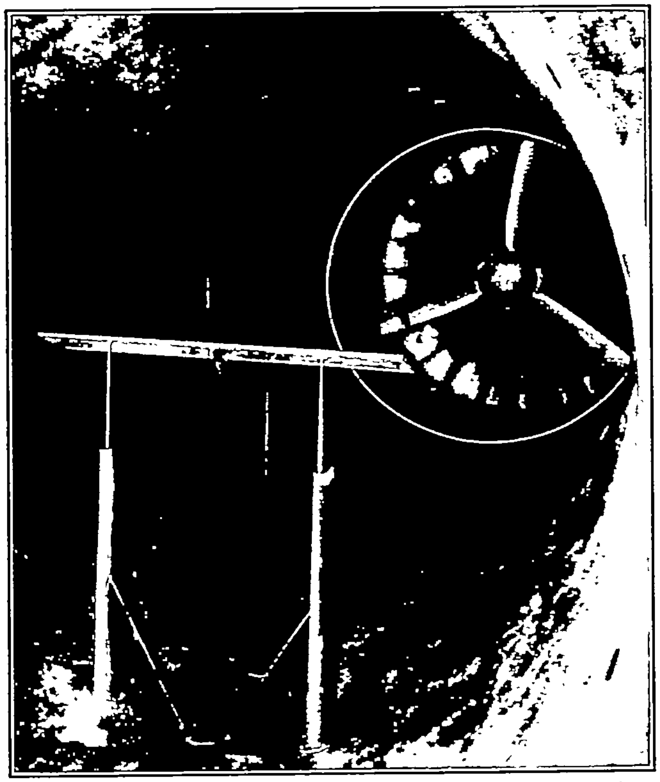

FIGURE 9.—Photograph of an airfoil model mounted in the tunnel at a positive angle of attack

Balance beams.—The balance beams are fastened to torque tubes which extend across the tunnel above the test section and move in arcs about the supporting fulcrums as the beams swing. Each balance beam is balanced by a moving counterpoise, the position of which is controlled by a motor-driven lead screw and indicated by a revolution counter. The beams swing between motor-operated adjustable stops that contain platinum contact points, which are connected in the circuits of the beam motors so that the beams may be balanced either automatically or by hand switches. The beams are calibrated so that one unit on the drag or moment beams indicates 1 gram, and on the lift beam 10 grams. As the forces to be measured on the balance are greater than the capacities of the beams, each beam is provided with a set of 10 counterweights (fig. 5), which may be applied as needed by means of motor-driven camshafts.

Model support.—The models are held in the tunnel by the partly shielded support struts shown in Figures 5 and 9. The two forward or main support struts, which carry most of the air load on the model, are rigidly attached to the balance cradle. The model is attached to the upper ends of these support struts by pins about which the model rotates in changing angle of attack. The pins are located with reference to the balance in line with the intersections of the lift and drag balance linkages. If possible, the pins are fastened in the model on the line about which moments are desired; for airfoils, on the chord line one-quarter of the chord behind the leading edge. The moment balance then reads directly the pitching moment.

The angle of attack of the model is controlled by a vertical motor-driven screw which carries the lower end of the angle-of-attack strut and is geared to a revolution counter. A sting attached to the lower surface of the airfoil model, as shown photographically in Figure 9, connects the angle-of-attack strut and the model. For special tests other types of support are used, but the main support struts are usually employed.

For some special tests, such as airship-model tests, an auxiliary drag balance may be used instead of the main balance. The auxiliary balance is described in reference 3.

OPERATING PROCEDURE

Velocity determination.—To guard against errors, two independent sets of static-pressure orifices and manometers are used to measure the air velocity. Each manometer is connected between a set of four orifices spaced around the inner wall of the return passage and a set of four orifices spaced around the entrance cone near the test section. These manometers, which are similar in principle to the one described in reference 4, have stationary index tubes and movable reservoirs carried on motor-driven lead screws. Revolution counters geared to the motors indicate the heads to 0.1 millimeter. The temperature of the manometer liquid is measured to 1° C. by a distant-reading thermometer. Pure ethyl alcohol with a known variation of specific gravity with temperature is used for the manometer liquid. The manometers are calibrated by balancing the head of alcohol in the manometers against a head of distilled water.

The static-pressure orifices are calibrated at all tank pressures at which tests are to be made by making velocity surveys (with a calibrated Pitot tube) along the horizontal diameter of the tunnel. The ratio of the dynamic pressure to the pressure across the static-pressure orifices is then plotted (fig. 3) and the calibration factor is taken as the mean value of this ratio.

Balance alignment.—The lift, drag, and pitching moments measured by the balance are actually vertical and horizontal forces applied at, and the moment about, the line joining the points of intersection of the lift and drag linkages. It is essential that any one force or moment does not affect the value of any other, and that the measured values be the true ones. To satisfy these conditions the theoretically vertical and horizontal portions of the balance linkages must be exactly vertical and horizontal.

The balance is assembled as nearly aligned as possible by measurement and all balance beams are balanced. Weights are then placed successively on each of the counterweight bridges, and adjustments are made until a weight placed on the bridge of any balance beam does not affect the balance of any other beam. The pivot points of the model support struts are aligned with the points of intersection of the lift and drag linkages by a similar method. The balance alignment is checked and changed if necessary from time to time.

As the balance is aligned, the measured lift and drag forces are respectively vertical and horizontal; but since the air-flow direction is not exactly horizontal, the measured forces are not the true lift and drag. The deviation of the direction of the air flow from the horizontal is determined by the well-known method of testing an airfoil in the erect and inverted positions. The deviation is so small that the corrections to the lift and moment are not appreciable if the zero angle of attack is set with reference to the air-flow direction. The measured drag is corrected by adding to it a small component of the lift. The air-flow alignment is checked periodically.

Balance calibration.—The balance is calibrated by means of standard weights checked by the Bureau of Standards. The counterweights used on the balance bridges are checked against these weights, and the balance beams are calibrated by weighing the standard weights which are placed on the counterweight bridges for this purpose. The weight of the moving counterpoise is adjusted until the beam counter reads the weights correctly.

Determination of tare forces.—The tare forces are evaluated by measuring the air forces on the supporting members while they are connected inside a hollow dummy airfoil mounted independently of the balance. These measurements, which are made with the dummy model at several angles of attack, include the interference of the model on the supports and the balance windage. The interference of the supports on the model is usually neglected.

The distribution of the weight of the model and sting between the lift and moment beams varies as the model pivots with changing angle of attack. A correction, which is evaluated by observing moment balance zero readings at two angles of attack, is applied to the measured moments to allow for this change of weight distribution.

A typical airfoil test.—The standard airfoil models, 30-inch span and 5-inch chord, used in this tunnel are made of heat-treated duralumin. A special airfoil-generating machine is employed that works from a 6-fold templet of the section. The templets are carefully laid out on a table that permits the plotting of the stations and ordinates to an accuracy of 0.001 inch. The templets are then cut out and checked for precision of contour. A section of the airfoil model is also checked after the cut has started and any necessary corrections are made on the templet. As the cut progresses, the maximum thickness is checked from time to time to guard against errors resulting from excessive tool wear. The models are hand finished to remove small tool marks and then buffed to produce a polished surface. To insure accuracy of alignment in the tunnel, a special drilling jig is employed to drill the airfoil models for mounting.

A sting is fastened to the lower surface of the model parallel to the chord, after which the model is mounted in the tunnel, as shown in Figure 9. The model is fastened to the support struts by lugs which are attached to the struts by pins and which lie completely within the model. A sensitive inclinometer is used to set the chord of the model successively parallel to the air flow and at a large angle of attack. From the data so obtained, the proper calibration table for the angle-of-attack counter is selected from a previously calculated set.

After the air in the tank is compressed to the desired pressure, the drive motor is run until the temperatures inside the tank are equalized. Two observers and one recorder stationed as shown in Figure 1 are required for the test. The recorder reads the tank pressure on a 12-inch bourdon-type pressure gauge and the temperature of the manometer liquid on a distant-reading thermometer. From the thermometer reading he calculates the manometer setting for the desired air speed, which is selected so that the counters on the balance beams read directly the force coefficients, or simple multiples of them.

The first observer sets the manometers, regulates the air speed, and balances the drag beam. He also operates a signal system which lights lamps visible to the three operators when the air speed is correct. The second observer balances the lift and moment beams. The swing of the lift beam affects the balance of the moment beam, so the lift beam is held in the balanced position by the contact points while the moment beam is being balanced. The final balance of all beams is obtained only when the signal lamps are lighted. Another signal lamp warns the recorder if the balance fouls during the test.

The recorder makes all necessary calculations and corrections to obtain the final force and moment coefficients of the airfoil as corrected to infinite aspect ratio, and plots these coefficients as the test progresses. These calculations are greatly simplified by the selection of the air speed and by previously calculated tables.

REDUCTION AND PRESENTATION OF DATA

Method of correcting data.—The formulas used in correcting the data to infinite aspect ratio and for the influence of the tunnel walls are from the works of Munk, Glauert, and Prandtl, and are summarized in reference 5. The notation and formulas used are as follows:

C_L,	absolute lift coefficient.
D,	diameter of wind-tunnel throat.
b,	span of airfoil.
S,	area of airfoil.
α,	angle of attack in free air.
α_T,	angle of attack as measured in the tunnel.
α_i,	induced angle of attack.
α_o,	angle of attack at which an airfoil of infinite span would give the same lift coefficient as the airfoil tested in the tunnel.
R,	actual aspect ratio of airfoil.
R_e,	effective aspect ratio of the airfoil; the aspect ratio of an airfoil which would give the same characteristics in free air as the airfoil tested in the tunnel.
$C_{m_{c/4}}$,	moment coefficient about a point one-quarter of the chord behind the leading edge.
C_D,	absolute drag coefficient for an airfoil in free air.
C_{D_o},	profile drag coefficient.
C_{D_T},	absolute drag coefficient obtained from the tunnel tests.
C_{D_i},	induced drag coefficient.

τ, a factor correcting the induced angle of attack to allow for the change from elliptical span loading resulting from the use of an airfoil of rectangular plan form.

σ, a factor correcting the induced drag to allow for the change from elliptical span loading resulting from the use of an airfoil of rectangular plan form.

$a=\frac{dC_L}{d\alpha}$, increase in lift coefficient per degree for an airfoil of aspect ratio R.

$a_o=\frac{dC_L}{d\alpha_o}$, increase in lift coefficient per degree for an airfoil of infinite span.

The formulas for correcting the data from the closed-throat tunnel conditions to free air are as follows:

$$\alpha=\alpha_T+\frac{C_L S}{2\pi D^2}\times 57.3$$

(Angles of attack are measured in degrees.)

$$C_D=C_{D_T}+\frac{C_L^2 S}{2\pi D^2}$$

Since the reduction to infinite aspect ratio is made from the uncorrected tunnel data, the effective aspect ratio (R_e) of the airfoil is used.

$$R_e=\frac{R}{1-\frac{1}{2}\left(\frac{b}{D}\right)^2}$$

then

$$\alpha_o=\alpha_T-\frac{C_L}{\pi R_e}(1+\tau)\times 57.3$$

$$C_{D_o}=C_{D_T}-\frac{C_L^2}{\pi R_e}(1+\sigma)$$

TABLE I

AIRFOIL: CLARK Y

Average Reynolds Number: 3,250,000.
Size of model: 5 by 30 inches.
Pressure, standard atmospheres: 20.7.
Test No. 525, Variable-density wind tunnel. Date: March 19, 1931.

C_L	α_o degrees	C_{D_o}	$C_{m_{c/4}}$
−0.224	−7.3	0.0110	−0.075
−.008	−5.0	.0099	−.068
.075	−4.2	.0099	−.067
.226	−2.7	.0098	−.066
.373	−1.2	.0099	−.063
.667	1.9	.0111	−.063
.962	4.9	.0134	−.061
1.237	8.1	.0194	−.063
1.473	11.3	.0310	−.063
1.560	13.0	.0443	−.071
1.518	15.2	.1135	−.093
1.283	19.9	.2734	−.138
1.032	26.7	.4499	−.170

Method of presenting data.—The results of a test of the Clark Y airfoil are given in Table I and Figure 10 to show the method of presenting airfoil data. It will be noticed that the characteristics of airfoils are presented by means of two independent sets of curves. The first is the conventional plot C_L, C_D, L/D, and *c. p.* against angle of attack, but differs from most previous plots in that the results are corrected for tunnel wall effects to aspect ratio 6. The second set of curves gives the deduced characteristics of an airfoil of infinite span. The profile drag coefficient C_{D_o}, the angle of attack α_o, and the moment coefficient about the quarter-chord point $C_{m_{c/4}}$ are plotted against the lift coefficient. This type of plot, which has been used in England, has three important advantages over the more familiar type. First, the characteristics are plotted against the lift coefficient as abscissa because the lift coefficient is usually treated as the independent variable. Second, the efficiency and pitching characteristics of different airfoils may be compared much more readily by comparing profile drag and moment coefficient curves rather than the familiar L/D and c. p. curves. This is particularly true if the moment coefficient about a point one-quarter of the chord behind the leading edge is used, because its value for a given airfoil is approximately constant over the working range. Third, in applying the results of airfoil tests, it is almost always necessary to correct them to another aspect ratio, and it is more convenient to correct from an infinite than from some finite aspect ratio.

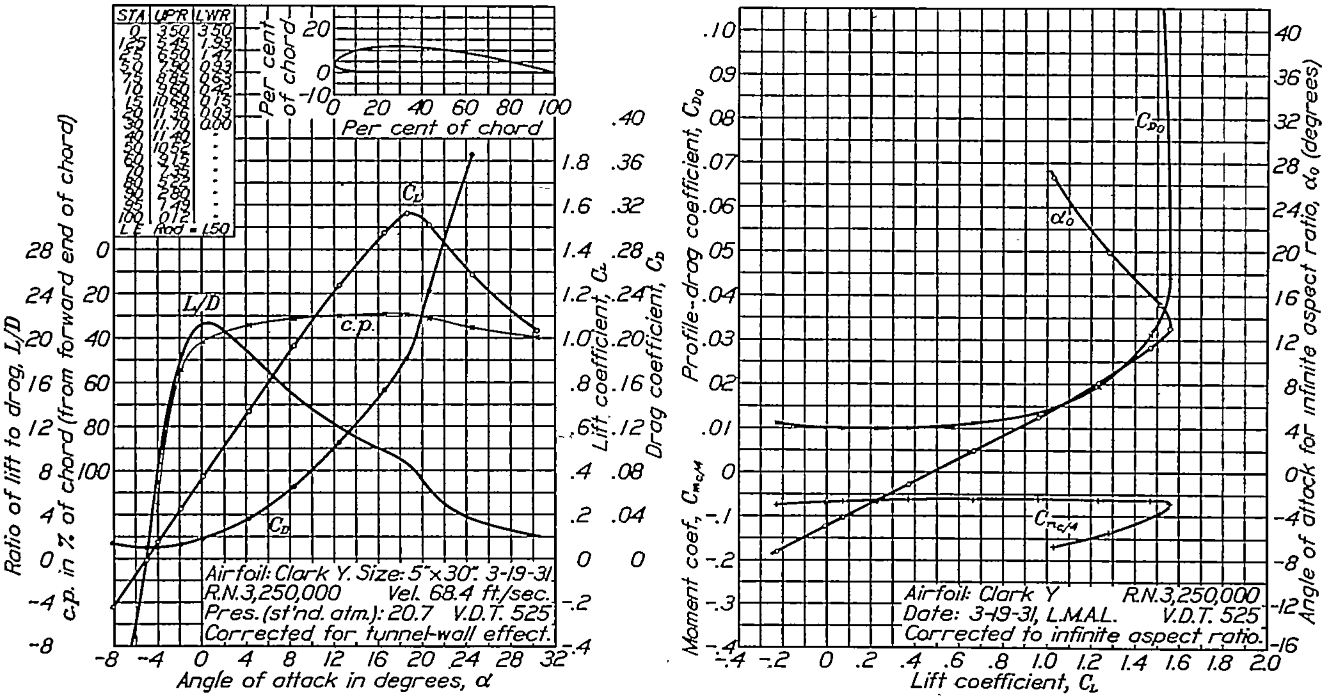

FIGURE 10.—Clark Y airfoil

Application of section data to the predictions of wing characteristics.—The formulas for predicting the characteristics of finite wings from the airfoil section data as they are usually presented (C_L, C_{D_0}, $C_{m_{c/4}}$) will also be summarized here for convenience.

The angle of attack in degrees for the lift coefficient C_L (the independent variable) is

$$\alpha=\alpha_0+\frac{C_L}{\pi R}(1+\tau)\times 57.3$$

or

$$\alpha=\alpha_0+\frac{18.24}{R}C_L(1+\tau)$$

The lift curve slope when angle of attack is measured in degrees is

$$a=\frac{a_0}{1+\frac{a_0}{\pi R}(1+\tau)57.3}$$

where a_0 is the slope for the wing of infinite span.

The drag coefficient is

$$C_D=C_{D_0}+\frac{C_L^2}{\pi R}(1+\sigma)$$

The values of τ and σ depend on the shape of the span-loading diagram of the airfoil. For an elliptical wing without effective twist they are zero and for a rectangular wing their values are given in Figure 11.

The moment coefficient at a given value of the lift coefficient may be taken as the same for any aspect ratio. The center of pressure, measured as a fraction of the chord from the leading edge, is given by

$$c.\ p.=0.25-\frac{C_{m_{c/4}}}{C_L\cos\alpha+C_D\sin\alpha}$$

where $C_{m_{c/4}}$ is the moment coefficient about a point one-quarter of the chord behind the leading edge.

The use of the foregoing formulas may be more easily understood from the following example. Suppose it is desired to find the aerodynamic characteristics of a rectangular Clark Y wing of aspect ratio 8. Since the lift coefficient is considered the independent variable, we shall select a value for this coefficient and calculate the other characteristics. For the sample calculation a lift coefficient of 0.7 will be taken.

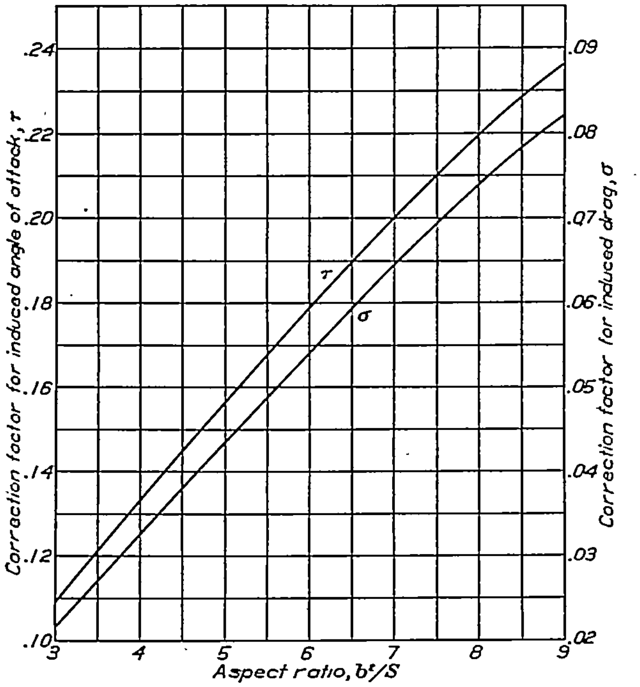

FIGURE 11.—Correction factors for rectangular airfoils

The angle of attack for a given value of C_L is

$$\alpha=\alpha_0+\alpha_i$$

$$\alpha=\alpha_0+18.24\frac{C_L}{R}(1+\tau)$$

From Figure 11, for an aspect ratio of 8, $\tau=0.22$. Then

$$\alpha=\alpha_0+2.780C_L$$

From Figure 10, when

$$C_L=0.7,\ \alpha_0=2.2°$$

$$\alpha=2.2°+1.9°$$

$$\alpha=4.1°$$

The drag coefficient is

$$C_D=C_{D_0}+C_{D_i}$$

$$C_D=C_{D_0}+\frac{C_L^2}{\pi R}(1+\sigma)$$

From Figure 11, for an aspect ratio of 8, $\sigma=0.074$. Then

$$C_D=C_{D_0}+0.0427C_L^2$$

From Figure 10, when $C_L=0.7$, $C_{D_0}=0.0112$

$$C_D=0.0112+0.0209$$

$$C_D=0.0321$$

$$\frac{L}{D}=\frac{0.7}{0.0321}=21.8$$

The moment coefficient about the quarter-chord point, from Figure 10, is -0.063 for a lift coefficient of 0.7. The position of the center of pressure measured as a fraction of the chord from the leading edge is

$$c.\ p.=0.25-\frac{C_{m_{c/4}}}{C_L\cos\alpha+C_D\sin\alpha}$$

$$c.\ p.=0.25-\frac{-0.063}{(0.7)\cos 4.1°+(0.0321)\sin 4.1°}$$

$$c.\ p.=0.25+0.090$$

$$c.\ p.=0.34 \text{ of the chord from the leading edge.}$$

This will be the position of the center of pressure for an angle of attack of 4.1°.

LANGLEY MEMORIAL AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY FIELD, VA., *November 23, 1931.*

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