REPORT No. 609

EXPERIMENTAL INVESTIGATION OF WIND-TUNNEL INTERFERENCE ON THE DOWNWASH BEHIND AN AIRFOIL

By Abe Silverstein and S. Katzoff

SUMMARY

The interference of the wind-tunnel boundaries on the downwash behind an airfoil has been experimentally investigated and the results have been compared with the available theoretical results for open-throat wind tunnels. As in previous studies, the simplified theoretical treatment that assumes the test section to be an infinite free jet has been shown to be satisfactory at the lifing line. The experimental results, however, show that this assumption may lead to erroneous conclusions regarding the corrections to be applied to the downwash in the region behind the airfoil where the tail surfaces are normally located. The results of a theory based on the more accurate concept of the open-jet wind tunnel as a finite length of free jet provided with a closed exit passage are in good qualitative agreement with the experimental results.

INTRODUCTION

A comprehensive theoretical treatment of wind-tunnel interference exists at present. The theory includes all the major effects attributable to the limited boundaries of the air stream and provides stream-angle corrections both at the airfoil and in the region behind the airfoil. Experimental verification of this theory has, in general, been satisfactory, although mainly confined to the corrections at the lifting line of the airfoil. The present investigation is concerned with the interference in the region behind the wing, a problem of importance in the testing of airplanes or airplane models, since the induced boundary effects at the wing and at the tail surfaces are usually different. A particular purpose of the present investigation was to provide correction factors for airplane test data obtained in the N. A. C. A. full-scale wind tunnel.

The theory of wind-tunnel interference on the downwash at the tail surfaces has been given in references 1, 2, and 3. Reference 3 also contains an evaluation of the correction factors for square and rectangular tunnels. These studies have indicated that the effect in the region of the tail surfaces is of the order of twice that at the wing. The work is based, however, on the assumption that the air stream is of infinite length. This assumption is permissible for a closed wind tunnel but is very questionable for an open tunnel because the actual open test section is usually only about one tunnel diameter long. The boundary condition for free jets, namely, uniformity of pressure over the surface of the jet, thus applies over only a short section; the boundary condition for closed tunnels, zero velocity normal to the surface, applies in front of and behind the open section. The disturbing effect of the exit cone is clear since, upon entering it, any inclination of the free jet induced by the lift on the wing must be so reduced that the air will follow more nearly the horizontal flow direction in the closed tube (fig. 1). From some recent boundary-

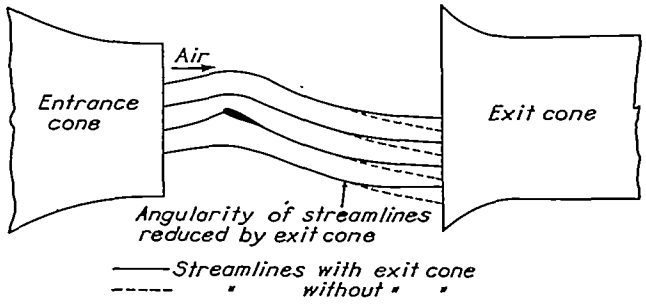


Figure 1.—Effect of exit cone on downwash behind an airfoil.

interference calculations (reference 4) for a circular open tunnel of finite length, it was concluded that the assumption of an infinitely long open jet would lead to very serious error in the region of the tail plane but to very little error at the wing. The results from reference 4 are reproduced in figure 2.

Conditions were particularly favorable for experimental investigation of the downwash corrections in the N. A. C. A. full-scale wind tunnel, as a 1/15-scale model of the tunnel was available. The procedure consisted in measuring the downwash angles behind small airfoils in the model tunnel and comparing them with the measured downwash angles behind the same airfoils in the full-scale wind tunnel. The full-scale wind tunnel is so large in comparison with the airfoils that the boundary interference is negligible. The correction factors thus obtained should be directly applicable to downwash data obtained behind large airfoils in the full-scale tunnel for there is little reason to expect an appreciable scale effect on the induced-velocity distribution. The

free-stream downwash data obtained from the measurements in the full-scale tunnel with the small airfoils should be valuable as standards for comparison with similar measurements in other tunnels. By a comparison, such as was made in the present work, the boundary-interference factors may be derived.

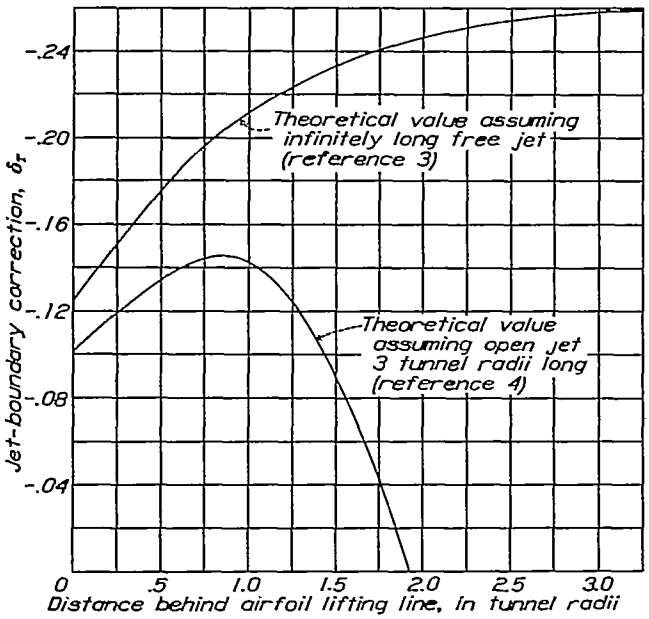


FIGURE 2.—Theoretical jet-boundary corrections for finite and infinite jets.

MODEL-TUNNEL TESTS

Apparatus.—The model tunnel used in these tests is a 1/15-scale replica of the N. A. C. A. full-scale wind tunnel. A complete description of the small tunnel and its equipment is given in reference 5. A wire balance was devised to measure the lift on the airfoils. The models were suspended from an overhead platform scale, and counterweights were provided below to maintain tension in the system. The angle of attack was changed by an adjustable quadrant on the scale platform.

The tests were made with two rectangular Clark Y airfoils, one with a 5-inch chord and a 30-inch span and the other with a 10-inch chord and a 30-inch span. The 5-inch-chord airfoil in the 2- by 4-foot jet of the model tunnel corresponds in the 30- by 60-foot jet of the full-scale wind tunnel to a 6.25- by 37.50-foot airfoil, which represents the average size of the airfoils tested in the large tunnel. The 10-inch-chord airfoil was chosen to exaggerate the effects investigated and the results from the measurements made with it are, perhaps, of greater academic than practical value. The airfoils were constructed of laminated mahogany, varnished and then polished to a smooth surface.

The downwash angles were measured by means of a calibrated yaw head consisting of two total-head tubes, each inclined at a 42° angle with the horizontal to form a Y with an 84° included angle. The inclination of the air stream was indicated by the pressure difference p between the two prongs of the Y and was measured by means of an alcohol manometer. The yaw head was calibrated in terms of the dynamic pressure q of the air stream, and the stream angle in degrees was obtained from a calibration chart showing p/q against ϵ, the angle of downwash. For measurements of dynamic pressure a small Prandtl-type pitot head was used.

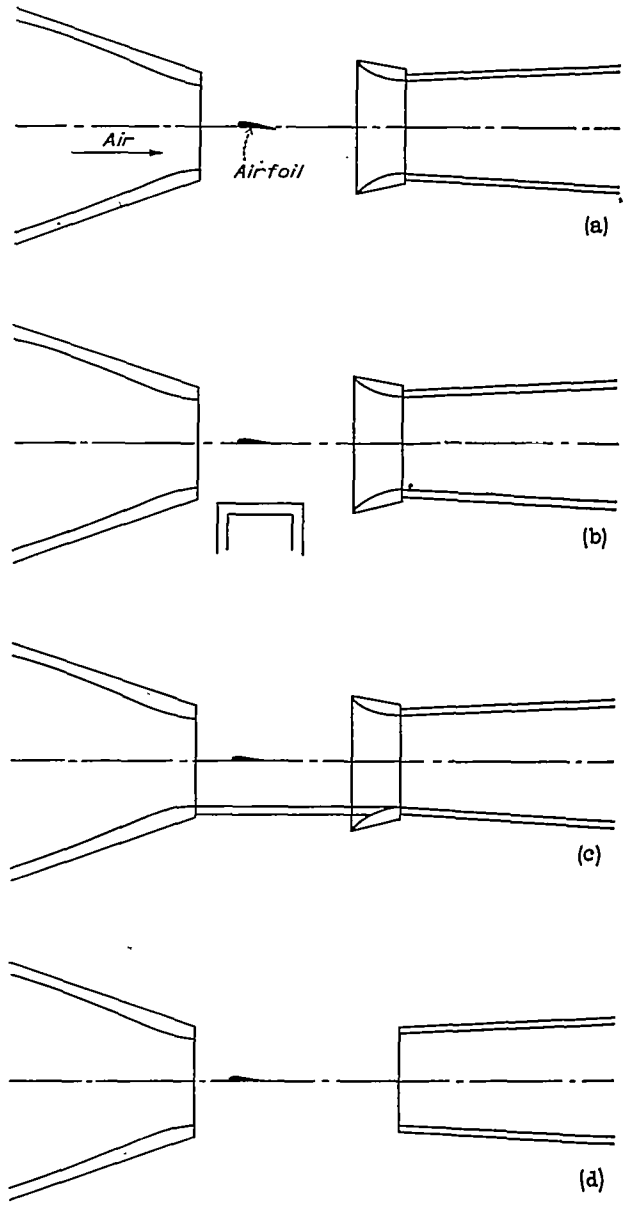


FIGURE 3.—The four test conditions of the model tunnel.
(a) Normal tunnel.
(b) Tunnel with balance house.
(c) Tunnel with ground board.
(d) Tunnel with exit-cone flare removed.

Tests.—Test data were obtained with the model tunnel in four different conditions (fig. 3) as follows:

1. Normal tunnel condition.

2. Normal tunnel condition with a model balance house to simulate the balance house of the full-scale tunnel.

3. Normal tunnel condition with a ground board 32 inches wide extending between the lower surfaces of the entrance and exit cones.

4. Flare removed from the exit cone, increasing the length of the open jet from 44 to 56 inches.

Conditions 1 to 3 simulate possible operating conditions of the full-scale tunnel; condition 4 was studied to determine whether increasing the length of the open section would appreciably affect the downwash at the tail. Tests were made for each of the four tunnel conditions with the 10- by 30-inch airfoil; only conditions 1 and 2 were studied with the 5- by 30-inch airfoil.

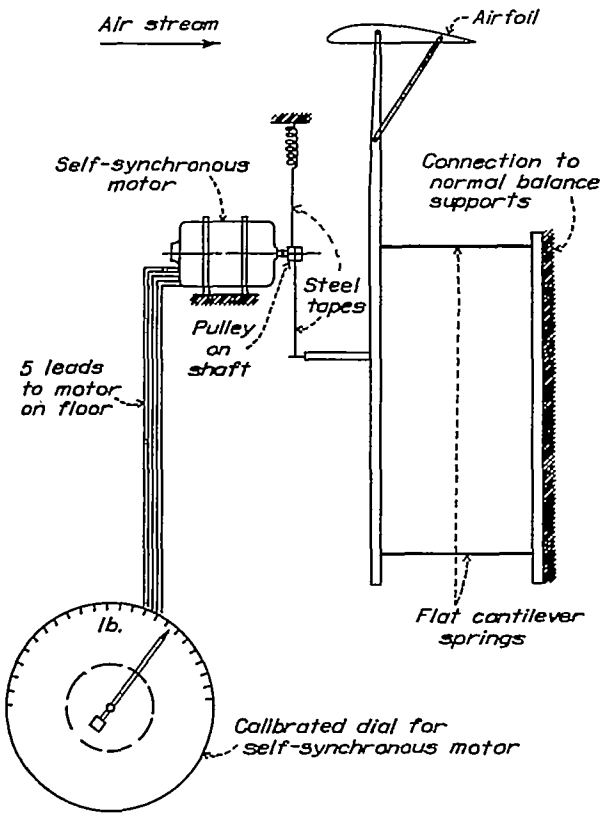


FIGURE 4.—Diagram of self-synchronous motor balance for small-airfoil tests in the full-scale tunnel.

For all the test conditions the air-stream angles in the tunnel at all the stations were obtained with the airfoils removed from the jet. The actual downwash angles were then taken as differences between the air-stream angles with the airfoil present and removed. Downwash surveys were made at three lift coefficients for each airfoil. The lift forces were measured in all cases over a range of angles of attack that included the angles of zero and maximum lift. The downwash surveys were limited to the plane of symmetry of the wing since tail surfaces do not normally extend a great distance on either side of this plane. Measurements were made between 4 inches above and 9 inches below the longitudinal axis through the quarter-chord point of the airfoils, at 1.0 and 1.65 chord lengths back of the trailing edge for the larger airfoil, and at 1, 2, and 3 chord lengths back of the trailing edge for the smaller airfoil. An air speed of about 60 miles per hour was used for all the tests.

FULL-SCALE WIND-TUNNEL TESTS

Apparatus.—Free-air data (free of tunnel-boundary interference effects) for the airfoils were obtained by tests in the full-scale tunnel (reference 6). Owing to the small forces encountered in measuring the lift, it was necessary to construct a special balance, a schematic diagram of which is shown in figure 4. The airfoil was supported on the balance by means of a forked

FIGURE 5.—The experimental set-up in the full-scale tunnel.

frame, this frame being supported in turn on a pair of flat cantilever springs. Vertical forces on the balance deflect the cantilever springs and the motion is converted into rotation of one of a pair of small self-synchronous motors by means of a thin strip of spring steel attached to its shaft. Remote recording of this motion was obtained on the complementary self-synchronous motor, placed in the balance house below the jet. By means of a calibrated dial and a pointer attached to the motor shaft, the lift forces on the airfoils could be observed directly. Effective damping was obtained by means of an oil dashpot. The entire balance was enclosed in a streamline fairing and

attached to one of the normal balance supports (fig. 5). Downwash angles and dynamic pressures were measured with the same instruments used in the model-tunnel tests. These instruments were attached to the survey apparatus in the tunnel (reference 6).

Tests.—Preliminary measurements in the full-scale wind tunnel, with the airfoil removed, consisted of surveys of air-stream angle and dynamic pressure and the determination of tare lift forces on the balance. For each airfoil, the lift forces were measured over the range of angles of attack between zero and maximum lift, and the downwash angles were measured for three lift coefficients. As in the model-tunnel tests, surveys were made only in the plane of symmetry of the airfoil. A slightly larger area was surveyed in

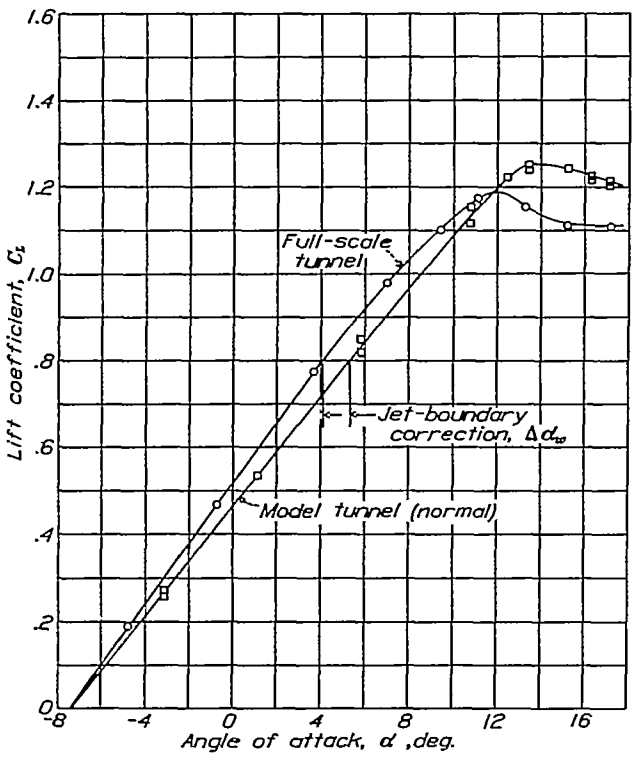


FIGURE 6.—Comparison of lift curves for the 5- by 30-inch airfoil in the normal model tunnel and in the full-scale tunnel.

the full-scale tunnel than in the model tunnel. Downwash measurements were made between 8 inches above and 12 inches below the longitudinal axis, from 1 to 5 chord lengths back of the quarter-chord point for the smaller airfoil, and from 1 to 4 chord lengths back for the larger airfoil.

RESULTS

Representative experimental data are plotted in figures 6 to 9. The final derived jet-boundary corrections are given in figures 10 to 13, in which is plotted the coefficient δ_T used in the usual boundary-correction formula

$$\Delta\alpha=57.3\ \delta_T\frac{S}{C}C_L$$

in which S and C are the areas of the airfoil and jet cross section, respectively, and $\Delta\alpha$ is the induced downwash angle in degrees due to the influence of the boundaries. The coefficient δ_T represents the total jet-boundary effect rather than the increase in the correction over that at the wing; i. e., $\delta_T=\delta_w+\delta_A$, in which δ_w is the correction factor for the wing and δ_A is the additional factor for the tail. Accordingly, in the application of the results, it must be remembered that, if the angle of attack of the airplane has already been corrected for the jet-boundary effect at the wing, the correction factor for the tail will be only the difference between the δ_T values at the tail and at the wing.

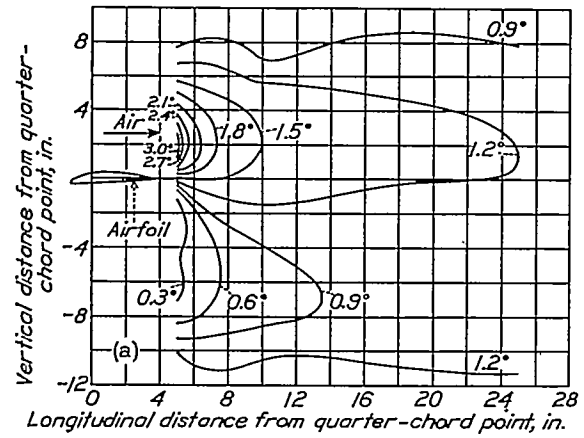
The tunnel-boundary effects at the airfoils were obtained directly from the lift curves (fig. 6) as the difference between the full-scale and model-tunnel angles of attack at a particular lift coefficient. Figures 7, 8, and 9 illustrate some intermediate steps in the derivation of the boundary-interference corrections behind the airfoil. Figure 7 comprises contour maps of the downwash measured in the full-scale tunnel; figures 8 and 9 compare plots of the downwash measured in the model tunnel and in the full-scale tunnel.

The corrections were primarily obtained for application to tests performed in the full-scale wind tunnel and are accordingly plotted against distance downstream in full-scale dimensions (figs. 10 to 13). Points are shown that correspond to each of the two airfoils at each of two lift coefficients. These points are not actual experimental values but were obtained after some interpolation, as the measurements in the two tunnels were made at slightly different lift coefficients and at slightly different positions back of the wing. For comparison with the theoretical values calculated for an infinitely long open jet, the corrections of reference 3 are included with the experimental data (figs. 10, 11, and 13).

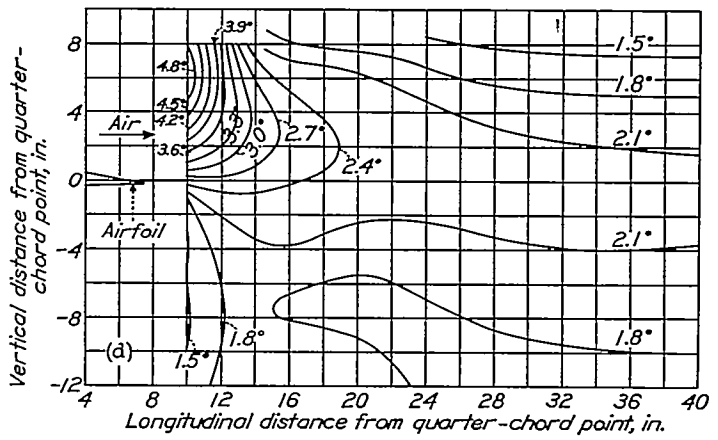
The scattering of the experimental points on some of the curves is very noticeable. Although theoretical reasons exist for expecting that the four cases would not exactly check, they appear insufficient to explain the observed amount of variation. The experimental error may possibly have exceeded the estimated value of 0.15°.

DISCUSSION

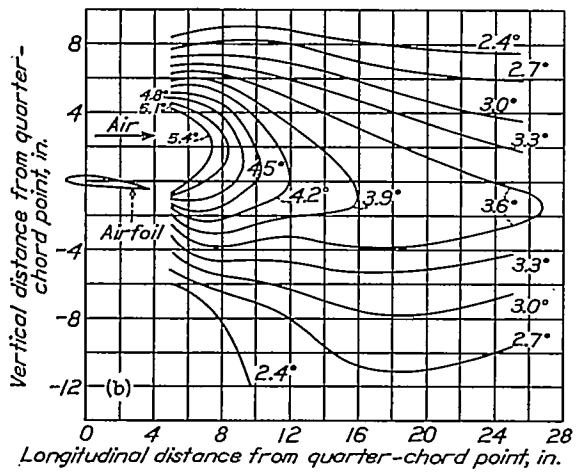
The results of greatest interest are those for the normal tunnel (fig. 10). It is seen that, whereas the correction at the wing has the theoretical value, the corrections on the longitudinal axis back of the wing not only do not approach twice that at the wing, as given by the theory, but actually decrease rapidly after the first 20 feet behind the wing (about 3 chord lengths). This effect is due to the exit cone. It is therefore apparent that the conception of the open jet as one of infinite length may lead to gross error in applying corrections at the tail surfaces. The curves show a marked resemblance to the one theoretically obtained considering the jet to be of finite length. (See fig. 2 taken from reference 4.)



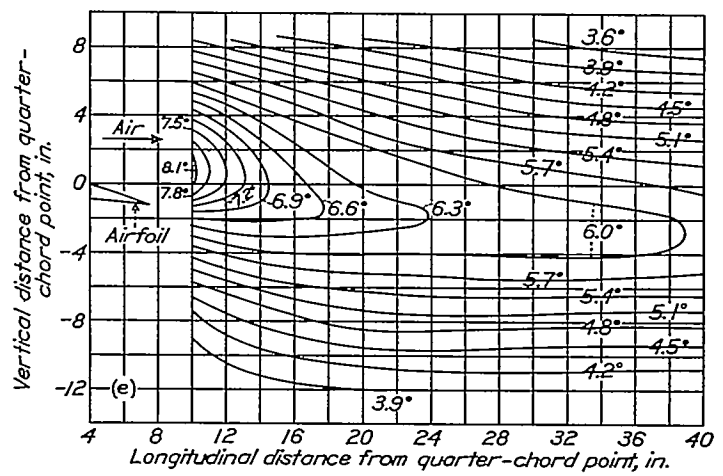
(a) 5- by 30-inch airfoil; α, −3.8°; C_L, 0.25.



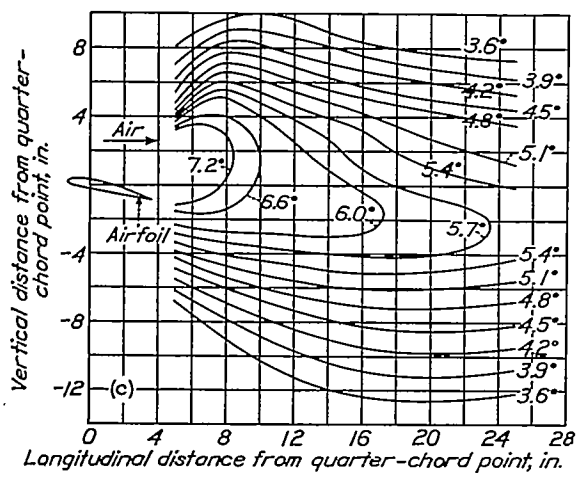
(d) 10- by 30-inch airfoil; α, −1.8°; C_L, 0.21.



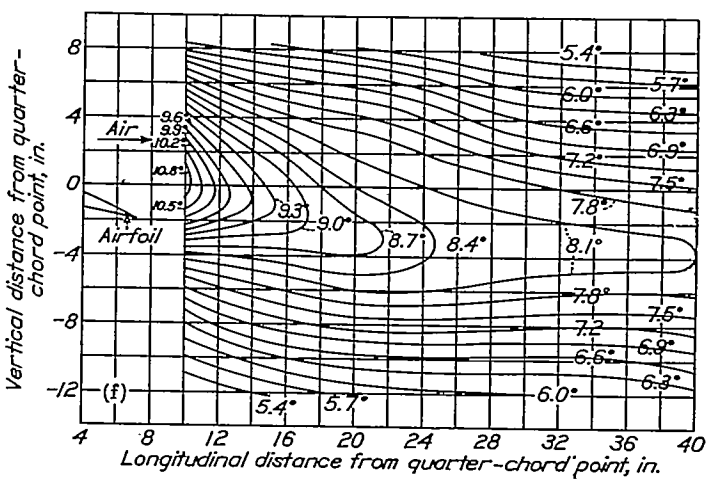
(b) 5- by 30-inch airfoil; α, 3.2°; C_L, 0.74.



(e) 10- by 30-inch airfoil; α, 5.0°; C_L, 0.59.



(c) 5- by 30-inch airfoil; α, 9.2°; C_L, 1.09.



(f) 10- by 30-inch airfoil; α, 11.2°; C_L, 0.91

FIGURE 7.—Downwash-angle contour lines from surveys in the full-scale wind tunnel on two airfoils of Clark Y section.

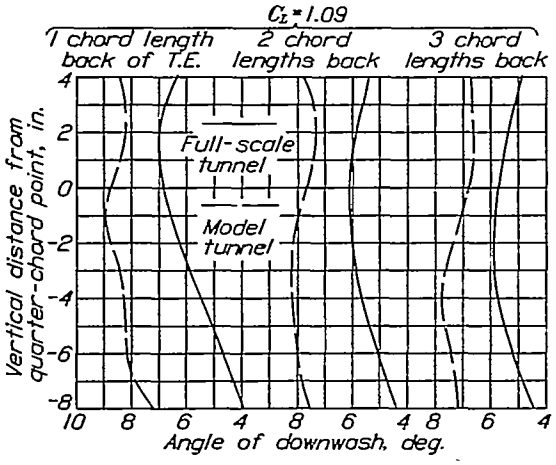


FIGURE 8.—Comparison of model and full-scale tunnel downwash; 5- by 30-inch airfoil; normal model tunnel.

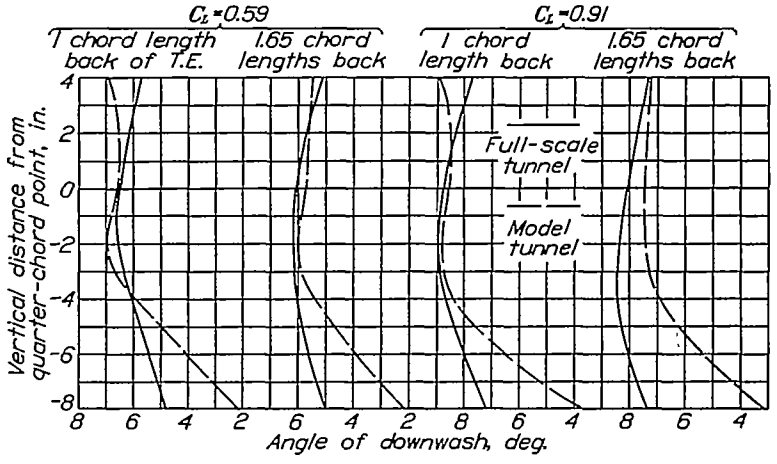


FIGURE 9.—Comparison of model and full-scale tunnel downwash; 10- by 30-inch airfoil; ground board in model tunnel.

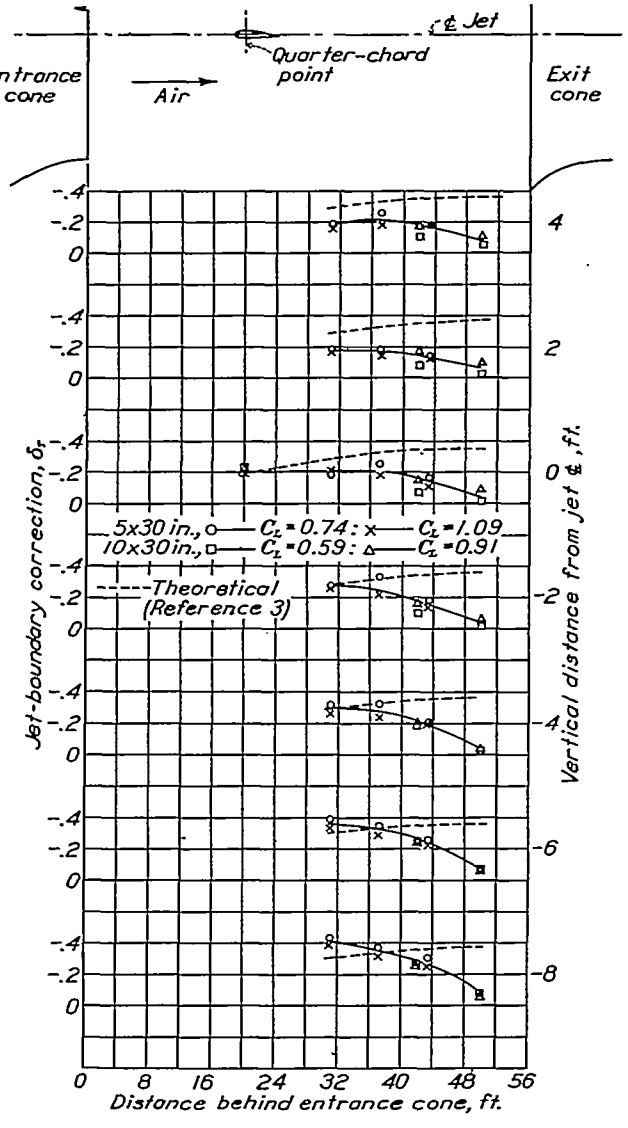


FIGURE 10.—Jet-boundary correction against distance behind entrance cone; tunnel normal.

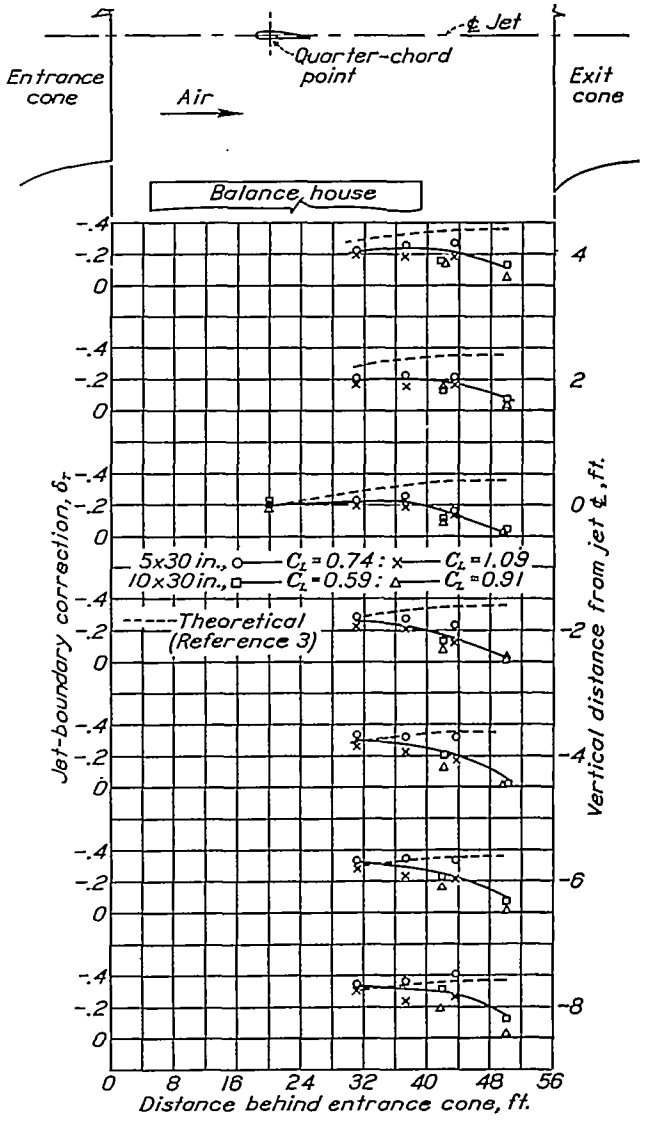


FIGURE 11.—Jet-boundary correction against distance behind entrance cone; tunnel with balance house.

The differences between the experimental and theoretical values are least in the region 4 to 8 feet below and 12 to 20 feet behind the wing. For a high-wing monoplane the tail is in this region at high lift coefficients; so in this case the theoretically calculated effect, assuming an infinitely long section, will not usually be in error by as much as 1°. For low-wing or midwing monoplanes the tails will lie relatively higher and somewhat above this region. For these cases it may be sufficiently accurate to assume that the correction is uniform over the entire airplane and equal to the theoretically calculated effect at the wing.

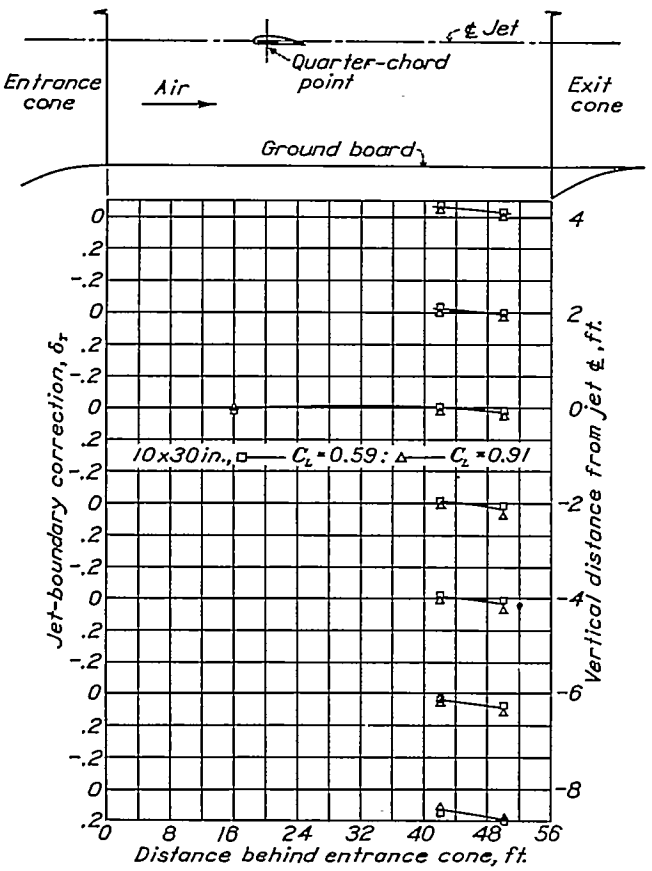


FIGURE 12.—Jet-boundary correction against distance behind entrance cone; tunnel with ground board.

A point of interest is that the observed jet-boundary effect is not symmetrical with respect to the horizontal center plane of the tunnel. This dissymmetry is probably due to the fact that the trailing vortices do not extend straight back from the wing but are inclined downward, owing to the downwash. No theoretical treatment has yet taken this feature into account, although the calculations for a wing placed below the center line should be somewhat comparable and they do indicate the same type of dissymmetry in the downwash. (See fig. 25 of reference 3.)

The results with the model balance house in place (fig. 11) are, as expected, about the same as those without it, except possibly in that portion of the jet closest to it.

Removal of the exit cone causes somewhat closer approach of the experimental to the theoretical results (fig. 13); it is clear, therefore, that the proximity of the closed section forming the exit cone of the jet contributes considerable inaccuracy to the results of a theory that assumes an infinitely long free jet.

The downwash results when the ground board was used (fig. 12) are, on the other hand, in agreement with the results of the theoretical treatment for an infinitely long jet with bottom boundary. For a long 2:1 rectangular jet, which is open on three sides and closed at the bottom, the theory predicts relatively small

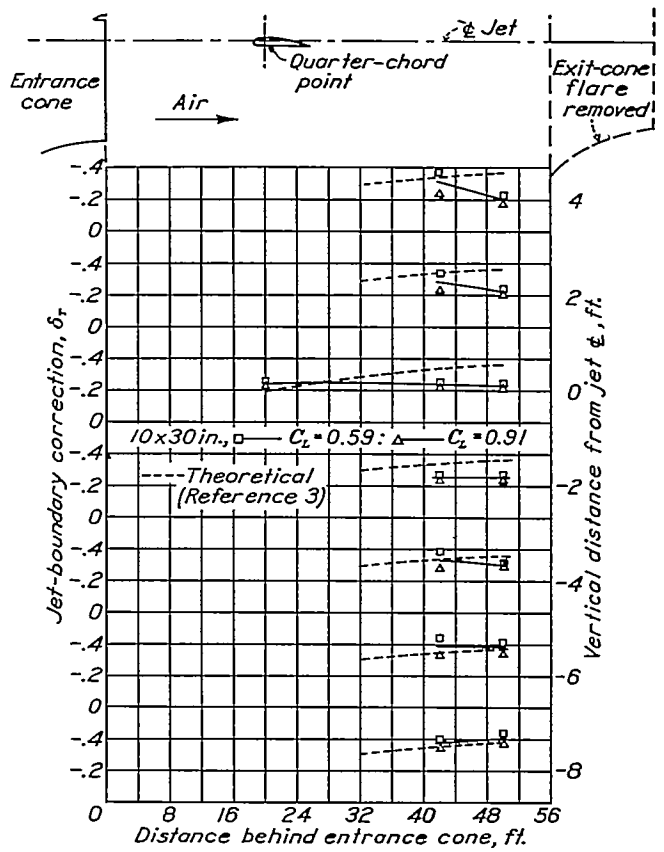


FIGURE 13.—Jet-boundary correction against distance behind entrance cone; tunnel with exit-cone flare removed.

tunnel-wall corrections in the region of the axis. The experimental results verified this prediction, although the agreement is somewhat fortuitous since (1) the jet is not quite rectangular, (2) it is not infinitely long, and (3) the ground board did not extend across the entire width. The lift curves were practically the same as those obtained in the full-scale tunnel, as were the downwash angles in the region of the tunnel axis. Near the ground board, however, the deviation from the free-stream downwash becomes very large, owing to the fact that the inclination of the stream must approach zero at the board.

In all the model-tunnel experiments, the lifting line, assumed to be located at the quarter-chord point of the airfoil, was placed 16 inches back of the entrance

cone on the horizontal center line. The results are then strictly applicable to the full-scale tunnel only when the airplane wing is 20 feet behind the entrance cone and on the horizontal center line. This location is approximately the usual one of the wings tested in the tunnel.

The boundary corrections for other wind tunnels may be found by using the downwash contours of figure 7, which are for free-stream conditions. By a comparison of the data obtained in the full-scale wind tunnel with those obtained in other tunnels behind similar airfoils at the same lift coefficients, the boundary-interference corrections may be directly obtained. This method assumes that the scale effects on the downwash contour map and on the jet-boundary effect are negligible.

CONCLUSIONS

1. For an open-jet wind tunnel the boundary corrections at the wing itself may be predicted from the simplified theory, which assumes the jet to be of infinite length; however, the theory gives erroneous results downstream. In the region of the tail surfaces, the jet-boundary corrections are less than those predicted by the simplified theory but are in good qualitative agreement with the results of a theory that considers the jet to be of finite length.

2. For the case of an open rectangular tunnel with ground board, the experiments substantiate the theoretical prediction that in such a tunnel there is relatively little jet-boundary effect either at the wing or at the tail.

3. With special reference to the full-scale wind tunnel, the experiments show that the presence of the balance house below the jet has no appreciable effect on the corrections. Removal of the exit bell improved the agreement between the experimental downwash and that predicted by the simplified theory.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *June 4, 1937.*

REFERENCES

1. Glauert, H., and Hartshorn, A. S.: The Interference of Wind Channel Walls on the Downwash Angle and the Tailsetting to Trim. R. & M. No. 947, British A. R. C., 1925.
2. Lotz, Irmgard: Correction of Downwash in Wind Tunnels of Circular and Elliptic Sections. T. M. No. 801, N. A. C. A., 1936.
3. Silverstein, Abe, and White, James A.: Wind-Tunnel Interference with Particular Reference to Off-Center Positions of the Wing and to the Downwash at the Tail. T. R. No. 547, N. A. C. A., 1935.
4. Weinig, F.: Der Strahleinfluss bei offenen Windkanälen. Luftfahrtforschung, Bd. 13, Nr. 7, 20. Juli 1936, S. 210–213.
5. Theodorsen, Theodore, and Silverstein, Abe: Experimental Verification of the Theory of Wind-Tunnel Boundary Interference. T. R. No. 478, N. A. C. A., 1934.
6. DeFrance, Smith J.: The N. A. C. A. Full-Scale Wind Tunnel. T. R. No. 459, N. A. C. A., 1933.