NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED

September 1945 as
Advance Restricted Report L5G31

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NACA

WASHINGTON

NACA ARR No. L5G31

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SUMMARY

Numerical values of the jet-boundary corrections to the angle of attack and the induced-drag, rolling-moment, and yawing-moment coefficients have been calculated for complete airplane or wing models in 7- by 10-foot closed rectangular wind tunnels. Variations in aspect ratio, taper ratio, wing area, wing span, flap span, aileron span, and vertical location of the wing in the tunnel were included in the computations. The numerical values of the corrections were obtained by a graphical-integration process that permitted the use of the actual span loading and spanwise variation of upwash velocity. The corrections are given in equations containing correction factors that are presented in the form of easily used charts.

The results showed that the wing area was the most important variable, as has usually been assumed in previous calculations. When the corrections were based on wing area, the effect of most of the other variables was negligible. A comparison of the corrections for tunnels of several different shapes showed that, for geometrically similar wings having the same ratio of wing area to tunnel cross-sectional area, the corrections were very nearly the same as those for 7- by 10-foot rectangular tunnels. Correction factors and equations are presented for determining corrections to the pitching-moment coefficient, downwash angle, and wake or slipstream location. These correction factors account for wing span, tail length, and vertical location of the wing and tail in the tunnel. First-order effects of compressibility on the jet-boundary corrections are included in the charts.

INTRODUCTION

Calculations of the jet-boundary corrections for complete models previously have involved some assumptions to simplify the computations. In calculating the upwash velocity and subsequently the corrections, the span load distribution has usually been considered uniform or elliptical. In addition, in many cases the upwash velocity across the wing span has been assumed to be constant. The purpose of this investigation was to calculate the jet-boundary corrections as accurately as possible by using the actual span load and upwash-velocity distributions for wings of various plan forms and to obtain charts from which the corrections for 7- by 10-foot closed rectangular wind tunnels may be easily determined for a wide range of model sizes and configurations.

The formulas and methods for calculating the jet-boundary corrections have been presented in detail in references 1 to 4. The term "jet-boundary corrections" as used herein refers to the corrections necessitated by the vertical velocity induced by the tunnel walls and does not include the effects of the induced horizontal velocity caused by the constriction effect, which leads to the blocking corrections. The graphical-integration process of reference 3 was used herein to calculate the corrections. Jet-boundary corrections were computed for the angle of attack and for the induced-drag, rolling-moment, and induced-yawing-moment coefficients. In preparing the correction charts, the effects of some of the plan-form variables were considered to be negligible. In order to justify this procedure, an examination was made of the probable accuracy of the corrections presented.

The correction factors given in reference 2 for use in the equations for corrections to the pitching-moment coefficient, downwash angle, and wake or slipstream location covered only a small range of model locations. Calculations of these correction factors have therefore been made for a greater range of wing and tail locations above or below the tunnel center line; the results are presented in a form slightly different from that used in reference 2.

All the curves of corrections and correction factors presented herein were calculated for an unyawed model. The method of calculation and some computations of the effect of yaw on the jet-boundary corrections for a typical model are given in reference 4. By use of the results of reference 4, some equations were derived for approximating the effect of yaw on the various corrections.

SYMBOLS

C_L	lift coefficient
C_D	drag coefficient
C_n	yawing-moment coefficient
C_m	pitching-moment coefficient
ΔC_m	correction to the pitching-moment coefficient
C_l	rolling-moment coefficient
w	induced upwash velocity, parallel to Z-axis
q	dynamic pressure at a particular point
q_o	free-stream dynamic pressure
M	Mach number
Γ	circulation strength of vortex
b	wing span
b_f	flap span
b_a	span of one aileron
C	tunnel cross-sectional area
λ	ratio of tip chord to root chord
A	aspect ratio
x	distance parallel to X-axis
y	distance from plane of symmetry, body axes
α	angle of attack, degrees
ψ	angle of yaw, degrees

S wing area

δ jet-boundary correction factor $\left(\frac{C}{4s}\frac{w}{\Gamma}\right)$; aileron deflection when used with subscript a

i_t angle of stabilizer setting

$\Delta\epsilon$ correction to downwash angle

$\frac{\partial C_m}{\partial i_t}$ stabilizer effectiveness, change of pitching-moment coefficient per degree change in stabilizer setting

s vortex semispan

d distance of lifting line above or below horizontal center line of tunnel, feet

$\Delta z'$ correction to vertical displacement of wake or slipstream

Subscripts:

$l.l.$ lifting line

s.c. streamline curvature

w wing

f flap

a aileron

c.s. center section of lifting line of wing

m measured

x at a distance x behind lifting line

i induced

g geometric

av average

ψ at a particular angle of yaw

o free stream

The axes used herein are wind axes; the X-axis is parallel to the relative wind and the Z-axis is in the plane of symmetry of the model and perpendicular to the relative wind.

RESULTS

Use of Charts

The methods used herein for calculating the jet-boundary corrections have been set forth in detail in references 2 to 4. The corrections to the angle of attack and the induced-drag, rolling-moment, and yawing-moment coefficients were computed for a wide range of model dimensions. The ranges of model dimensions are as follows:

Aspect ratio	6 to 16
Wing span, feet	5 to 8
Taper ratio	0.25 to 1.00
Wing area, square feet	1.56 to 10.7
Flap-span ratio, b_f/b	0.40 to 1.00
Aileron-span ratio, $\frac{b_a}{b/2}$	0.30 to 1.00

In making the calculations, the theoretical span load distributions for angle-of-attack changes and aileron and flap deflections were used for the wings considered. The span load distributions were taken from references 5 and 6. The spanwise variation of boundary-induced upwash velocity was calculated as in reference 3 for the theoretical span loading.

The corrected value of the angle of attack is given by

$$\alpha = \alpha_m + (2 - \cos\psi)S\left\{\left[\left(\frac{\Delta\alpha}{SC_L}\right)_{l.l.} + \left(\frac{\Delta\alpha}{SC_L}\right)_{s.c.}\right]\left(C_{L_m}\right)_{\delta_a=0^\circ} + \left(\frac{\Delta\alpha}{SC_l}\right)C_{l_m}\right\} \quad (1)$$

where the values of $\frac{\Delta\alpha}{SC_L}$ and $\frac{\Delta\alpha}{SC_l}$ are those obtained from figure 1. The corrected induced-drag coefficient is

$$C_D = C_{D_m} + (2 - \cos\psi)S\left[\left(\frac{\Delta C_{D_i}}{SC_L^2}\right)\left(C_{L_m}^2\right)_{\delta_a=0^\circ} + \left(\frac{\Delta C_{D_i}}{SC_l C_L}\right)C_{l_m}\left(C_{L_m}\right)_{\delta_a=0^\circ}\right] \quad (2)$$

where the values of $\frac{\Delta C_{D_i}}{S C_L^2}$ and $\frac{\Delta C_{D_i}}{S C_l C_L}$ are those obtained from figure 2. The corrected rolling-moment coefficient may be found from the equation

$$C_l = C_{l_m} + (-1.5 + 2.5 \cos \psi) S \left(\frac{\Delta C_l}{S C_l}\right) C_{l_m} \tag{3}$$

The values of $\frac{\Delta C_l}{S C_l}$ are those indicated in figure 3. The correction to the yawing-moment coefficient depends upon the aileron deflected when the model is yawed. When the deflected aileron is on the leading wing, the corrected yawing-moment coefficient is

$$C_n = C_{n_m} + (-0.3 + 1.3 \cos \psi) S \left(\frac{\Delta C_{n_i}}{S C_l C_L}\right) C_{l_m} \left(C_{L_m}\right)_{\delta_a = 0^\circ} \tag{4}$$

When the aileron is on the trailing wing, the corrected yawing-moment coefficient is

$$C_n = C_{n_m} + (4.3 - 3.3 \cos \psi) S \left(\frac{\Delta C_{n_i}}{S C_l C_L}\right) C_{l_m} \left(C_{L_m}\right)_{\delta_a = 0^\circ} \tag{5}$$

In equations (4) and (5) the values of $\frac{\Delta C_{n_i}}{S C_l C_L}$ are those given in figure 4.

First-order compressibility effects on these corrections, as calculated in reference 7, have been accounted for in figures 1 and 3. The streamline-curvature correction to lift was derived in reference 2 in three ways: as a correction to the lift coefficient, as a correction to the angle of attack, and as corrections to both lift coefficient and angle of attack. The entire streamline-curvature correction is applied herein to the angle of attack.

Although the corrections were calculated for a wide range of model dimensions, the results presented in figures 1 to 4 are for only a few dimensions. As will be shown later, the effects of the other variables were very small and could be neglected. The calculations are for a range of ±1.0 foot in the vertical distance of the wing from the center line of the tunnel. Distances greater than 1 foot from the center line should be avoided in mounting the model in the tunnel because of the large increase in the corrections for greater distances.

The effects of yaw on the various corrections are included in equations (1) to (5) and were determined from the calculations of reference 4 that were made for one model. The variation of the corrections with angle of yaw is assumed to be approximately the same for all models.

The corrections in figures 3 and 4 may be used to correct the rolling-moment and yawing-moment coefficients produced by the dihedral effect of a yawed wing. By use of this procedure the measured data are corrected for the unsymmetrical upwash and lift distribution caused by dihedral by assuming that these effects are similar to those produced by aileron deflection. The rolling-moment coefficient produced by a yawed wing should not be used in the corrections to the angle of attack and induced-drag coefficient because the effects on the left and right wings will tend to cancel each other.

For corrections to the angle-of-attack and the induced-drag, rolling-moment, and yawing-moment coefficients of models that do not come within the range of plan-form variables considered herein, the upwash-velocity curves of figure 5 and equations similar to those of reference 3 may be used for the calculations.

Corrections to the pitching-moment coefficient, downwash angle, and wake or slipstream location could not be given in the form of charts because of the large number of variables involved, some of which must be determined from test data. The correction factors in figures 6 to 8 include a larger range of dimensions than and are plotted in a slightly different form from the factors in reference 2. It should be noted that some of the symbols used herein are different from those used in reference 2. Equations for calculating corrections to elevator hinge moments and elevator floating angles are given in reference 2, but these corrections are ordinarily small enough to be within the experimental accuracy obtained in measuring the quantities and may thus be neglected.

The equation from reference 2 for the correction to the pitching-moment coefficient is

$$\Delta C_m = -\left[\frac{(\delta_x C_L)_{w+f}}{\sqrt{(q/q_o)_{av}}} - (\delta_{l.l.} C_L)_{w+f}\right] \frac{S}{C}\left(\frac{\partial C_m}{\partial i_t}\right) 57.3 \qquad (6)$$

The correction to the downwash angle at any point (reference 2) is

$$\Delta\epsilon = \frac{(\delta_x C_L)_{w+f}}{\sqrt{q/q_o}} \frac{S}{C} 57.3 \qquad (7)$$

This correction to the downwash angle should be applied only to downwash angles that are measured by an air-flow survey. When average downwash angles at the tail are determined from stabilizer-effectiveness data by use of corrected pitching-moment coefficients, no corrections to the downwash angles are necessary.

The displacement of the wake or slipstream (reference 2) is given by

$$\Delta z' = \int_{T.E.}^{x} \frac{1}{\sqrt{q/q_o}} (\delta_x C_L)_{w+f} \frac{S}{C}\, dx \qquad (8)$$

In equations (6) to (8)

$$(\delta_x C_L)_{w+f} = (\delta_{x_w} C_{L_w} + \delta_{x_f} C_{L_f})$$

and

$$(\delta_{l.l.} C_L)_{w+f} = (\delta_{l.l._w} C_{L_w} + \delta_{l.l._f} C_{L_f})$$

where the subscripts on the correction factors indicate that the factors are determined for the wing and flap tip vortices, respectively. If the values of δ_x for the wing and for the flap are within 0.03 of each other, an average value of δ_x may be used with the total lift coefficient instead of separate values as shown.

The factor $\delta_{l.l.}$ is determined from figure 6 for the following values of s:

Wing or full-span flap		$\frac{s}{b/2}$
Shape	λ	
Rectangular	1.00	0.93
Tapered	.50	.88
Tapered	.25	.83
Partial-span flap		$\frac{s}{b_f/2}$
$b_f/b > 0.6$		1.00
$b_f/b < 0.6$		1.30

The value of d_{g_w} is the height of the wing trailing edge above or below the tunnel center line at the spanwise station equal to s. The value of d_{g_f} is measured from the position of the flap trailing edge for plain or slotted flaps or a point midway between the wing and flap trailing edges for a split flap at the spanwise station equal to s. The effects of yaw on $\delta_{l.l.}$ may be accounted for by use of the following equation:

$$\delta_{l.l._\psi} = \delta_{l.l.}(2 - \cos\psi) \tag{9}$$

In order to determine δ_x from figure 7, an effective height d must be used instead of the actual height d_g to account for the downward displacement of the tip vortices behind the wing. The effective height d for determining δ_x can be found from

$$d = d_g - 0.05C_Lx \tag{10}$$

for wings and for flaps having spans greater than 0.6 of the wing span. For flaps with spans smaller than 0.6 of the wing span, the effective height d is

$$d = d_g - 0.1C_L x \tag{11}$$

The value of x for use with figure 7 and equations (10) and (11) is the distance from the quarter-chord point of the wing to the three-quarter-chord point of the tail for ΔC_m and the distance from the quarter-chord point of the wing to the point in question for $\Delta\epsilon$ and $\Delta z'$. If values of x smaller than 2.5 feet are required, an interpolation may be made by using for the values of δ_x at $x = 0$ the curves of $\delta_{c.s.}$ in figure 8. For values of s other than those given in figure 7, linear interpolation or extrapolation may be used. In order to account for the effects of yaw on δ_x, the following equation should be used:

$$\delta_{x_\psi} = \delta_x (1.67 - 0.67 \cos \psi) \tag{12}$$

If air-flow surveys for determining $(q/q_o)_{av}$ have not been made, this quantity may be estimated from the relation

$$(q/q_o)_{av} = \frac{\dfrac{\partial C_m}{\partial i_t}}{\left(\dfrac{\partial C_m}{\partial i_t}\right)_o}$$

where $\left(\dfrac{\partial C_m}{\partial i_t}\right)_o$ should be determined from tests of the isolated horizontal tail. If these tests have not been made, an approximation to $\left(\dfrac{\partial C_m}{\partial i_t}\right)_o$ may be found by using the largest value of $\dfrac{\partial C_m}{\partial i_t}$ obtained from propeller-off tests. Propeller-windmilling tests have been used to determine $\left(\dfrac{\partial C_m}{\partial i_t}\right)_o$, but the value obtained is subject to some doubt because experience has shown that $(q/q_o)_{av}$ may vary from 0.75 to a value greater than 1.00 for propeller-windmilling tests; the value of $(q/q_o)_{av}$ determined in this way depends upon the propeller size and location with respect to the tail surface.

The lift coefficients C_L to be used in calculating ΔC_m should be the trim lift coefficients determined from a series of tests with different stabilizer settings for each power condition. For each power condition, therefore, the same curve of ΔC_m against C_L is used for all stabilizer or elevator settings in correcting the tunnel data. This procedure accounts for the fact that no additional corrections are calculated for the effect of the tail lift as would be necessary if the lift coefficient for the tail-off condition were used to compute ΔC_m. The correction factors for the tail lift would be of the same order of magnitude as the factors for the wing lift, but the corrections would probably be somewhat smaller. This procedure will make the correction to the pitching-moment coefficient most accurate at the trim lift coefficients and only slightly less accurate at all other lift coefficients.

First-order compressibility effects on the corrections to the pitching-moment coefficient, downwash angle, and wake or slipstream location may be accounted for by multiplying the length x by $\frac{1}{\sqrt{1 - M^2}}$, as indicated in figure 7.

Accuracy of Charts

During the analysis of the calculations, corrections for closed-throat tunnels of circular, elliptical, octagonal, and rectangular cross sections of various proportions were compared. It was found that, for geometrically similar wings having the same ratio of wing area to tunnel cross-sectional area, the corrections were all within ±15 percent of those for 7- by 10-foot tunnels. The corrections in figures 1 to 4 were therefore based on the wing area. With this procedure, the effects of most of the other variables were negligible and only the most important of these effects are indicated in figures 1 to 4.

An examination was made of the inaccuracies involved in the correction factors in figures 1 to 4 and the results are shown in figures 9 and 10. The abscissas in figures 9 and 10 are the values of the corrections from the curves of figures 1 to 4, and the ordinates are the calculated values of the corrections. The lines indicate zero error; the vertical distances between the points and the lines represent the inaccuracies caused by neglecting the effects of some of the plan-form variables on the corrections presented in figures 1 to 4.

For the conditions assumed in the preparation of figure 9 $(C_L = 1.0;\ C_l = 0.03)$, the maximum error in the angle-of-attack correction will be 0.05° and the maximum error in the correction to the induced-drag coefficient will be 0.0008. From figure 10 the maximum errors in the induced-yawing-moment coefficient and rolling-moment coefficient are 0.00013 and 0.0002, respectively. All these errors are about the same as or are smaller than the usual experimental errors for complete-model tests.

Some calculations were made of the component of induced-drag-coefficient correction caused by aileron deflection alone $\dfrac{\Delta C_{D_i}}{S{C_l}^2}$. The total drag-coefficient correction due to this component is only about 0.0003 and may be neglected. Computations of the component of induced-yawing-moment coefficient due to aileron deflection alone $\dfrac{\Delta C_{n_i}}{S{C_l}^2}$ indicated a maximum value of ΔC_{n_i} of about -0.0001, which is also negligible.

In order to determine the allowable simplifying assumptions and the accuracy to which the corrections to the pitching-moment coefficient, the downwash angle, and the wake or slipstream location need be computed, a sample computation is made. An average value of stabilizer effectiveness is about -0.030. By using this value with a wing having an area of 10 square feet and a span of 8 feet and by assuming for simplicity that $\dfrac{q}{q_o} = 1.0$, equations (6) to (8) become

$$\Delta C_m = 0.245 \left[(\delta_x C_L)_{w+f} - (\delta_{l.l.} C_L)_{w+f}\right]$$

$$\Delta\epsilon = 8.2\ (\delta_x C_L)_{w+f}$$

and

$$\Delta z' = 0.143 C_L \int_{T.E.}^{x} \delta_x\, dx$$

The order of magnitude of the corrections for this case will then be

$$\Delta C_m = 0.020C_L$$

where ΔC_m is equivalent to a 2-percent shift in neutral point in the direction of instability;

$$\Delta\epsilon = 1.64C_L$$

where $\Delta\epsilon$ is in degrees; and

$$\Delta z' = 0.090C_L$$

where $\Delta z'$ is in feet. An accuracy of ±15 percent in any of these corrections would be within the experimental accuracy usually obtained. This degree of accuracy requires that both δ_x and the difference $\delta_x - \delta_{l.l.}$ be accurate within about ±0.03. Except for unusual cases in which the wing is located at large distances from the tunnel center line, a change of 2 or 3 inches in the tail length or in the vertical location of the wing or tail in the tunnel will have a negligible effect on the corrections. In addition, an error of 10 percent in determining the q/q_o ratio will not cause excessive errors in the final correction.

CONCLUSIONS

The jet-boundary corrections to the angle of attack and the induced-drag, rolling-moment, and yawing-moment coefficients have been calculated for complete airplane or wing models in 7- by 10-foot closed rectangular wind tunnels. Variations of aspect ratio, taper ratio, wing span, wing area, flap span, aileron span, and vertical location of the wing in the tunnel were considered. First-order effects of compressibility on the corrections were included. The equations and correction factors for determining the corrections to the pitching-moment coefficient, downwash angle, and wake or slipstream location were determined from a previous report and are presented along with some additional values of the correction factors that include a larger range of model dimensions. The correction factors account for wing span, tail length, and vertical location of the wing and tail in the tunnel.

An analysis of the calculated corrections showed that:

1. When the corrections were based on wing area, the effect of most of the other variables was small and was in many cases within the experimental accuracy of the tunnel measurements.

2. For geometrically similar wings having the same ratio of wing area to tunnel cross-sectional area, the corrections for tunnels of several different shapes were within ±15 percent of those for 7- by 10-foot tunnels.

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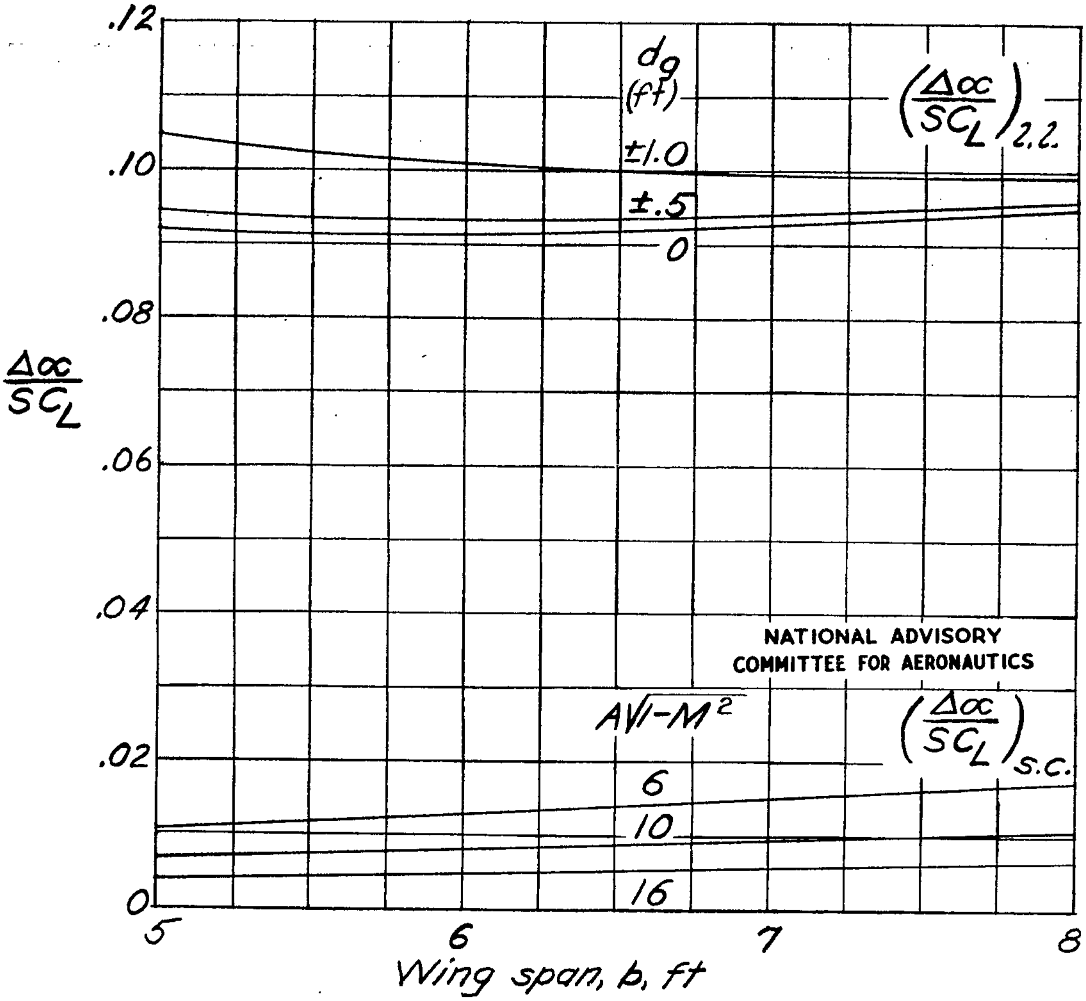
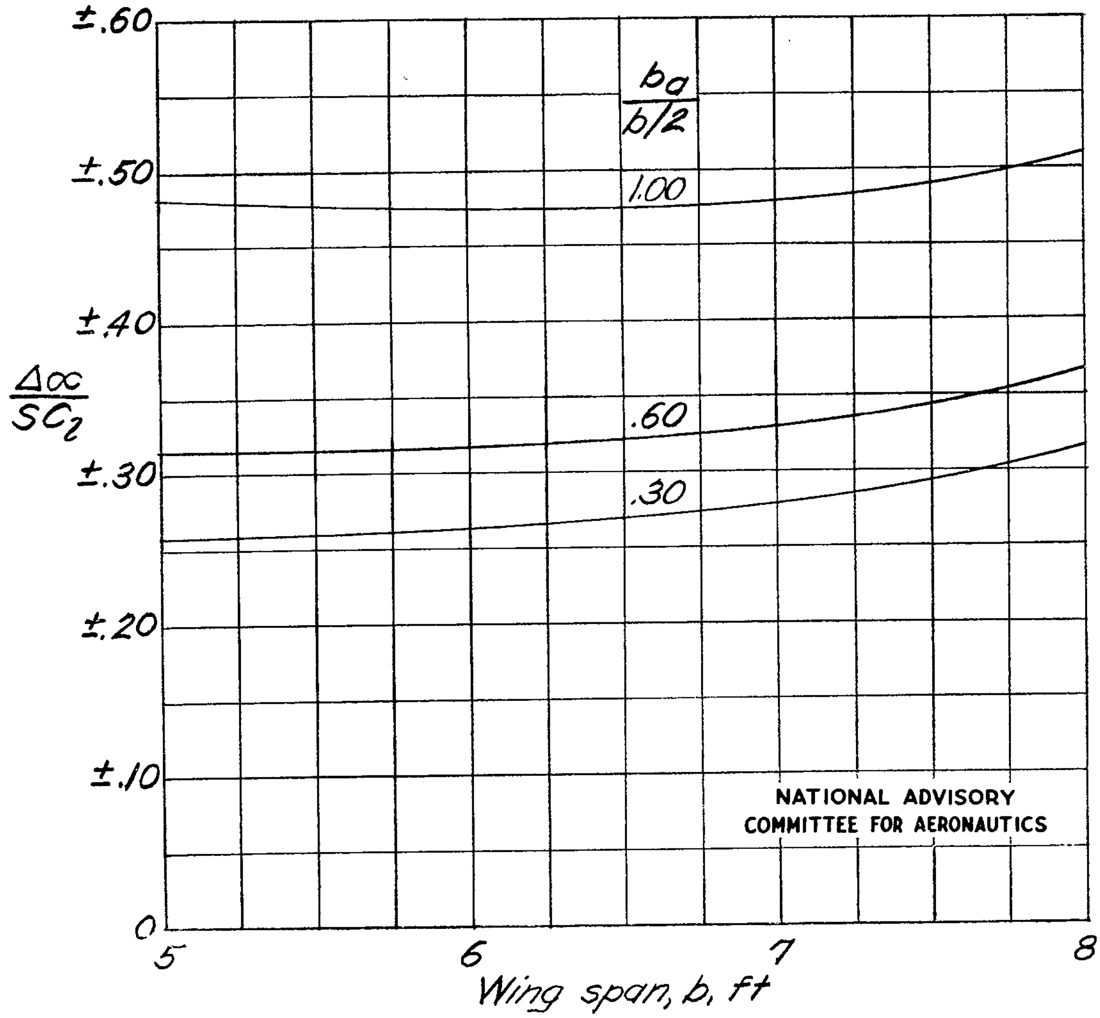


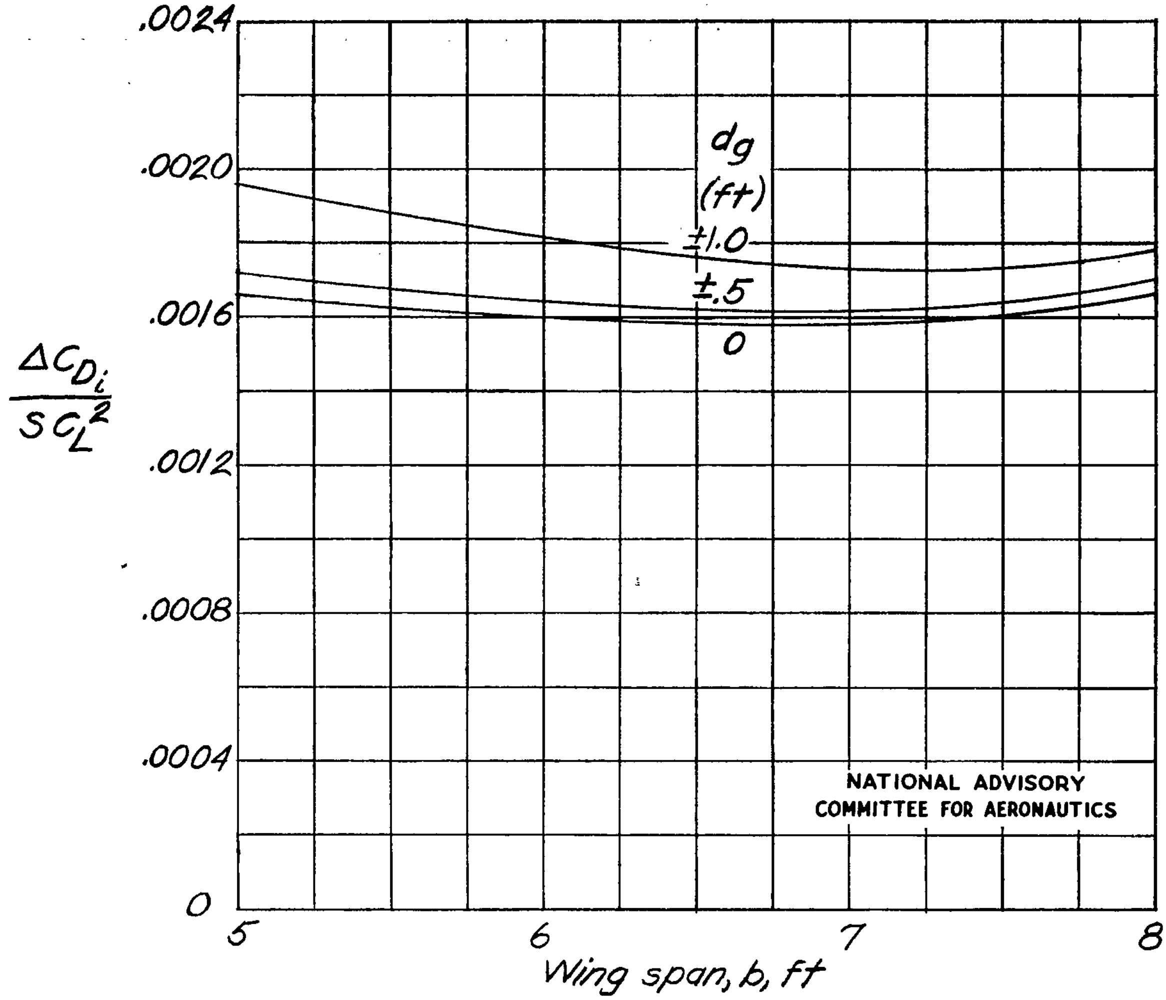
(a) $\frac{\Delta\alpha}{SC_L}$.

Figure 1.- Jet-boundary correction to the angle of attack for complete models in 7-by 10-foot closed rectangular wind tunnels.



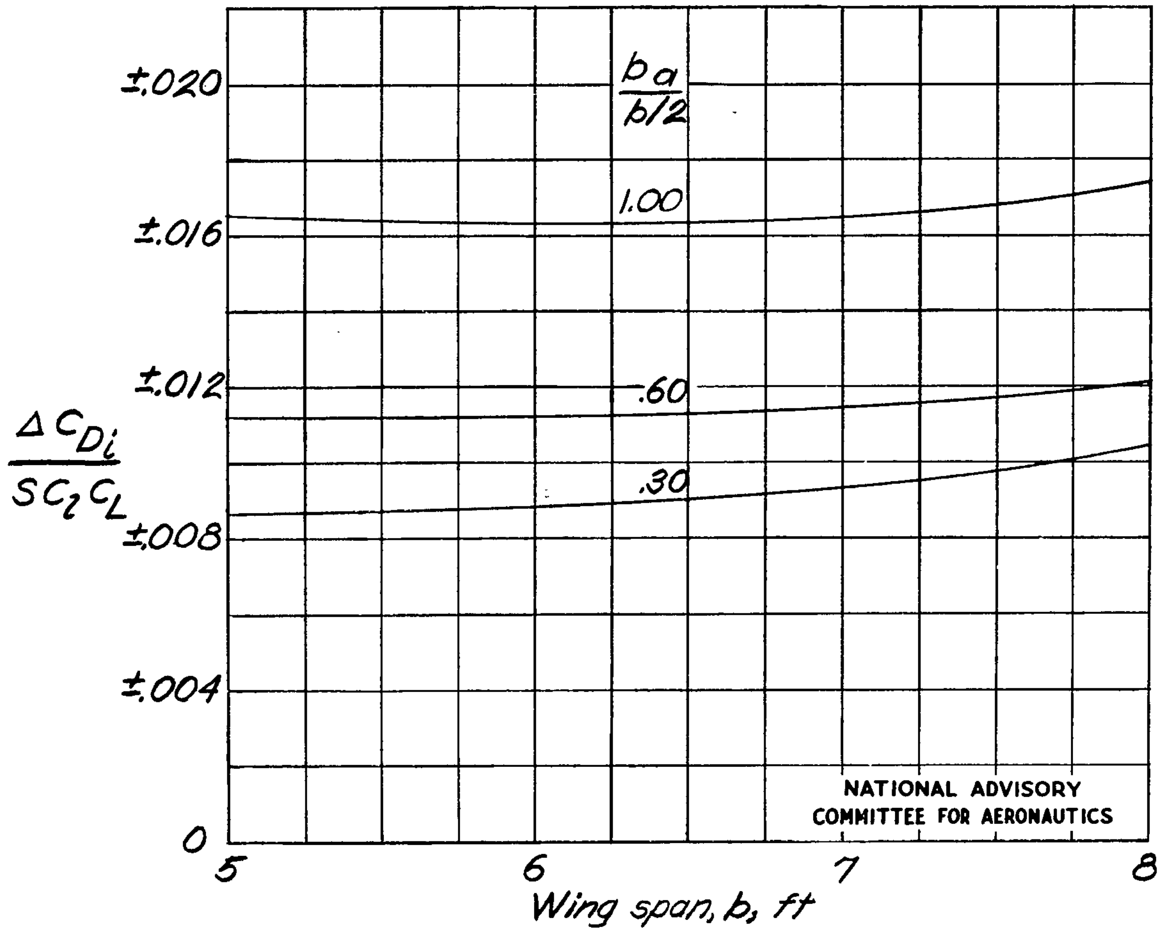
(b) $\frac{\Delta\alpha}{SC_l}$ (+, left aileron deflected; −, right aileron deflected).

Figure 1.- Concluded.



(a) $\frac{\Delta C_{D_i}}{S C_L^2}$.

Figure 2.- Jet-boundary correction to the induced-drag coefficient for complete models in 7-by 10-foot closed rectangular wind tunnels.



(b) $\frac{\Delta C_{D_i}}{S C_L C_l}$ (+, left aileron deflected; −, right aileron deflected).

Figure 2.- Concluded.

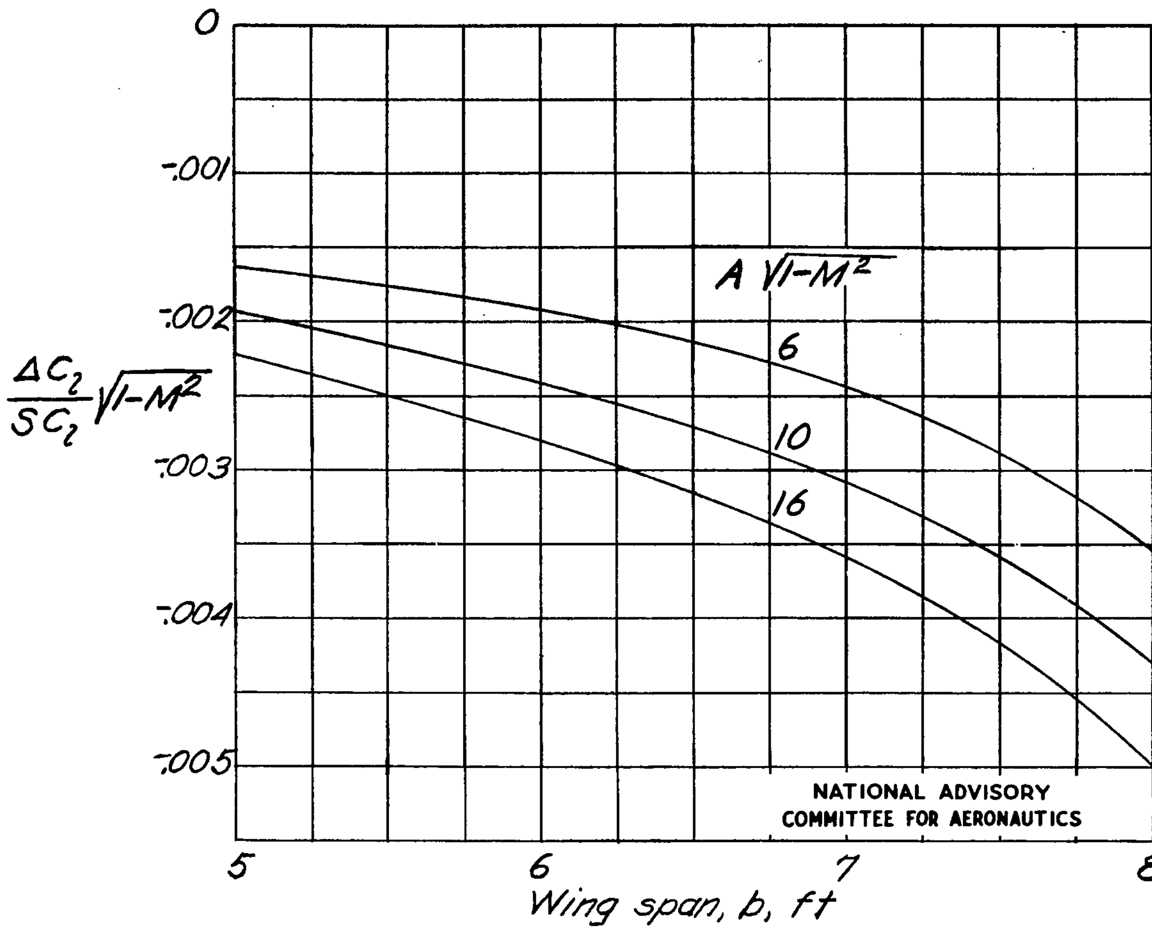


Figure 3.- Jet-boundary correction to the rolling-moment coefficient for complete models in 7-by 10-foot closed rectangular wind tunnels.

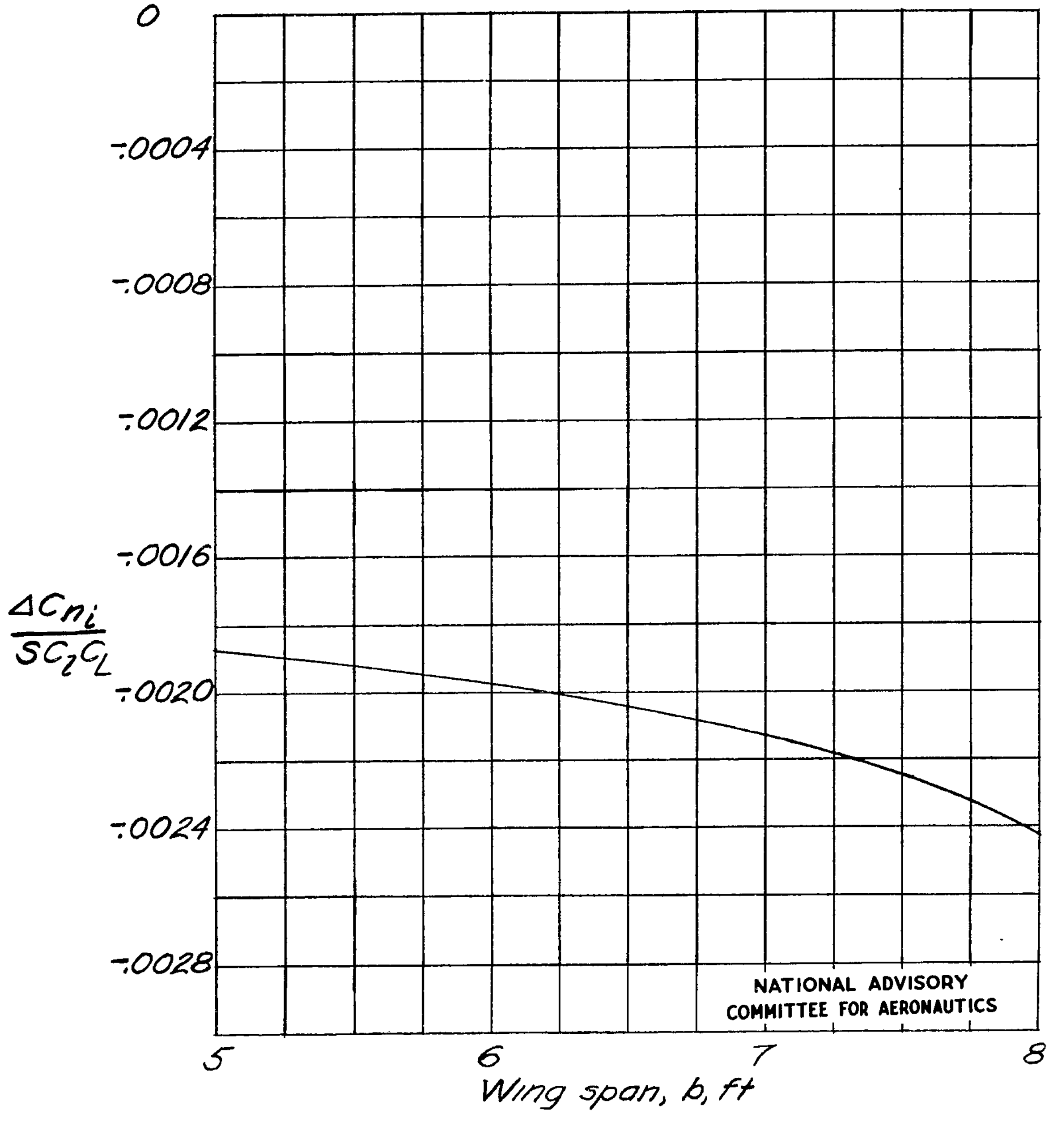
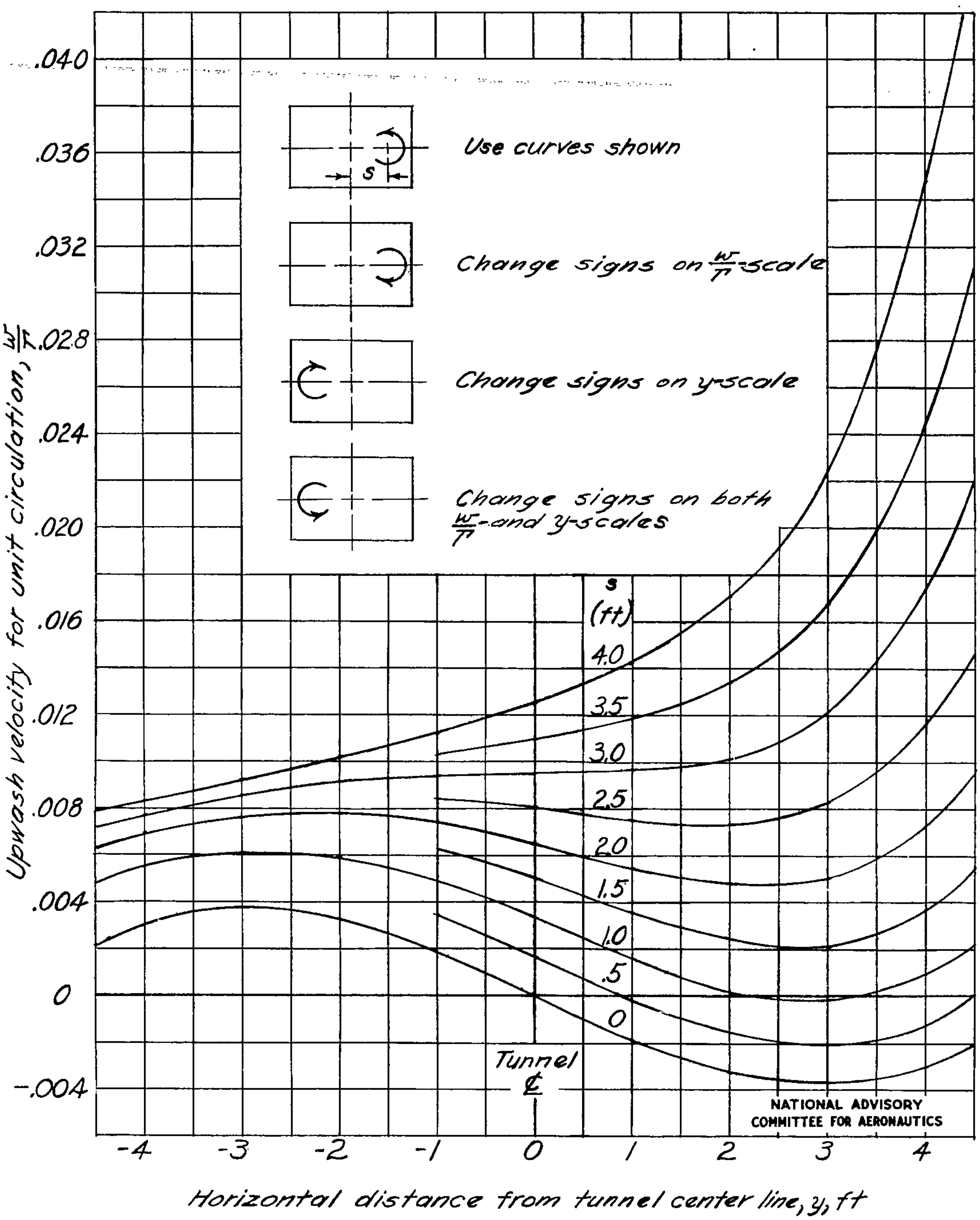
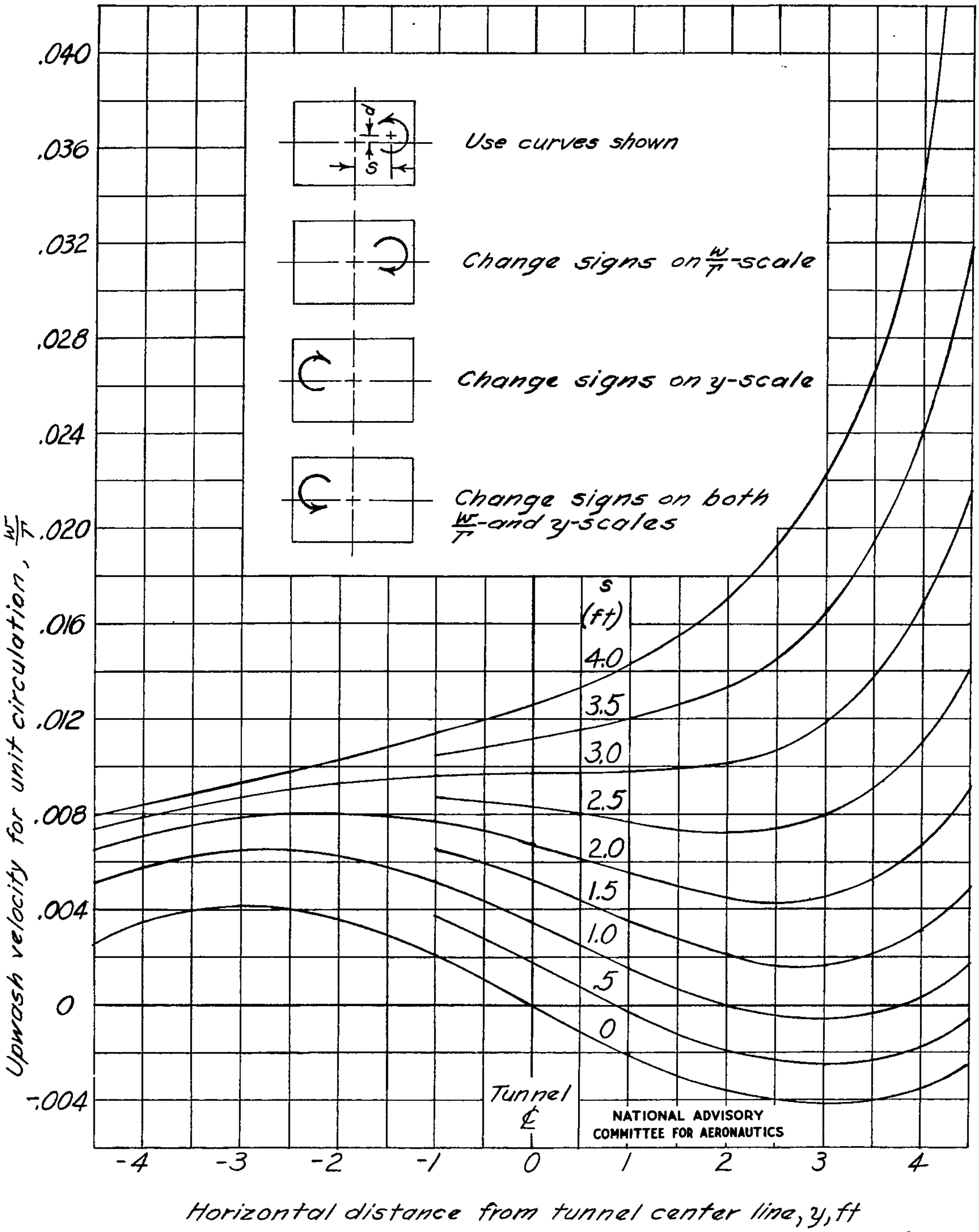


Figure 4.- Jet-boundary correction to the induced-yawing-moment coefficient for complete models in 7-by 10-foot closed rectangular wind tunnels.



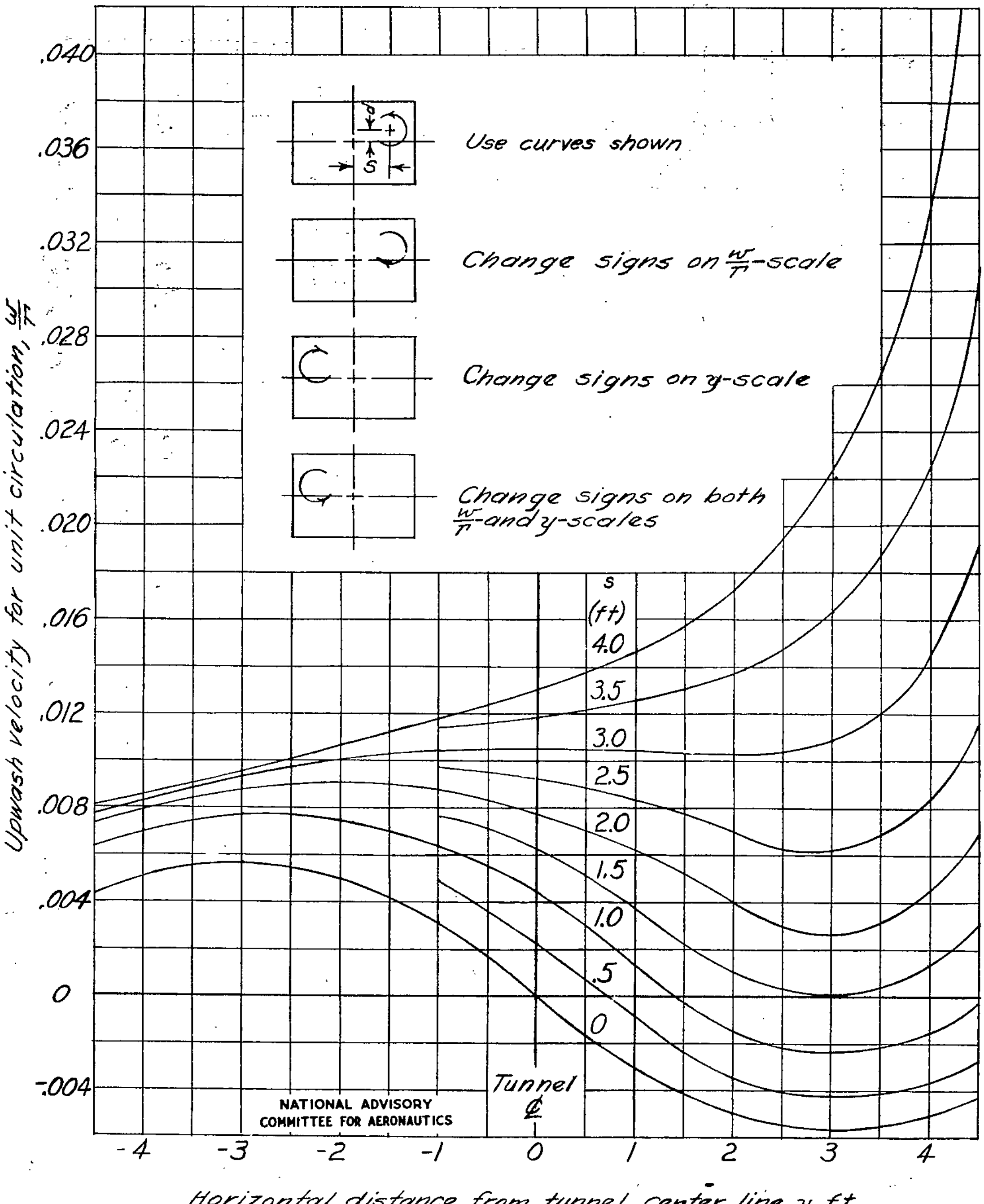
(a) Vortex on horizontal center line of tunnel (d=0).

Figure 5.-Boundary-induced upwash velocity at the lifting line due to a single trailing vortex located at various distances s from the vertical center line in 7-by 10-foot closed rectangular wind tunnels.



(b) Vortex 1/2 foot above or below horizontal center line of tunnel ($d=\pm0.5$).

Figure 5.- Continued.



(c) Vortex 1 foot above or below horizontal center line of tunnel ($d = \pm 1.0$).

Figure 5.-Concluded.

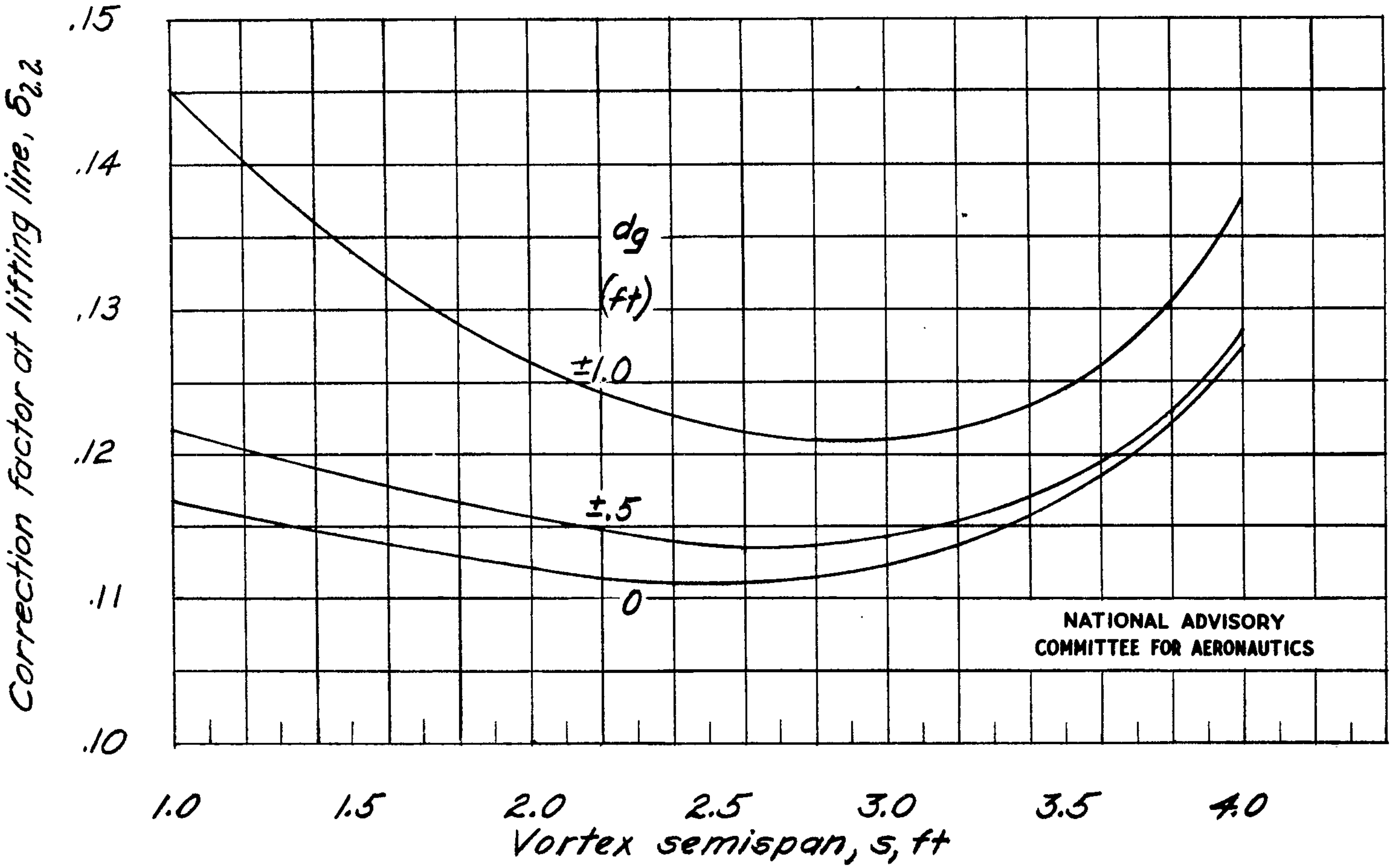
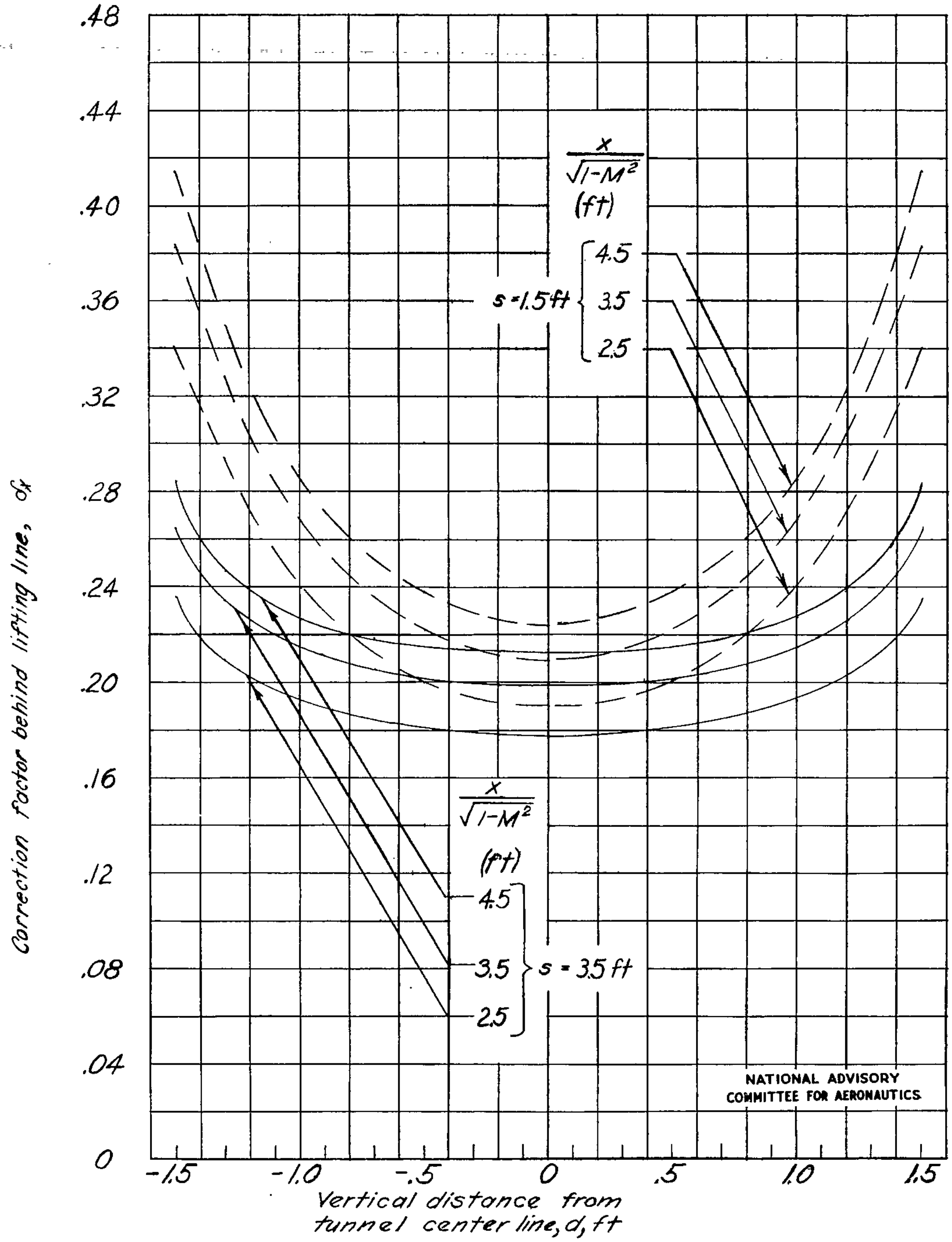
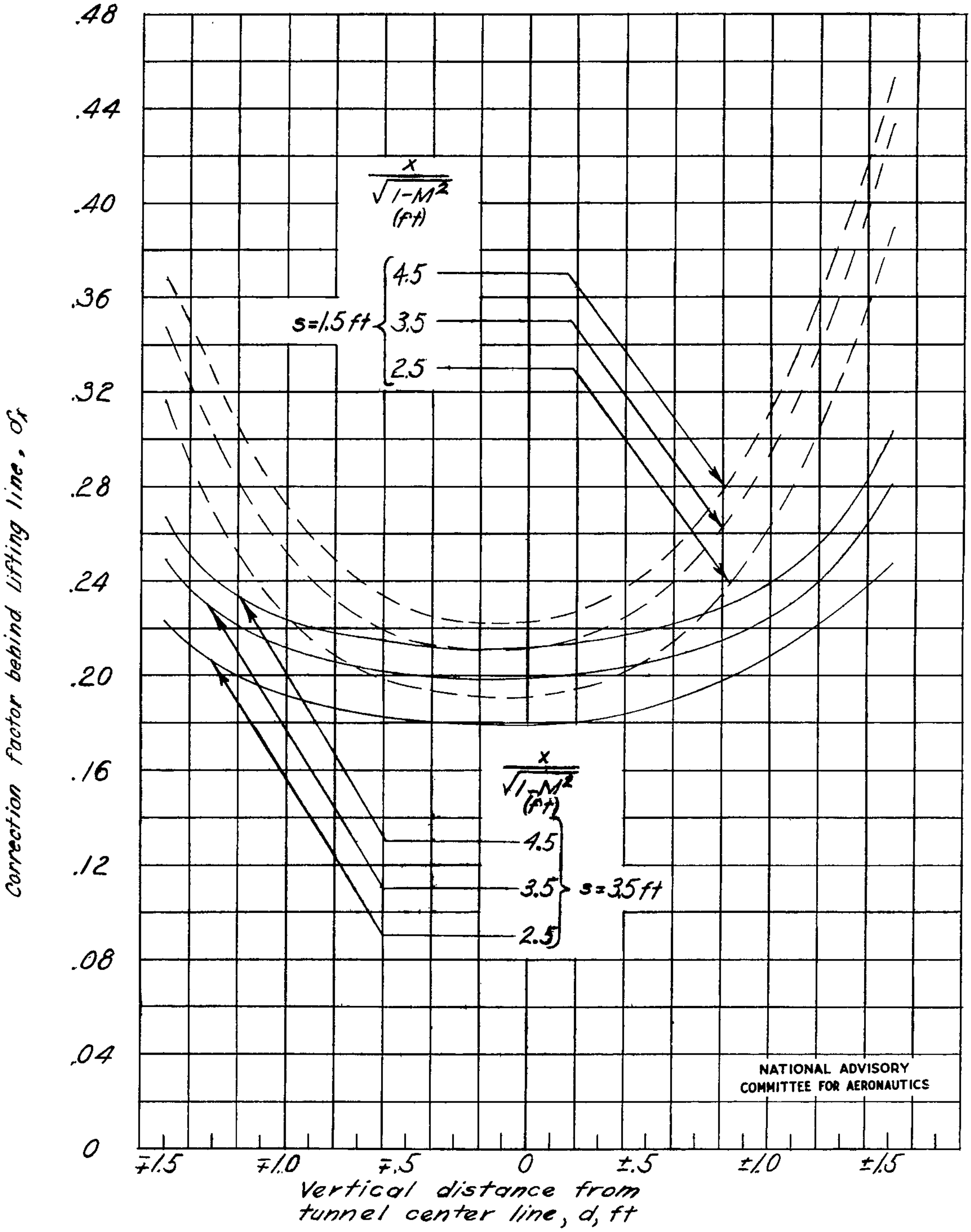


Figure 6.- Correction factor at the lifting line in 7- by 10-foot closed rectangular wind tunnels.



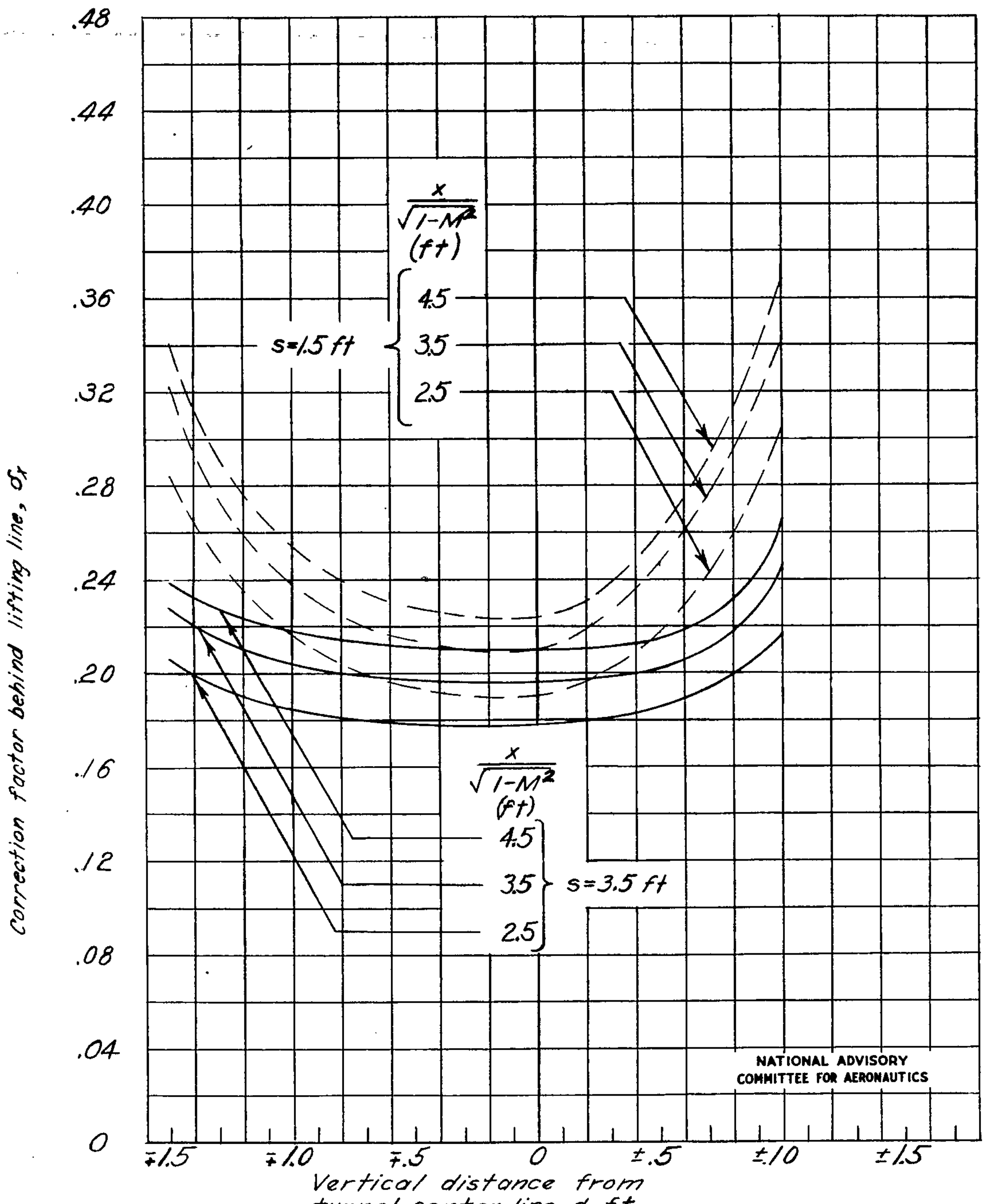
(a) $d_x = d$.

Figure 7. - Correction factor behind lifting line for 7-by 10-foot closed rectangular wind tunnels.



(b) $d_x = d \pm 0.5$ foot; upper signs correspond to $d_x = d + 0.5$ foot; lower signs correspond to $d_x = d - 0.5$ foot.

Figure 7.- Continued.



(c) $d_x = d \pm 1.0$ foot; upper signs correspond to $d_x = d + 1.0$ foot; lower signs correspond to $d_x = d - 1.0$ foot.

Figure 7.- Concluded.

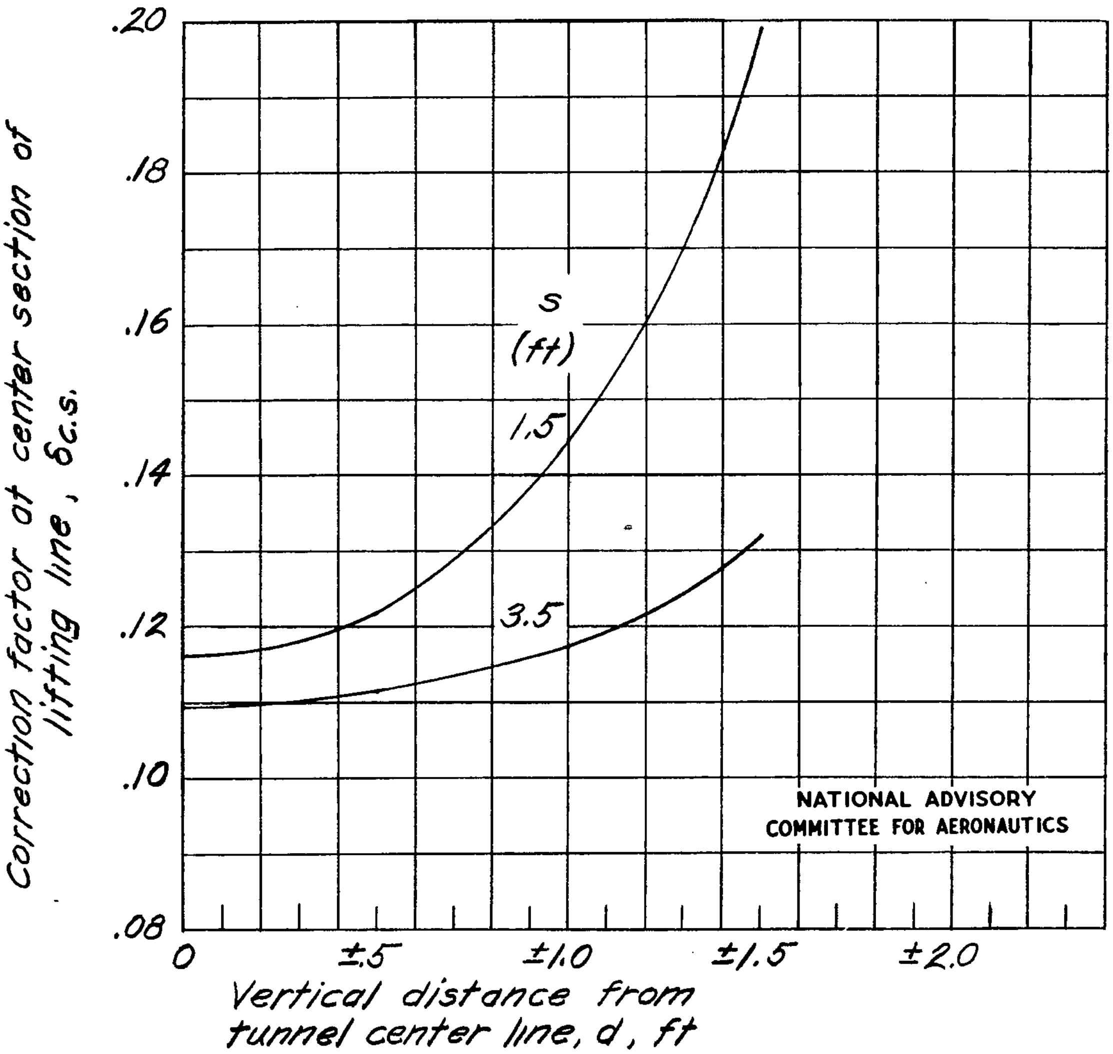


Figure 8.- Correction factor at the center section of the lifting line in 7-by 10-foot closed rectangular wind tunnels.

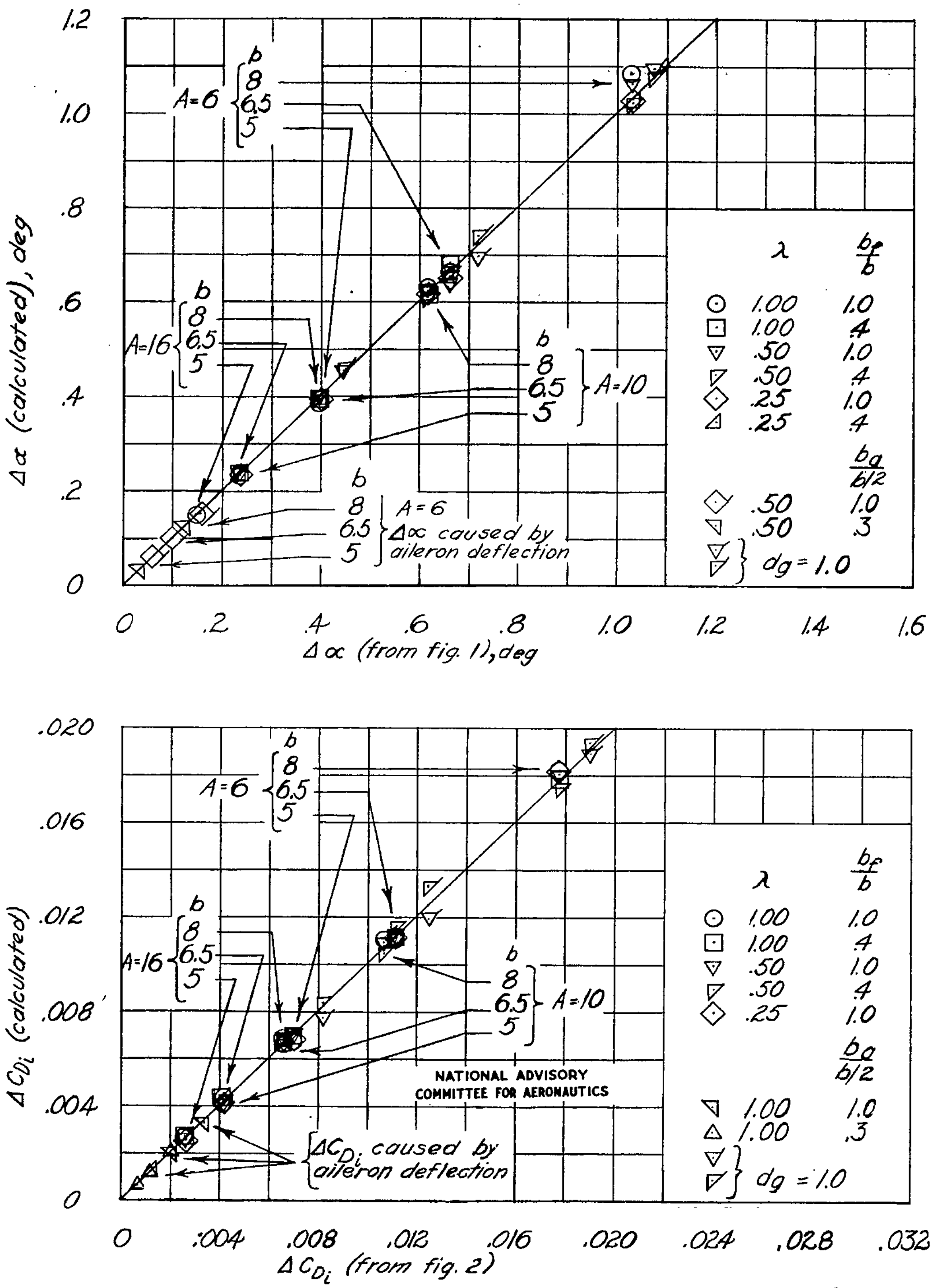


Figure 9.- Comparison of calculated values and values obtained from curves for corrections to angle of attack and induced-drag coefficient at $C_L = 1.0$ and $C_l = 0.03$; M = 0.

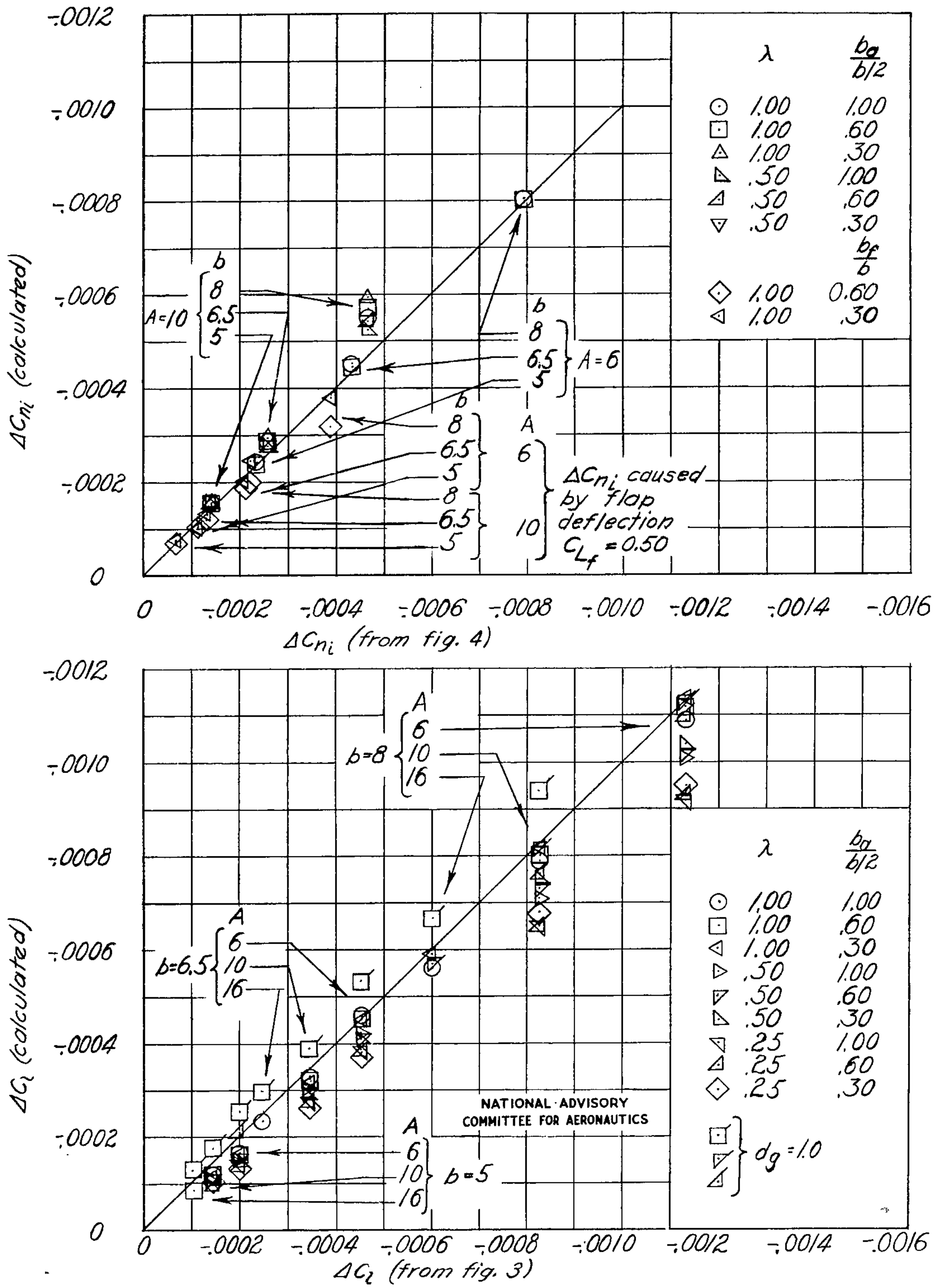


Figure 10.- Comparison of calculated values and values obtained from curves for corrections to induced-yawing-moment and rolling-moment coefficients at $C_L = 1.0$ and $C_l = 0.03$; $M = 0$.