Effects of Aspect Ratio and Sidewall Boundary-Layer in Airfoil Testing

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A correction to account for the sidewall boundary-layer effects in two-dimensional airfoil testing is presented by taking into consideration the nonlinear variation of the crossflow velocity across the width of the tunnel. The crossflow effects in the wind tunnel are represented in an empirical manner by considering the inviscid, compressible flow between a straight and a wavy wall. The analysis shows significant reduction in sidewall boundary-layer effects on airfoil midspan measurements with increasing aspect ratio of the model. Application of the correction to wind-tunnel data on airfoils demonstrated the method to be satisfactory in correlating shock location and also in giving good agreement between the measured pressure distribution and computed free air predictions.

Nomenclature

b = semiwidth of the tunnel
c = airfoil chord
C_ℓ = lift coefficient
C_p = pressure coefficient
H = shape factor of the sidewall boundary layer
k = constant, Eq. (16)
k_1 = constant, Eq. (5)
k_2 = constant, ($= 2\pi\beta\, b/$)
ℓ = wavelength of the wavy wall
M = Mach number
n = coordinate normal to the wavy wall (Fig. 2)
U = velocity
u = perturbation velocity in the x direction
v = perturbation velocity in the y direction
w = perturbation velocity in the z direction
w_0 = crossflow velocity at the sidewall
x = streamwise coordinate
x_s = shock location on airfoil surface
y = normal coordinate
z = spanwise coordinate
β = $(1-M^2)^{1/2}$
δ^* = sidewall boundary layer displacement thickness
ϵ = amplitude of the wavy wall
ϕ = velocity potential for the two-dimensional wavy-wall flow (Fig. 2)
ϕ_w = velocity potential corresponding to wind-tunnel flow

Subscripts

c = corrected values
e = conditions at the edge of boundary layer
exp = experimental values
∞ = freestream condition

Introduction

THE flowfield of an airfoil spanning the width of a two-dimensional wind tunnel influences the growth of the boundary layers on the sidewall. This interaction leads to an additional source of interference on airfoil measurements. Methods to account for the sidewall effects have been primarily based on two different considerations. First, as proposed by Preston,[1] it is assumed that trailing vorticity is shed due to loss of lift in the boundary layer and a consequent change in the effective angle of incidence. The second approach, proposed independently by Barnwell[2] and Winter and Smith,[3] assumes the changes in the boundary-layer thickness due to model-induced pressure field to have a significant effect on the flow over the airfoil. Using the small disturbance equation and accounting for the changes in the width of the flow passage, Barnwell presented a simplified correction for the measured forces in the form of a modified Prandtl-Glauret rule to account for the attached sidewall boundary-layer effects. Barnwell's correction gave good agreement with the experiments of Bernard-Guelle[4] at low Mach numbers. Sewall[5] extended Barnwell's approach to transonic speeds using the von Karman similarity parameter. Recently, an alternative simpler form of the correction encompassing both the Barnwell and Sewall methods has been proposed by Murthy.[6] The Barnwell-Sewall correction appears to be effective in giving a satisfactory comparison between the measured and calculated pressure distributions on several airfoils tested in the NASA Langley 0.3-m Transonic Cryogenic Tunnel.[7-9] These studies suggest that the change in the sidewall boundary-layer thickness due to the airfoil pressure field can be a significant source of blockage correction, particularly at transonic speeds.

The Barnwell-Sewall correction has been derived under certain assumptions of simplified boundary-layer treatment and linear variation of the crossflow velocity across the width of the tunnel. These assumptions imply that the airfoil chord is sufficiently large so that the effect of the sidewall boundary layers can be considered to be quasi-one-dimensional. Barnwell[10] has shown recently that the linear crossflow assumption is justified provided $(4\delta^*/b)(b/c)^2$ is small. Hence, this assumption is likely to become less accurate when the width of the tunnel is much larger than the airfoil chord (i.e., for high-aspect-ratio models).

The inapplicability of Barnwell's correction to large-aspect-ratio models is mainly due to the linear crossflow assumption. With increasing aspect ratio, the crossflow velocity tends to become nonlinear. The present paper deals with a method to account for the nonlinear variation of the crossflow velocity. The crossflow velocity is proportional to the local slope of the boundary layer at the sidewall and reduces to zero at the midspan because of the symmetry. This flow situation is analogous to the inviscid, compressible flow between a straight wall representing the midspan and a wavy wall representing the sidewall of the wind tunnel. It can be argued that the wavelength of the wall is in some way related to the chord of the airfoil, and the amplitude to the undisturbed sidewall boundary-layer thickness. For this problem, the ratio of the crossflow velocity at any point in the flow

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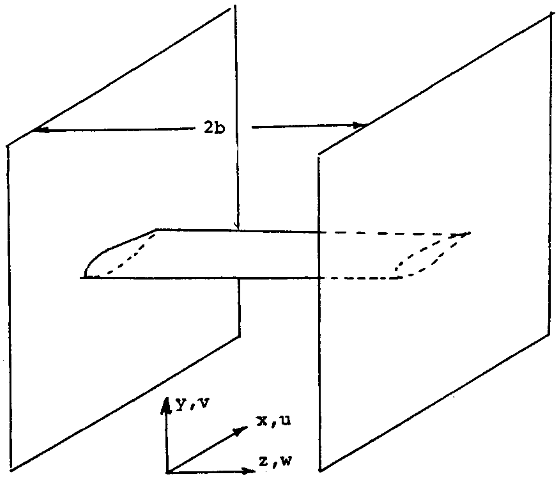

Fig. 1 Airfoil model in a two-dimensional wind tunnel and the coordinate system.

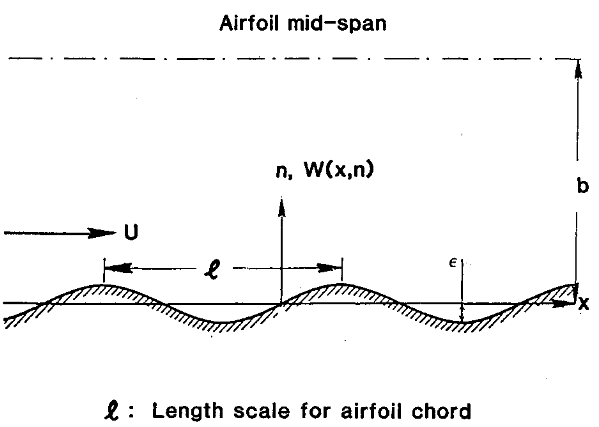

Fig. 2 Flow between a wavy wall and a straight wall.

to that at the wavy wall is only a function of the distance from the wavy wall. This relation for the crossflow velocity variation can be used as a multiplicative factor to represent the sidewall boundary-layer effects in the wind-tunnel flow. Using this approach, a modification to the sidewall boundary-layer correction of Refs. 2, 5, and 6 is proposed to account for the airfoil aspect ratio.

Analysis

For the steady subsonic flow over an airfoil in a nominally two-dimensional wind tunnel of width $2b$ (Fig. 1), the development of the boundary-layer on the sidewalls introduces a spanwise velocity across the width of the tunnel. This spanwise velocity is maximum at the sidewall and zero at the midplane because of the symmetry. In general, the flow in the tunnel tends to become three-dimensional, and the corresponding small perturbation equation for the flow in the tunnel is

$$(1 - M_\infty^2)\,\phi_{w,xx} + \phi_{w,yy} + \phi_{w,zz} = 0 \tag{1}$$

The corresponding boundary condition for the spanwise velocity is imposed at the sidewall ($z = \pm b$)

$$\frac{\partial \phi_w}{\partial z_{z=\pm b}} = \mp U_e \frac{\partial \delta^*}{\partial x} \tag{2}$$

where U_e is the velocity at the edge of the boundary layer. Following Barnwell, the rate of boundary-layer growth on the sidewalls can be approximated by

$$\frac{\partial \delta^*}{\partial x} = -\frac{\partial^*}{U_e}\left(2 + \frac{1}{H} - M_e^2\right)\frac{\partial U_e}{\partial x} \tag{3}$$

In arriving at Eq. (3), it is assumed that the sidewall boundary layer can be approximated by a flat plate boundary layer with its equivalent length much longer than the airfoil chord c, so that the change in the sidewall boundary-layer thickness is predominantly due to model-induced chordwise pressure gradients. In airfoil tests, the interest is often confined to pressure measurements over the midspan region of the airfoil. The influence in this region due to sidewall boundary layers is an integrated effect of what is happening at the airfoil/sidewall junction and will be relatively insensitive to the details of the boundary-layer development at the sidewall. Hence, instead of solving the complicated problem of three-dimensional boundary-layer development at the airfoil/sidewall junction, Barnwell combined Eqs. (2) and (3) and assumed a linear variation of the spanwise velocity between the sidewall and the midspan.

The linear crossflow velocity variation assumption implies that the change in the streamtube area is gradual so that the sidewall boundary-layer effect can be treated one-dimensionally.[6] This would be true in the limit when the airfoil chord is large in comparison with the width of the tunnel. With shorter-chord models, one can speculate the sidewall effects to decay much faster along the span of the model. A qualitative representation of this effect is possible by considering the two-dimensional flow in the channel formed between a straight wall and a wavy wall (Fig. 2). Due to symmetry, the straight wall corresponds to the midspan in the wind-tunnel flow.

The effective sidewall shape in the wind-tunnel flow will be that formed by the displacement surface of the boundary layer. Due to model flowfield, the approaching boundary-layer thickens in front of the model and decreases rapidly over the model region due to acceleration of the flow. Subsequently, the thickness increases again due to adverse pressure gradient downstream. The physical distance over which these changes occur is proportional to the model chord. Decreasing the model chord will result in increased gradients at the wall since approximately the same changes in the boundary-layer thickness will occur over a much shorter distance. However, one can speculate that these gradients will decay rapidly away from the wall. These qualitative features of the changes in boundary-layer thickness in the wind tunnel with different chord models can be studied by varying the wave length while keeping the channel width constant. It can be argued that the amplitude ϵ and the wavelength ℓ will be related in some way to the sidewall boundary-layer thickness and the airfoil chord, respectively. While it may be difficult to identify a priori the exact nature of dependence, the results still provide an insight into the variation of sidewall boundary-layer effects with changes in ϵ and ℓ, which are in effect equivalent to changing the sidewall boundary-layer thickness and the airfoil aspect ratio.

For the two-dimensional wavy-wall model shown in Fig. 2, the perturbation velocity potential can be written as[11]

$$\phi = k_1 e^{-k_2 n/b}\,[1 + e^{2k_2(n/b - 1)}]\,\sin\frac{2\pi x}{\ell} \tag{4}$$

where

$$k_1 = \frac{U_\infty}{\beta}\;\frac{\epsilon}{1 - e^{-2k_2}} \tag{5}$$

and

$$k_2 = \frac{2\pi\beta b}{\ell} \tag{6}$$

By differentiating Eq. (4), the normal velocity variation can be written as

$$\frac{\partial \phi}{\partial n} = \frac{k_1 k_2}{b}\left[-e^{-k_2 n/b} + e^{-2k_2}\cdot e^{k_2 n/b}\right]\sin\frac{2\pi x}{\ell} \tag{7}$$

At the wavy wall ($n = 0$), the normal velocity is given by

$$\left(\frac{\partial \phi}{\partial n}\right)_{n=0} = \frac{k_1 k_2}{b}\left(e^{-2k_2} - 1\right)\sin\frac{2\pi x}{\ell} \tag{8}$$

At the straight wall, the normal velocity is zero. Therefore,

$$\left(\frac{\partial \phi}{\partial n}\right)_{n=b} = 0 \tag{9}$$

Using Eqs. (7) and (8), the ratio of the normal velocity at any point to that at the wavy wall can be written as

$$\frac{w}{w_0} = \frac{\sinh\,[k_2\,(1 - n/b)]}{\sinh k_2} \tag{10}$$

In terms of distance $z(= b - n)$, Eq. (10) can be written as

$$\frac{(\partial\phi/\partial z)}{(\partial\phi/\partial z)_{z=b}} = \frac{\sinh(k_2\,z/b)}{\sinh k_2} \tag{11}$$

Equation (11) gives a relation for the variation of the spanwise velocity which reduces to a linear relationship for small values of the parameter k_2. This situation occurs either when the Mach number approaches unity or the wavelength (alternatively the airfoil chord) is large compared to the width of the tunnel.

The relation derived in Eq. (11) can be used in an empirical manner to represent sidewall boundary-layer effects by using the value of the spanwise velocity induced due to boundary layer at the sidewall. Combining Eqs. (2) and (11) yields

$$\frac{\partial \phi_w}{\partial z} = -U_e\frac{\partial \delta^*}{\partial x}\frac{\sinh\,(k_2\,z/b)}{\sinh k_2} \tag{12}$$

$$= \delta^*\left(2 + \frac{1}{H} - M_e^2\right)\frac{\sinh(k_2\,z/b)}{\sinh k_2}\,\phi_{w,xx} \tag{13}$$

Differentiating Eq. (13) with respect to z, it follows that

$$\frac{\partial^2 \phi_w}{\partial z^2} = \frac{k_2\delta^*}{b}\left(2 + \frac{1}{H} - M_e^2\right)\frac{\cosh\,(k_2 z/b)}{\sinh k_2}\frac{\partial^2\phi_w}{\partial x^2} \tag{14}$$

Combining Eqs. (1) and (14), the flow in the wind tunnel with sidewall boundary layers can be approximated by

$$(1 - M_\infty^2 + k)\,\phi_{w,xx} + \phi_{w,yy} = 0 \tag{15}$$

where

$$k = \frac{\delta^*}{b}\left(2 + \frac{1}{H} - M_e^2\right)\left[k_2\,\frac{\cosh(k_2\,z/b)}{\sinh k_2}\right] \tag{16}$$

At the median section ($z = 0$), Eq. (16) reduces to

$$k = \frac{\delta^*}{b}\left(2 + \frac{1}{H} - M_e^2\right)\left(\frac{k_2}{\sinh k_2}\right) \tag{17}$$

The factor $k_2/\sinh k_2$ depends on the test Mach number and the airfoil aspect ratio. The form of the equation [see Eq. (15)] is the same as that originally proposed by Barnwell except that in the present case, the definition of the term k is different as given by Eq. (16). It has been shown in Ref. 6 that the small disturbance equation (15) representing the sidewall effects can be interpreted as causing changes in both the test Mach number and the airfoil thickness. The modifications to account for the transonic effects are given in Refs. 5 and 6. Hence, the correction to the test Mach number and forces can be done in a similar manner using the value of k defined by Eq. (17), which also accounts for the airfoil aspect ratio.

The corresponding expressions for the corrected Mach number (M_c) and the corrected pressure coefficient ($C_{p,c}$) are given by

$$\frac{1 - M_\infty^2 + k}{M_\infty^{4/3}} = \frac{1 - M_c^2}{M_c^{4/3}} \tag{18}$$

$$C_{p,c} = \left(\frac{M_\infty^2}{M_c^2}\right)^{1/3} C_p \tag{19}$$

Results and Discussion

The present analysis allows for the nonlinear variation of the spanwise velocity as compared to Barnwell's assumption of linear variation which is strictly correct for narrow tunnels or low-aspect-ratio models. This is demonstrated in Fig. 3 by plotting the ratio of the spanwise velocity (w) at any spanwise station to that at the wall (w_0) for the wavy-wall flow for values of $k_2 = 0$, 2, and 5. The variation is linear for only small values of the parameter k_2. In the limit of k_2 tending to zero, it can be shown by expanding Eq. (17) that the neglected terms are of the order $(b/\ell)^2$, which agrees with the result of Barnwell.[10] For values of $k_2 > 0$, the spanwise velocity variation becomes nonlinear. This nonlinear variation introduces nonuniform sidewall boundary-layer effects across the span of the airfoil. The magnitude of the sidewall boundary-layer effect is given by the gradient of the spanwise velocity (Fig. 4). For $k_2 = 0$, corresponding to Barnwell's assumption of linear variation of the spanwise velocity, the gradient is uniform across the width of the tunnel. With increasing k_2, the gradient at the wall increases almost linearly like $k_2/\tanh(k_2)$. However, the severity of this gradient does not extend to the midspan but reduces rapidly to the value given by $k_2/\sinh(k_2)$. The value at the midspan is a function of the reduced aspect

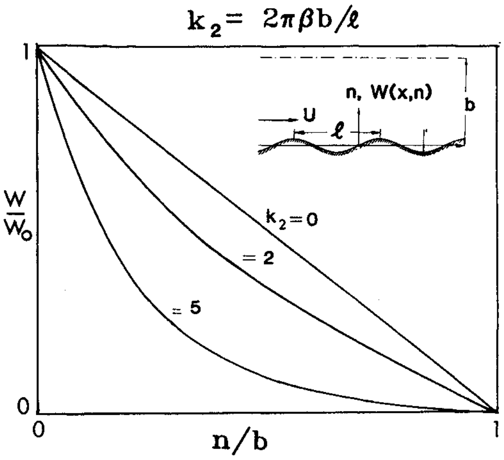

Fig. 3 Variation of the normal velocity across the width of the tunnel for different k_2.

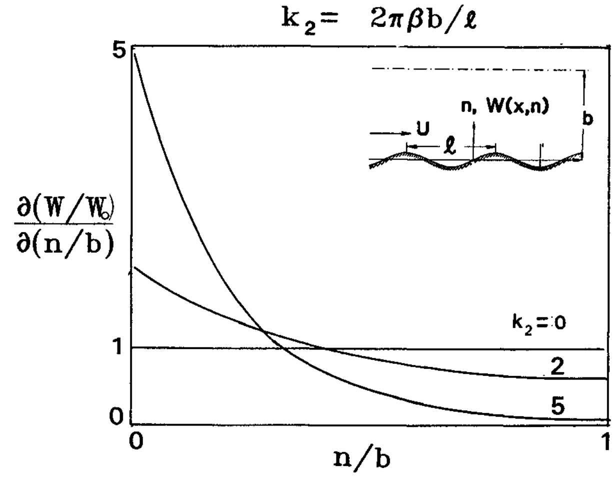

Fig. 4 Variation of the normal velocity gradient across the width of the tunnel for different k_2.

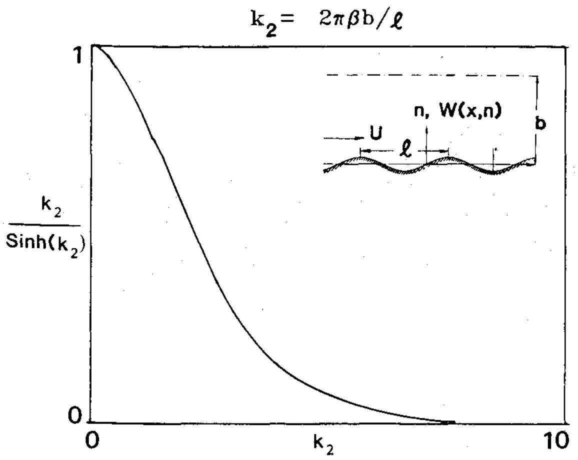

Fig. 5 Variation of the normal velocity gradient (i.e., aspect ratio correction factor) in the median plane.

ratio parameter ($\beta b/\ell$), and its variation is shown in Fig. 5. From this it is clear that the effect of a decrease in the wavelength (or equivalently, an increase in the aspect ratio of the airfoil) is to reduce the crossflow velocity gradient at the midspan.

It must be noted that the present method is based on two-dimensional considerations and represents conservative values of the aspect ratio correction factor. It is likely that the three-dimensional nature of the flow at the airfoil/sidewall junction will further alleviate the effects near the midspan.

When applying the present aspect ratio correction, it is necessary to define what constitutes a typical length scale ℓ in terms of the airfoil chord c. This is examined by comparing the present results with some of the experimental data. Initially, the shock position correlation on a supercritical airfoil tested in the ONERA tunnel[4] is attempted. The measured shock positions for two different sidewall boundary-layer thicknesses of $\delta^*/b = 0.023$ and 0.054 are shown in Fig. 6a. The effect of applying the Barnwell-Sewall correction without accounting for aspect ratio effects is shown in Fig. 6b. It may be noticed that this method tends to overcorrect and that the correlation is not entirely satisfactory. The effect of incorporating the aspect ratio correction is shown in Fig. 6c, assuming $\ell = c$. For this case, assuming the wavelength to be equal to the airfoil chord appears to give better correlation.

Assuming $\ell = c$, the normal coefficient measurements[5] on a supercritical airfoil in the Langley 6- × 19-in. tunnel have been correlated in Ref. 12. For this case, considering the scatter in the experimental data, the aspect ratio correction did not seem to influence the correlation significantly.

It may be noted that the aspect ratio of the models in the ONERA tests[3] and the Langley tests[5] were, respectively, 0.73 and 1. These tests do not represent a wide range of aspect ratios, and it is difficult to generalize from these limited comparisons what is the best value for the representative length scale in terms of the airfoil chord.

To gain a better understanding, the proposed correction was used to compare the pressure distribution measurements on two different chord Cast-10[8] airfoil models with free air calculations. The airfoil measurements were made in the Langley 0.3-m Transonic Cryogenic Tunnel slotted wall test section designed for minimum blockage. The aspect ratios of the models tested were 1.33 and 2.66, respectively. For free air calculations, the GRUMFOIL[13,14] computer program for transonic airfoil analysis was used. The method, in addition to treating the viscous boundary-layer displacement effects on the airfoil, considers an accurate analysis of the trailing edge region, where the interaction effects are quite strong. The test data on the lower-aspect-ratio (= 1.33) model and other airfoil models of same aspect ratio tested earlier in the 0.3-m

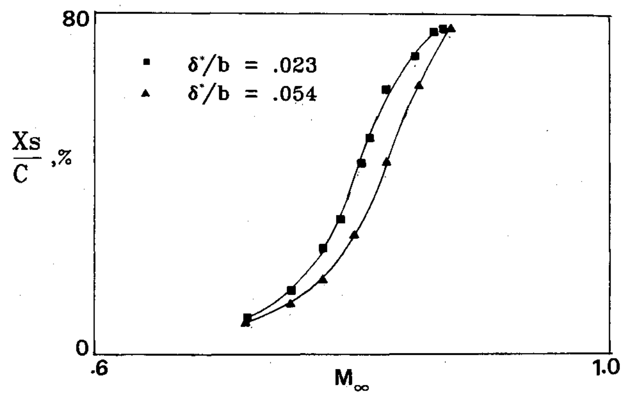

Fig. 6a Measured shock locations on a supercritical airfoil with different sidewall boundary-layer thickness (data from Ref. 4).

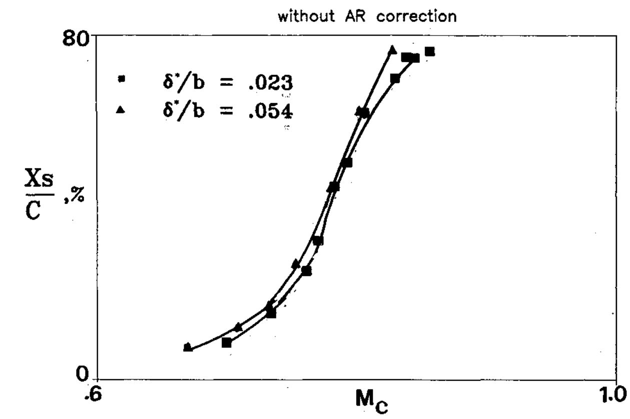

Fig. 6b Correlation of shock location using Barnwell-Sewall sidewall boundary-layer correction.

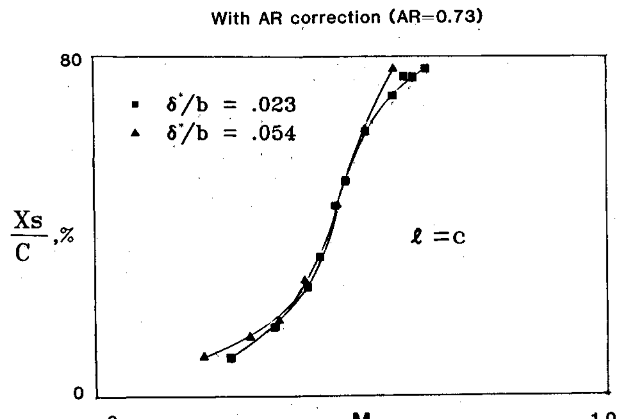

Fig. 6c Correlation of the shock location using the present method.

transonic cryogenic tunnel (TCT) had indicated that the Barnwell-Sewall correction to the test Mach number was adequate to give a satisfactory agreement with the GRUMFOIL predictions for the pressure distribution. However, a similar application of the Barnwell-Sewall method for the higher- aspect-ratio (= 1.66) model resulted in overcorrecting for sidewall boundary-layer effects. This is shown in Fig. 7a, with the predicted shock position on the airfoil upper surface being much ahead of the measured location. The effect of including the present aspect ratio correction for the sidewall boundary-layer effects is shown in Fig. 7b. For applying the aspect ratio correction, it has been assumed that $\ell = 2c$. This assumption is based on the fact that the effect of the airfoil on the sidewall boundary layer is distributed over a distance of

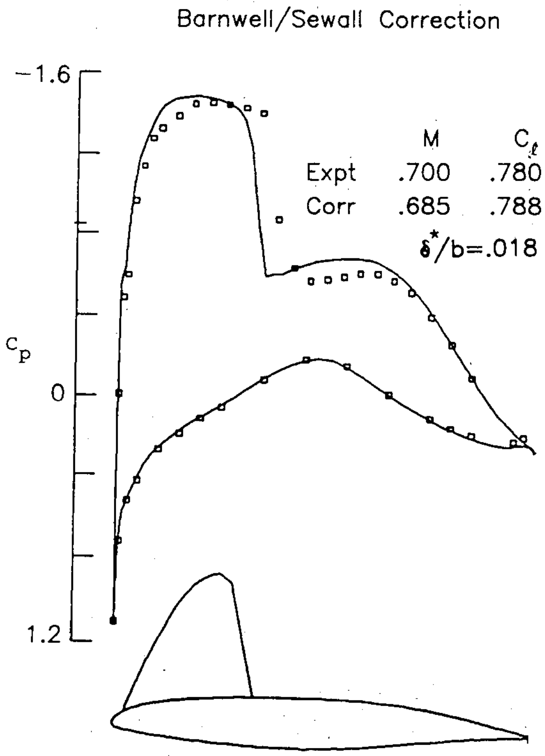

Fig. 7a Comparison of pressure distribution on Cast-10 airfoil with GRUMFOIL free air calculations using Barnwell-Sewall correction.

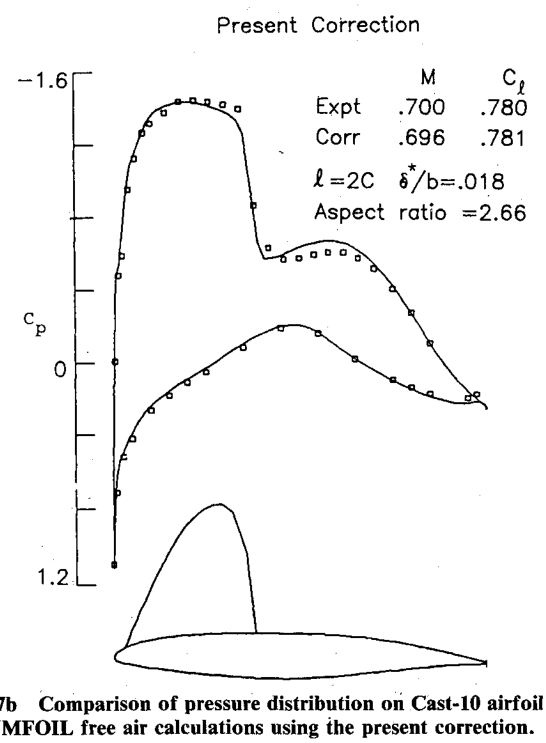

Fig. 7b Comparison of pressure distribution on Cast-10 airfoil with GRUMFOIL free air calculations using the present correction.

about twice the chord of the airfoil. From Figs. 7a and 7b it may be seen that the aspect ratio correction certainly improves the agreement between the measurements and the calculated pressure distribution using the GRUMFOIL code. For this aspect ratio, with the assumption of $\ell = 2c$, the correction to the test Mach number is small.

The limited comparison shown in Fig. 7 demonstrates the importance of accounting for the model aspect ratio while correcting for the sidewall boundary-layer interference. The proposed correction based on two-dimensional flow considerations provides a conservative estimate of the reduction in the sidewall boundary-layer effects on higher-aspect-ratio models. Actual corrections are likely to be smaller than predicted because of the three-dimensional nature of the sidewall boundary-layer interference. Recently, Green and Newman[15] have applied the present aspect ratio correction with a nonlinear, four-wall post-test residual interference assessment code. The results of Ref. 15 indicate that the present approximation for the aspect ratio gives the best overall correction for the airfoil data obtained in the 0.3-m TCT adaptive wall test section.

There are primarily two important effects associated with the nonlinear variation of the spanwise velocity across the width of the tunnel. First, there is a change in the effective streamwise velocity along the model span that manifests as a negative blockage effect. The present approach as well as those of Barnwell and Sewall account only for this negative blockage effect. Second, trailing vortices are shed due to spanwise variation of lift. This introduces downwash, which changes the effective incidence. Experimental evidence[16] suggests that the downwash effect can be significant. The physical phenomena associated with the downwash effect are quite complex, and methods based on simple vortex models to calculate the effects are not entirely satisfactory.[17] However, considering the uncertainties in the angle of attack in two-dimensional airfoil testing, the present correction is useful in making theoretical calculations of the pressure distribution with prescribed lift coefficient.

Conclusions

1) A correction for the sidewall boundary-layer effect in airfoil testing has been proposed, taking into account the aspect ratio of the model.

2) The correction proposed, based on the flow between a wavy wall and a straight wall, shows significant reduction in sidewall boundary-layer effects with increasing aspect ratio of the model.

3) Comparison with the experimental data on shock location and pressure distribution on airfoils using the present correction gave good correlation.

4) In the limit of vanishing aspect ratio, the present correction reduces to the Barnwell-Sewall method.

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