

NASA Contractor Report 4042

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0.3-Meter Transonic Cryogenic Tunnel**

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SUMMARY

A simplified fourwall interference assessment method has been described, and a computer program developed to facilitate correction of the airfoil data obtained in the Langley 0.3-m Transonic Cryogenic Tunnel (TCT). The procedure adopted is to first apply a blockage correction due to sidewall boundary-layer effects by various methods. The sidewall boundary-layer corrected data are then used to calculate the top and bottom wall interference effects by the method of Capallier, Chevallier and Bouinol, using the measured wall pressure distribution and the model force coefficients. The interference corrections obtained by the present method have been compared with other methods and found to give good agreement for the experimental data obtained in the TCT with slotted top and bottom walls.

INTRODUCTION

Wall interference is a problem of concern in testing of airfoils in wind tunnels, particularly at transonic speeds. This is largely due to the complex flow features at the ventilated walls introducing uncertainties in the boundary conditions. Therefore, modern wall interference calculation methods, in lieu of the classical boundary conditions, use experimentally measured values of the pressure and/or flow inclinations at the wall to correct the test data.

A comprehensive review of the different methods of calculating the two-dimensional wall interference has been given recently by Mokry et al (ref. 1). Table I lists the salient features of some of these methods. Most of them are based on subsonic flow theory and still give useful results in the low transonic regime as long as the flow is subcritical at the walls. The only methods which employ transonic analysis are those of Murman (ref. 2) and Kemp (ref. 3).

Kemp's method employs numerical solution of the transonic small disturbance equation, and requires as input the measured pressure distributions on the airfoil model, and near the top and bottom walls. The solution of this inverse problem gives an effective shape of the airfoil, which accounts indirectly for the viscous effects also, on the airfoil. This effective airfoil shape is then used to calculate the unbounded or free air solution. The Mach number and the angle of attack are iterated to give the best match between the calculated and the measured pressure distributions.

Kemp's method can be considered to represent the state of the art in interference calculations and can be used as a standard of comparison against which other simpler methods can be validated.

Another method of analysis which uses the panel technique to calculate numerically the entire interference velocity field is due to Smith (ref. 4).

Most of the literature on interference calculation in two-dimensional wind tunnels deal with top and bottom wall influence which is inviscid in nature and is uniform across the span. It is generally assumed that the flow in the wind tunnel is nearly two-dimensional. Another source of interference which has been receiving considerable attention recently is the influence of the sidewall boundary-layers which is essentially viscous in nature and introduces three-dimensional perturbations across the width of the tunnel.

Though, it was recognised by Preston (ref. 5) in 1944 that the interaction of the sidewall boundary-layers with the airfoil flowfield can cause departure from two-dimensional conditions, only recently there has been systematic effort towards understanding the extent of three dimensional influence and means to correct for the same. Most noticeable

development has been due to Barnwell (ref. 6) who considered the changes in the sidewall boundary-layer to introduce crossflow velocities across the width of the test-section. Assuming linear variation of the crossflow velocity, and using a simplified treatment of the sidewall boundary-layer growth, Barnwell suggested a simple correction in the form of a modified Prandtl-Glauret rule, in terms of the test section Mach number and the undisturbed values of the sidewall boundary-layer displacement thickness and shape parameter. Sewall (ref. 7) extended this approach to include transonic effects by using the von Karman similarity rule. A modified form of the correction was proposed recently by the present author (ref. 8), by considering the sidewall boundary-layer to cause changes in both the Mach number and the airfoil thickness. Also, a new approach which accounts for the nonlinear variation of the crossflow velocity across the width of the tunnel has been suggested and the correction to the test Mach number has been shown to be a function of the airfoil aspect ratio (ref. 9).

A four-wall interference assessment procedure in two-dimensional airfoil testing was suggested by Kemp and Adcock (ref. 10) by combining the Barnwell-Sewall sidewall boundary-layer correction with the Kemp's method for top and bottom wall interference calculations. This four-wall interference assessment code (ref. 11) has been used extensively to make post-test corrections for the airfoil test data obtained in the NASA Langley 0.3-Meter Transonic Cryogenic Tunnel (TCT). Since, this method requires significant computational effort, its use is recommended for selected data points requiring accurate treatment.

For routine calculation of interference to all the data points in an airfoil test, it is desirable that a simpler approach amenable for quick calculation is employed.

Particularly, when the interest is confined to making global corrections in the region of the airfoil, the methods due to Capalier et al. (ref. 12), Mokry (ref. 13), Sawada (refs. 14, 15), and of Ashill and Weeks (refs. 16, 17) are attractive. These methods require little computational effort and are well suited for on-line calculations, if necessary.

The method of Ashill and Weeks requires measured pressure distribution and flow inclination at the walls, and is well suited for solid wall tunnels where flow inclinations at the wall are known more accurately. The corresponding Cauchy Integral formula is solved, and no model representation is required.

For ventilated wall tunnels, where the flow inclinations are difficult to measure, the other methods are convenient. These methods use the measured pressure distribution near the wall in conjunction with the model representation by appropriate singularities. Mokry's method solves the potential flow problem in the rectangular domain bounded by the testsection geometry. The methods of Capalier et al., and of Sawada, though based on different approaches, solve the problem in the infinite strip bounded between the top and bottom walls, and give similar results to a first approximation. All these methods, including the Kemp's method have been found to give nearly identical interference corrections for the BGK-1 airfoil test data obtained in the NAE 15"x60" tunnel with perforated top and bottom walls (ref. 1).

The good agreement between the various methods for the NAE test case prompted the present investigation to examine the application of the method of Capalier et al., to the airfoil test data obtained in the 0.3-m TCT two-dimensional test section with slotted top and bottom walls. In addition to facilitate calculation of fourwall interference effects, the sidewall boundary-layer correction methods of references

6 - 9, were considered in a sequential manner. The approach was validated by comparing results obtained with Kemp's method for some test cases, and good agreement was observed. This suggests that for routine calculation of interference corrections in the 0.3-m TCT airfoil tests, the method of Capalier et al., can be successfully employed. This method has been implemented in a computer program to facilitate calculation of interference corrections directly from the airfoil test data files, either for sidewall or top/bottom wall, or both. The objective of this report is to present the method of analysis used, its validation results and details of the computer program developed for correcting the 0.3-m TCT test data.

NOMENCLATURE

A	non-dimensional area of the model
b	width of the tunnel
c	model chord length
c_d	drag coefficient
c_l	lift coefficient
C_p	pressure coefficient
f_u, f_l	functions defined by eqns. (12) and (13)
h	total height of the tunnel
H	sidewall boundary-layer shape factor
k	$= (2\delta^*/b)(2 + 1/H - M_t^2)$
k_m	modified form of k (see equation 6)
k_2	$= (\pi\beta b/l)$
l	wave length in terms of model chord
M_c	corrected Mach number
$M_{c,b}$	corrected Mach number by Barnwell-Sewall Method
$M_{c,m}$	corrected Mach number by Murthy's method
M_t	test Mach number
R_c	Reynolds number based on model chord
Re_m	freestream Reynolds number/meter
u_w, v_w	non-dimensionalised interference velocities in x and y direction due to top and bottom walls

u_m	non-dimensionalised induced velocity due to model
v_i	tunnel upstream flow inclination
W_1, W_2	Functions defined by equations (18) and (21)
Y	$= \beta h/2$
x, y	streamwise and normal coordinates
a	angle of attack
β	$= (1 - M^2)^{1/2}$
γ	vortex strength
δ^*	displacement thickness (sidewall boundary-layer)
ϕ	velocity potential
μ	doublet strength
σ	source strength
ΔM	correction to Mach number
Δa	correction to angle of attack

Subscripts:

e	refers to end of the testsection
s	refers to beginning of the testsection
l	testsection lower wall
u	testsection upper wall
w	refers to wake

DESCRIPTION OF THE METHOD

Sidewall Boundary-Layer Correction

The method adopted in the present analysis to calculate the fourwall interference effects is to apply first the sidewall boundary-layer correction. The option to use either the method of Barnwell-Sewall, or Murthy has been considered. Briefly both the methods employ the simplified assumption that the sidewall boundary-layer growth can be represented by von Karman's momentum integral equation and the effect of skin friction can be ignored in comparison with the model induced pressure gradients.

In the Barnwell-Sewall method, it is further assumed that the sidewall boundary-layers induce spanwise velocities which vary linearly across the width of the test-section. Using the von Karman's similarity parameter, a correction to the measured test-section Mach number is suggested in terms of the empty tunnel sidewall boundary-layer displacement thickness and the shape factor. The value of the corrected Mach number $M_{c,b}$ is given by (ref. 7)

$$\frac{(1 - M_{c,b}^2)^{3/4}}{M_{c,b}} = \frac{(1 - M_t^2 + k)^{3/4}}{M_t} \quad (1)$$

where M_t corresponds to the test Mach number, and k is a constant calculated using the empty tunnel boundary-layer displacement thickness (δ^*) and the shape parameter H .

$$k = (2\delta^*/b)(2 + 1/H - M_t^2) \quad (2)$$

The measured pressure and force coefficients are multiplied by the factor (ref. 8)

$$= (M_t/M_{c,b})^{2/3} \quad (3)$$

to give the corrected values.

It may be noted that in the Barnwell-Sewall method, the correction to the test Mach number is proposed only for transonic speeds. In a form proposed earlier by Barnwell (ref. 18), the correction to the test Mach number was not defined at lower Mach numbers. This deficiency was overcome by Murthy (ref. 8), by using a modified coordinate transformation of the governing small disturbance equation. It was shown that the flow in the wind tunnel with sidewall boundary-layers can be considered as an equivalent two-dimensional flow over an airfoil of reduced thickness at a reduced Mach number. With

this approach, the corrected Mach number $M_{C,m}$ can be expressed in a simplified form as (ref. 8)

$$M_{C,m} = M_t / (1 + k)^{1/2} \quad (4)$$

The corrected Mach number $M_{C,m}$ given by equation (4) is valid from subsonic speeds to transonic speeds, and agrees with the Barnwell-Sewall correction at transonic speeds for small values of k . The corresponding correction factors for the measured pressure and force coefficients are

$$\text{for subsonic speeds :} \quad = (1 + k)^{1/2} \quad (5a)$$

$$\text{for transonic speeds:} \quad = (1 + k)^{1/3} \quad (5b)$$

The difference between the corrections obtained by the Barnwell-Sewall method and the Murthy's method is not significant at transonic speeds, and either of them can be considered to be equally valid within the small disturbance approximations made in deriving the corrections. The method of reference (8), however, appears much simpler and facilitates a continuous correction from subsonic to transonic speeds.

Aspect Ratio Effects

Methods discussed above for calculating the sidewall boundary-layer effects are not entirely satisfactory. The corrections derived depend only on the sidewall boundary-layer parameters, model span and the test Mach number, and are independent of the model chord. They can be considered to be applicable only when the reduced aspect ratio ($= \beta b/c$) of the model is small, so that the effect of the sidewall boundary-layers is nearly one-dimensional, at least in the vicinity of the airfoil. For higher aspect ratio models, one can expect the effects to be much smaller in the mid-span region of the model where the measurements are made. To represent this

diminishing effect of the sidewall boundary-layers with increasing aspect ratio, an improved correction suggested by the present author (ref. 9), has been used. This method, instead of the linear crossflow velocity assumption, considers the two-dimensional flow between a wavy wall and a fixed wall to represent the cross flow velocity effects. With this wavy wall approach, the effect of aspect ratio is included by defining the constant k in equations (1) to (5), in a modified form k_m given by

$$k_m = (2 \delta^*/b) (2 + 1/H - M_t^2) \{k_2/\text{Sinh}(k_2)\} \quad (6)$$

where $k_2 = (\pi \beta b/l)$ (7)

The factor $k_2/\text{Sinh}(k_2)$ depends on the test Mach number, the model span and a length scale l representing the model chord. In the limit of vanishing aspect ratio, this factor approaches a value of one, and the equation (6) reduces to equation (2).

When considering the aspect ratio correction, it is necessary to define what constitutes a typical length scale in terms of the model chord. This has been examined in reference (9), and it appears that a value of $l = 2c$ appears reasonable considering the fact that the effect of the airfoil on the sidewall boundary-layers is distributed over a distance of about twice the chord of the airfoil. It may be noted that this aspect ratio correction is based on two-dimensional analysis. Hence, it is likely that the reduction in the sidewall boundary-layer effects can be smaller than predicted due to three-dimensional nature of the flow at the junction.

It may be noted that the sidewall boundary-layer correction methods discussed account only for the negative blockage effect caused by the thinning of the boundary-layer in the airfoil region due to favourable pressure gradient. It is likely that downwash effects can be present as evidenced by

detailed measurements on a Cast-7 airfoil over a wide range of aspect ratios (ref. 19). However, the physical mechanism causing such effects does not appear to be well understood and cannot be represented by simple mathematical models. A detailed discussion of the physical phenomenon associated with the sidewall boundary-layer effects has been presented by Winter and Smith (ref. 20), and it now appears that the changes in the boundary-layer displacement thickness suggested by Barnwell appears the most plausible one. Considering the uncertainties in angle of attack in two-dimensional airfoil testing, the simple sidewall boundary-layer correction is quite useful, particularly in ventilated wall tunnels designed for minimum blockage (ref. 21).

Sidewall Boundary-Layer Parameters

To apply the sidewall boundary-layer correction, it is necessary to know the empty tunnel boundary-layer displacement thickness and the shape factor at the location of the model. These parameters are generally measured during tunnel calibration. If the measured values are not available, theoretical estimates can be made by assuming a fictitious flat plate boundary-layer growth (ref. 22). For the 0.3-m TCT, measurement of the sidewall boundary-layers have been made at various times using a wall mounted rake located upstream of the model station (see ref. 23). Using these measurements, the values at the model station were estimated using flat boundary-layer theory. Based on these calculations, the following empirical formulae have been used in the program for calculation of boundary-layer parameters.

$$\delta^* (\text{mm}) = 6.42266 - 0.59613 \log(\text{Re}_m) + M_t \{0.44608 - 0.01333 \log(\text{Re}_m)\} \quad (8)$$

$$H = 1.54608 + 0.44299M_t - 0.04828 \log(\text{Re}_m) \quad (9)$$

TOP AND BOTTOM WALL INTERFERENCE

The method used in the present report to calculate the top and bottom wall effects is that due to Capalier et al. The details of the method are given in references (1) and (12). In this method, the pressure coefficients at or near the top and bottom walls from upstream infinity to downstream infinity, are used to prescribe the boundary conditions to solve the interference problem. For an airfoil located midway between the two walls of a tunnel (fig. 1), the components of the non-dimensionalised interference velocities u_w and v_w , in the x and y directions at the location of the model are given by

$$u_w(0,0) = (1/\beta h) \int_{-\infty}^{\infty} [f_u(x) + f_l(x)] / [2 \cosh(\pi x/\beta h)] dx \quad (10)$$

$$v_w(0,0) = v_i + (1/h) \int_{-\infty}^{\infty} [f_u(x) - f_l(x)] / [1 + \exp(2\pi x/\beta h)] dx \quad (11)$$

where f_u and f_l are functions of the measured pressure coefficients $C_{p,u}$ and $C_{p,l}$ on the upper and lower walls, and the non-dimensionalised induced velocities $u_{m,u}$ and $u_{m,l}$ due to airfoil model in free air. The corresponding expressions for f_u and f_l are

$$f_u = -(1/2)C_{p,u}(x) - u_{m,u}(x) \quad (12)$$

$$f_l = -(1/2)C_{p,l}(x) - u_{m,l}(x) \quad (13)$$

The term v_i in equation (11) is a constant, and refers to the tunnel upstream flow inclination which has to be arrived at by empty tunnel calibration. The induced velocities $u_{m,u}$ and $u_{m,l}$ near upper and lower walls due to airfoil model in free air are obtained by representing the model by appropriate

singularities: doublet for model blockage, source for wake blockage and vortex for lift effects. The corresponding velocity potentials are given by

$$\text{doublet: } \phi = (\mu/2\pi\beta) [x/(x^2+\beta^2y^2)] \quad (14a)$$

$$\text{source : } \phi = (\sigma/4\pi\beta) \log(x^2+\beta^2y^2) \quad (14b)$$

$$\text{vortex : } \phi = -(\gamma/2\pi) \tan^{-1}(\beta y/x) \quad (14c)$$

By differentiating equations 14a-c, the corresponding model induced velocities at the top and bottom wall locations ($y=\pm h/2$) can be written as

$$\text{doublet : } u_{m,u} = u_{m,l} = (-\mu/\pi\beta) [(x^2-y^2)/(x^2+y^2)^2] \quad (15a)$$

$$\text{source : } u_{m,u} = u_{m,l} = (\sigma/2\pi\beta) [x/(x^2+y^2)] \quad (15b)$$

$$\text{vortex : } u_{m,u} = -u_{m,l} = (\gamma/2\pi) [y/(x^2+y^2)] \quad (15c)$$

where $Y = \beta h/2$.

For a thin airfoil at incidence, the strength of the various singularities are determined by the model area of cross-section, and the lift and drag force coefficients.

$$\text{doublet : } \mu = A c^2 \quad (16a)$$

$$\text{source : } \sigma = (c c_{d,w})/2 \quad (16b)$$

$$\text{vortex : } \gamma = (c c_l)/2 \quad (16c)$$

The calculation of the Mach number and the angle of attack corrections is quite straightforward provided the measured wall pressure data are available over a sufficiently long distance both upstream and downstream of the model, so

that the errors in integration due to truncation is small. However, this is a factor that is largely governed by the available length of the tunnel test-section, and suitable extrapolations may have to be made.

Correction for Mach number

Substituting equations (12) and (13), the equation (10) for the blockage interference velocity at the model $u_w(0,0)$ can be written as

$$u_w(0,0) = -(1/h) \int_{-\infty}^{\infty} [(C_{p,u} + C_{p,l})/2 + (u_{m,u} + u_{m,l})] W_1 dx \quad (17)$$

$$\text{where } W_1(x) = 1/[2\cosh(\pi x/\beta h)] \quad (18)$$

The function $W_1(x)$ can be considered as a weighting factor which multiplies the measured wall pressures, and the model induced velocities. The variation of $W_1(x)$ along the length of the testsection is shown in figure (2), for Mach numbers 0.0 and 0.7. Its value is maximum at the center of the testsection and decays exponentially both upstream and downstream for large (x/h) . Beyond $x/h = \pm 2$, its contribution is negligible, and the blockage correction will be insensitive to uncertainties or errors in wall pressure measurements in this region. Also, with increase in the test-section test Mach number, the contribution to correction is limited to a narrower region about the test-section centerline. Hence, the exponential behaviour of the weighting function W_1 has the beneficial effect that the integration of equation (17) can be limited between the upstream and downstream ends of the test-section without loss of accuracy. The test Mach number corrected for the top and wall interference is given by (ref. 1)

$$M_C = M_t [1 + (1 + 0.2 M_t^2) u_w(0,0)] \quad (19a)$$

The force coefficients are referenced to the corrected Mach number M_C , by multiplying the measured values by the factor

$$= \frac{M_t^2 [1 + 0.2 M_C^2]}{M_C^2 [1 + 0.2 M_t^2]} \quad (19b)$$

Correction for Angle of Attack

Substituting equations (12) and (13), the equation (11) for the interference velocity $v_w(0,0)$, at the model can be written as

$$v_w(0,0) = -(1/h) \int_{-\infty}^{\infty} [(C_{p,u} - C_{p,l})/2 + (u_{m,u} - u_{m,l})] W_2 dx \quad (20)$$

where

$$W_2(x) = 1/[1 + \exp(2 \pi x/\beta h)] \quad (21)$$

The variation of the weighting function $W_2(x)$ with x is shown in figure (3), and it may be noted that it has an asymptotic value of one upstream and zero downstream. The variation between these two limits occurs over a narrow region extending about one testsection height either side. This suggests that the integration of equation (20) can be truncated at a suitable location downstream, since the contribution beyond that region will be negligible. However, the same argument does not apply for the upstream end, since the weighting function $W_2(x)$ is almost equal to one beyond about one testsection height. Hence, the contribution to the integral from the upstream region needs to be examined properly.

Upstream Contribution

For purposes of calculation, the integration of equations (17) and (20) can be split into three regions:

- a) from upstream infinity to the beginning of the testsection ($x=x_s$),
- b) from x_s to the end of the testsection ($x=x_e$),
- c) from x_e to downstream infinity.

Of these, as discussed above the contribution from region (c) is small for both test Mach number and angle of attack corrections, for practical size of the testsection lengths generally used. The region (b) is over which the wall pressure measurements are available, and is amenable for accurate calculation. However, the contribution from region (a), for the angle of attack correction cannot be ignored and needs to be accounted properly. Since the wall pressure measurements are generally not available in region (a), judicious interpolation across the front end or extrapolation of the range of measured pressure data to upstream infinity may be necessary in most of the interference calculation methods (ref. 24).

For large negative x , $W_2(x)$ tends to unity and the integral in equation (20) can be written as

$$v_w(0,0) = -I_1 - I_2 \quad (22)$$

where

$$I_1 = \int_{-\infty}^{x_s} [(C_{p,u} - C_{p,l})/2] dx/h \quad (23)$$

$$I_2 = \int_{-\infty}^{x_s} [(u_{m,u} - u_{m,l})] dx/h \quad (24)$$

The value of the integral I_1 depends on the method used to extrapolate the experimental data beyond $x=x_s$. If the

difference between the measured upper and lower wall pressures at the most upstream location is small, the contribution from I_1 can be ignored. However, when this is not possible, a suitable assumption for the variation of pressure coefficient with x has to be made.

One of the methods suggested in reference (25), is to use an exponential decay of the type $C_p \exp(x)$. This was found to give satisfactory results for the test case experimental data obtained in the NAE perforated wall testsection on a BGK airfoil (ref. 1). However, it may be noted that for this test case, the difference between the upper and lower wall pressure coefficients at the most extreme upstream location is 0.0001, and hence the calculated value of I_1 is small in comparison with I_2 , and can be ignored.

In the present investigation, an extrapolation based on the pressure distribution due to a vortex placed between two solid walls distance h apart has been considered. For this problem, the pressure coefficients on the top and bottom walls are given by

$$C_p(x, h/2) = -C_p(x, -h/2) = -(\gamma/\beta h) / [\cosh(\pi x/\beta h)] \quad (25)$$

Using equation (25), the difference between the top and bottom wall pressure coefficients can be written as

$$C_p(x, h/2) - C_p(x, -h/2) = -(2\gamma/\beta h) / [\cosh(\pi x/\beta h)] \quad (26)$$

The equation (26) can be expressed in terms of the measured pressure coefficients at the most upstream location as

$$\frac{C_p(x, h/2) - C_p(x, -h/2)}{C_p(x_s, h/2) - C_p(x_s, -h/2)} = \frac{[\cosh(\pi x_s/\beta h)]}{[\cosh(\pi x/\beta h)]} \quad (27)$$

For large negative x , equation (27) behaves as

$$\frac{C_p(x, h/2) - C_p(x, -h/2)}{C_p(x_s, h/2) - C_p(x_s, -h/2)} = \exp[(x-x_s)(\pi/\beta h)] \quad (28)$$

It is expected that the extrapolation suggested by equation (28) may represent an upper bound, since for ventilated walls, the actual value may be expected to be between the open jet and solid wall limits. The effect of ventilated walls is taken into account in an indirect manner by using the measured values of the pressure coefficients at $x=x_s$ in equation (28). Substituting equation (28) in equation (23), the integral I_1 can be evaluated to give

$$I_1 = (\beta/2\pi)(C_{p,u} - C_{p,l})_{x=x_s} \quad (29)$$

It may be observed that this value can be significant, if the wall pressure measurements are not extended far enough upstream so that the difference are small enough and can be ignored. Because of this, care should be exercised in determining the location of x_s for calculations, to ensure that the pressure measurements are not affected by any local flow conditions such as the beginning of ventilations.

The integral I_2 represents contribution due to a vortex in free air, and forms a significant portion of the correction. A closed form expression can be obtained for its value. For a vortex of strength γ , the streamwise component of the induced velocity is given by

$$u_m(x, y) = [(\gamma/2\pi)(\beta y)]/[x^2 + \beta^2 y^2] \quad (30)$$

and hence

$$u_m(x, h/2) - u_m(x, -h/2) = (\gamma/\pi)(\beta h/2)/[x^2 + (\beta h/2)^2] \quad (31)$$

Substituting equation (31) in equation (24), the integral I_2 can be evaluated to give

$$I_2 = (cC_1/2h\pi)[(\pi/2) + \tan^{-1}(2x_s/\beta h)] \quad (32)$$

The variation of I_2 with x_s/h is shown in figure (4), and it may be seen that the contribution due to vortex singularity, from far upstream can form a significant portion of the correction. For $(c/h) = 0.25$ and $(x_s/h)=1$, the value of I_2 is about 0.8 degrees at a lift coefficient of about one.

FOURWALL INTERFERENCE CORRECTION

The procedure used for correcting the test data is the sequential approach suggested in reference (10). First the test Mach number, the measured wall pressures and the model force coefficients are corrected for the sidewall boundary-layer effects. It may be noted that the sidewall boundary-layer correction theories presently used account only for the negative blockage caused by the enlargement of the streamtube due to favourable pressure gradient in the airfoil region. These sidewall boundary-layer corrected values are then used to calculate the top and bottom wall interference effects which results in an additional blockage correction, and a correction for the incidence due to lift interference. The measured force coefficients are then corrected for the change in dynamic head, using equation (19b).

DESCRIPTION OF THE COMPUTER PROGRAM

The interference calculation method described above, has been incorporated into a Fortran computer program to facilitate calculation of wall interference effects on the airfoils tested in the Langley 0.3-m Transonic Cryogenic Tunnel. The

input details for the program are given in Appendix A. The first record of the input data determines one of the following options provided in the program:

- 1) The required test data for calculating the wall interference are read from the test data tapes. The array numbers where the values of the required test parameters are provided in a separate file. A typical example is shown in Appendix B. This file is incorporated into the main program by using the XEDIT facility.
- 2) The required test parameters may be provided through the input namelist IDAT.
- 3) The program can be run for the check case test data obtained on a BGK airfoil in the NAE perforated wall testsection. The required input data for this case are given in reference (1), and are incorporated in the present program.

For the first two options, the various control parameters determining the range of integration, and the type of correction to be applied are specified through the input namelist VALUS. The default values in the namelist have been set to correspond to cases generally used in evaluating interference for the airfoil test data in the 0.3-m TCT.

It has been the experience with tests in the TCT that some of the wall pressures can be affected by leakage and hence need to be dropped to avoid erroneous calculation of the wall interference effects. For this purpose, provision has been made to skip up to five pressure points on both the top and bottom walls, through the parameters ISKIPT, ISKIPL, IT(5) and IL(5). The wall pressures are interpolated linearly at the intermediate locations specified through the parameter XINCR.

The integrals in equations (10) and (11) required for the calculation of top and bottom wall interference effects are evaluated using trapezoidal rule. With the default options provided, the interference calculations are made for sidewall effects, top and bottom wall effects and combined fourwall effects. However, if necessary, calculations can be made either for sidewall or top and bottom wall effects only by specifying the appropriate values for the parameters ISWL and ITB.

The contribution to the angle of attack correction from upstream infinity to the beginning of the test-section due to extrapolation of the pressure coefficients is calculated using equation (29). This can be suppressed by setting IEXTR=0.

The calculation of the sidewall boundary-layer effects is straight forward and can be done by specifying test Mach number and the sidewall boundary-layer parameters DS ($=2\delta^*/b$) and the shape factor H. If a negative value is specified, the program calculates the required parameters using the empirical equations (8) and (9).

RESULTS AND DISCUSSION

Calculations for the NAE Test Case

For validation of the present program, first the top and bottom wall interference corrections were calculated for the test data given in reference (1). This test data was obtained with a 10" chord BGK-1 airfoil model in the NAE 15"x 60" two-dimensional test section with perforated top and bottom walls. The test Mach number and Reynolds number were 0.784 and 21×10^6 respectively. The model was set at an incidence of 2.56 degrees and the lift coefficient was 0.764. The results of interference corrections by various methods for this test case are summarised in reference (1).

The required wall pressure data and other parameters for the NAE test case have been incorporated into the program and can be run by using option (3) discussed in Appendix (A). The correction to the test Mach number obtained by the present method was $-.015$, and the correction to the angle of attack was -0.65 degrees. These values are compared in Table II, with the results of other methods taken from reference (1). It may be noted that there is close agreement between the various methods and the present calculations. The corresponding corrections by the Kemp's method is $-.017$ for the Mach number and $-.64$ degrees for the angle of attack without upstream flow adjustment. With upstream flow adjustment, the correction to the angle of attack by the Kemp's method happens to be -0.89 degrees.

As discussed earlier, the correction to the angle of attack is dependent on the type of extrapolation employed for extending the range of measured wall pressure data to upstream infinity, and the values of the top and bottom wall pressure coefficients at the most upstream location. For this test case, the difference between the top and bottom wall pressure coefficients at the most upstream location happens to be 0.0001 and hence the contribution from the extrapolation as calculated from equation (29) happens to be about $-.0006$ degrees and can be ignored. Hence the calculated angle of attack correction will not be much different, whether the wall pressures are extrapolated or not. In reference (25), an exponential type of extrapolation for the wall pressures was used and the results were found to agree with the other methods. Perhaps, the small difference between the pressure coefficients at the most upstream location accounts for this agreement.

However, the major upstream contribution to the angle of attack appears to come from the vortex singularity as calculated from equation (32). For a given test section and

airfoil chord, this is directly proportional to the lift coefficient of the airfoil, and can be calculated independently of the wall pressure distribution. This happens to be a significant portion of the total correction. For the NAE test case, this value is $-.26$ degrees which forms about 40% of the total correction. This contribution appears to be a consequence of the finite length of the testsection.

The foregoing discussion suggests that if the pressure measurements are available over a sufficiently long upstream distance so that the difference between the top and bottom wall pressure coefficients can be ignored in relation to other experimental uncertainties, all the methods give nearly same value of the correction for the both the Mach number and the angle of attack. When the difference between the most upstream top and wall pressure coefficients is significant, it may be necessary to consider extrapolation of the data. However, caution has to be exercised to ensure that the difference is really due to wall interference effect. Any extraneous local effect, or other experimental uncertainties can result in erroneous corrections for the angle of attack.

Calculations for a Sample Case from 0.3-m TCT

The sample case considered corresponds to the test data obtained on a 6" chord NACA 0012 airfoil in the Langley 0.3-m TCT. Results of fourwall interference calculations for this case using TWINTN4 have been given by Kemp in reference (10). The test Mach number and Reynolds number were 0.701 and 3×10^6 , respectively. The input data taken from reference (10) and used in the present calculations is given in Appendix C. The corrected Mach number obtained by the present combined four-wall calculations is 0.691 which is close to 0.689 obtained by Kemp's method. The corresponding values for the correction to angle of attack are $-.25$ and $-.15$ degrees for the present and Kemp's calculations respectively. It may be noted that

for this sample case, the pressure coefficients at the first measuring station located about four chords upstream are -0.005486 and -0.022372 respectively, on the top and bottom walls. Hence, the contribution from extrapolation of the pressure coefficients will be considerable and probably accounts for the difference in corrections obtained by the two methods.

Calculations for Specific Test Programs in 0.3-m TCT

The main objective of the present task was to automate the present fourwall interference correction procedure to facilitate a quick evaluation of the interference effects for all the data points in a specific test program. An assessment of these interference corrections can then form a basis for undertaking detailed interference calculations, if necessary, for specific data points likely to be affected by large transonic effects.

The present program was validated by applying it to some of the airfoil test programs conducted in the 0.3-m TCT. The example chosen to demonstrate the procedure is the unpublished data by Mineck and Lawing, on a 6" chord, 12% thick symmetric super-critical airfoil model in the 8"x 24" slotted wall testsection. The sequence of control cards and the input data, and typical output result obtained are shown in Appendix D. This particular example of a symmetric airfoil was chosen to identify the problems associated in making interference corrections and the associated uncertainties. As described in Appendix A, the program is run in option (1), by specifying the test and run numbers only. The program calculates the interference corrections for all the test points in the specified run number, and the results are printed in the output format shown in Appendix D. The corrections to the Mach number and the angle of attack (in degrees), and the corrected

values of the test parameters are printed for each type of correction: i.e., sidewall, top and bottom wall, and combined fourwall interference.

Correction for Blockage

The correction to the test section Mach number for a typical run in the 0.3-m TCT is shown in figure (5), at a Mach number of 0.6 and for various lift coefficients. It may be noted that the correction for the sidewall boundary-layer effects as obtained by equation (4), for the 0.3-m TCT is significant amounting to about -0.014. The correction due to top and bottom wall effects is about 0.002 and does not seem to vary significantly over the range of lift coefficients from -0.5 to 0.5. The relatively small blockage correction due to top and bottom wall effects is expected for the 0.3-m TCT slotted wall testsection which has been designed for low blockage effects using the method of reference (21). It may be noted that such slotted wall tunnels designed for low blockage effects, may introduce significant correction to the angle of attack. However, considering the uncertainties involved in determining the true angle of attack in two-dimensional airfoil testing, designing for low blockage effects is an attractive feature.

Correction for Lift Interference

It has to be noted that the calculated values of the correction for the angle of attack needs to be accounted for any testsection flow inclination. It is desirable that this information is to be obtained from empty tunnel calibration. However, for a symmetrical airfoil this can be deduced from lift coefficient versus angle of attack curves. For the symmetrical airfoil tested in the 0.3-m TCT, these are shown plotted in figure (6) for Mach numbers 0.5, 0.6, 0.76 and 0.8. From these lift curve data, it appears that an empty test-

section flow inclination of about -0.1 degree is required for the test data.

Again, for a symmetrical airfoil at zero lift, the top and bottom wall pressure signatures has to be identical and hence the calculated correction for the angle of attack has to be zero. However, any local flow conditions at the walls or other effects may yield a non-zero correction, which can be considered as a tare correction due to measured wall pressures at zero lift. This is demonstrated in figure (7) by plotting the calculated correction for the angle of attack for various lift coefficients at a Mach number of 0.6. The difference between the corrections obtained by extrapolating the measured pressures to upstream infinity, and without extrapolation is not significant for the case considered. The calculated value of the correction varies nearly linearly over the range of lift coefficients from -0.5 to 0.5 . The tare correction due to measured wall pressures at zero lift happens to be about 0.1 degree. Assuming this tare correction remains constant with lift, this value needs to be subtracted from the calculated value of correction using the measured pressure distribution. An example of the application of this correction procedure is illustrated in figure (8), corresponding to a test Mach number of 0.6. The corrected lift curve is closer to empirically correlated Davis-Moore theory (ref. 21 and ref. 26) for positive lift coefficients. For negative lift coefficients the difference between the two methods is noticeable.

Application to a Cambered Airfoil

The present correction procedure was applied to a recent test on a cambered super-critical airfoil in the 0.3-m TCT slotted wall test section. Detailed wall interference calculations by using the TWINTN4 code have been made recently⁺ for this airfoil, and hence it was thought that a comparison

⁺ C. B. Johnson (Private Communication)

of the present method with the calculations of TWINTN4 would provide a better assessment of the method. In figures (9) and (10), typical results obtained by the present method are shown for two Mach numbers, 0.6 and 0.73 respectively, for a chord Reynolds number of 30 million. Good agreement with the TWINTN4 results was found for these cases and for many other test conditions. This suggests that the present method can be employed to get first order interference corrections for a typical test program, which can subsequently be used to determine test conditions requiring more detailed evaluation using TWINTN4. With the present computer program, the calculations can be done for all the test points with little computational effort.

Practical Problems

From the several examples considered above, and the test case data shown in Table II, it follows that for a given subcritical wall pressure distribution, the interference corrections obtained by the present program and the various other methods are nearly same. The application of most of these methods is relatively straightforward except for the method of Kemp which solves the non-linear transonic problem. However, when applied to a specific test program, several difficulties can arise, mainly due to experimental limitations. This leads to uncertainties in the calculated value of the interference corrections and often it is difficult to overcome these problems by making refined calculations. Some of these problems have been addressed by Smith (ref. 24). With particular reference to measurements in the 0.3-m TCT, these problems are mainly

a) The upstream wall pressure measurements, depending on the location of the pressure orifices, can be affected by the local flow conditions in the vicinity of the beginning of the top and bottom wall ventilations. This can introduce spurious pressure signatures not related to the model perturbations.

Often judgement has to be exercised on deciding the most probable location where the measurements are not affected by the local flow conditions.

b) Ideally, it is desirable that the pressure measurements are made at a distance away from the wall by using pressure rails. However, for practical reasons, the measurements are often made on the slats. The accuracy of using the slat measurements instead of the pressure rail measurements has been examined by Smith (ref. 24) by making both the measurements in the NLR Pilot Tunnel. For the CAST-7 airfoil with a chord to tunnel height ratio of about 0.33, it was found that the differences between the two measurements were not significant, and the calculated values of the corrections were well within the overall experimental accuracies. However, this is a factor which depends largely on the ratio of slot spacing to tunnel height, and it is difficult to draw any firm conclusion in the absence of experimental data for a specific facility.

c) Due to limited testsection length, extrapolation or interpolation of the measured wall pressure data is necessary for interference calculation methods requiring boundary data. This is particularly important for determining the correction for the angle of attack. The suggested method of using the wall pressure distribution due to a vortex between solid walls provides a theoretical basis for extrapolation and can be expected to give an upper bound, since for an open jet the pressures will be identically same all along the boundary. However, it is desirable to check the angle of attack corrections obtained with and without extrapolation of the pressures and ensure that there is not significant difference between the two values. The present method provides a means for making such quick checks and sensitivity analysis of the interference corrections.

d) Far upstream, the difference between the wall pressures and the freestream static pressure tends to become small. Since the correction for the angle of attack depends on the difference between the top and bottom wall pressures, care needs to be taken to measure these differences accurately. If there is considerable noise, the measured data may have to be smoothed appropriately.

e) Ideally, for a symmetrical airfoil, one would expect the correction for the angle of attack to be of the same magnitude but of opposite sign when the airfoil is at negative angle of attack. However, it may be difficult to achieve this in ventilated walls due changing local flow conditions.

f) In ventilated wall tunnels, changes in upstream flow inclination can occur with change in lift coefficient. This problem has been addressed in detail by Kemp. It appears that the scope of the present program can be extended, if a suitable correction based on the upstream pressure measurements can be made to account for the upstream flow inclination.

CONCLUDING REMARKS

A simplified fourwall interference calculation procedure has been developed to correct the airfoil data obtained in the 0.3-m TCT. The procedure was applied to typical test cases and airfoil test programs in the TCT, and good agreement was observed with the results of other methods. While the application of the various interference calculation methods is straightforward, it appears that the practical limitations and uncertainties associated with the experimental data can impose limits on the accuracy to which the interference corrections can be assessed.

The correction to the test Mach number due to blockage effects is not much affected by the uncertainties associated with extending the range of the wall pressure distribution beyond the measured limits. However, the same argument does not hold true for the angle of attack correction in ventilated wall tunnels. This often forces the tunnel engineer to disregard the experimental angle of attack. To quote from reference (27),

- "For two-dimensional tests the wall ventilation is generally configured to minimize blockage interference which predominantly affects the Mach number of the freestream. The lift interference effects are so large that the experimental angle of attack is disregarded and section normal force coefficient is emphasized".

For the 0.3-m TCT, significant portion of the blockage correction comes from the sidewall boundary-layer effects, since the top and bottom slotted walls are designed for low blockage effects. Experience with the analysis of the 0.3-m TCT airfoil data (refs. 28, 29) suggests that a correction for the test Mach number based on the one-dimensional effect of sidewall boundary-layer effects is often adequate to give satisfactory results, for the 6" chord models generally tested in the TCT.

It appears that the empirically correlated Davis-Moore theory often gives acceptable correction for the angle of attack (e.g., fig. 8) for the 0.3-m TCT airfoil data. However, as has been observed in reference (26), this may not be true in general, and methods based on measured boundary conditions are superior and more reliable. However, while arriving at corrections for the angle of attack, care needs to be taken in ascertaining the quality of the wall pressure data.

The present method uses simple singularities for model representation, and the trapezoidal rule for integration of wall pressures. This was done to keep the calculation simple, so that, the method can be adopted for making on-line corrections for the airfoil tests in the TCT. However, the method can be improved by using a better model representation, and integrating the wall pressure using a spline fit for the measured data. Further, the scope of the approach can be improved if upstream flow inclination can be properly accounted.

Good agreement of the present method with the results of TWINTN4 code suggests that the method can be used to obtain a quick correction for all the data points in an airfoil test program. A detailed evaluation of the interference may then be made for selected conditions using TWINTN4.

The present approach can be used directly for calculating the correction for the angle of attack, even with upstream sidewall boundary-layer removal since it introduces identical pressure signatures on both the top and bottom walls. However, for the Mach number, a tare correction to account for mass removal effects will be required. This can be obtained either from empty tunnel calibration with sidewall boundary-layer removal or from theoretical considerations.

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Table I

Summary of 2-D Wall Correction Methods

Method	Input		Analysis
	Boundary	Model	
Mokry (Ref.13)	Pressures	Forces	Subsonic
Capalier et al. (Ref. 12)	Pressures	Forces	Subsonic
Ashill & Weeks (Refs. 16 & 17)	Pressures & Flow Incln.	None	Subsonic
Sawada (Refs. 14 & 15)	Pressures	Forces	Subsonic
Smith (Ref. 4) (Panel method)	Pressures	Pressures, Wake drag	Subsonic
Kemp (Ref. 3) (Finite difference)	Pressures	Pressures	Transonic
Murman (Ref. 2) (Finite Difference)	Pressures	Pressures	Transonic

Table II

Comparison of Corrections* for the NAE Test Case

Method	Correction for	
	Mach No.	Incidence
Mokry, Ohman (Ref. 13)	-.015	-.67 deg.
Capalier et al. (Ref. 12)	-.015	-.67 deg.
Gopinath (Ref. 25)	-.017	-.67 deg.
Smith (Ref. 4)	-.015	-.59 deg.
Sawada (Ref. 14, 15)	----	-.58 deg.
Kemp (Ref. 11)	-.017	-.64 deg.
		-.89 deg. ⁺
Present Calculations	-.015	-.65 deg.

*taken from reference (1)

⁺with upstream flow angle adjustment

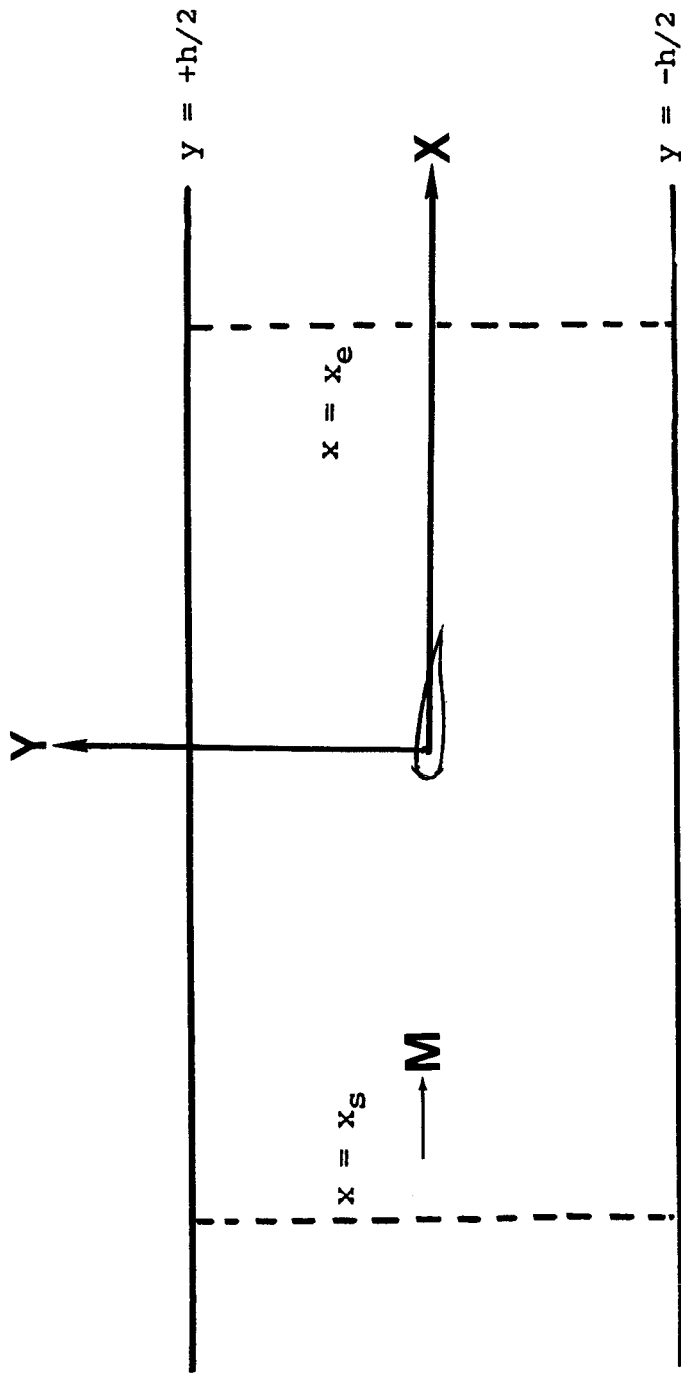


Figure 1: Coordinate system used for calculating the top and bottom wall interference.

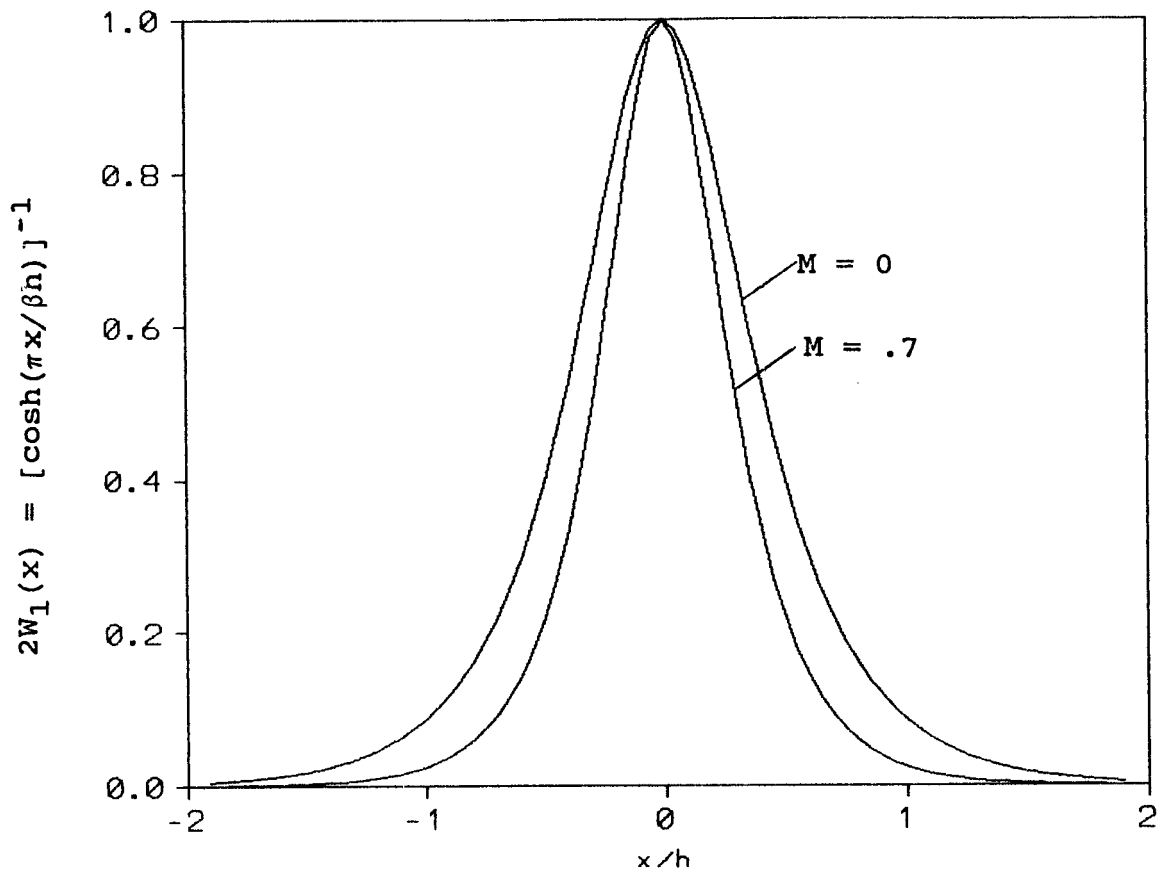


Figure 2: Variation of the weighting function $W_1(x)$ for the blockage correction (See equation 18).

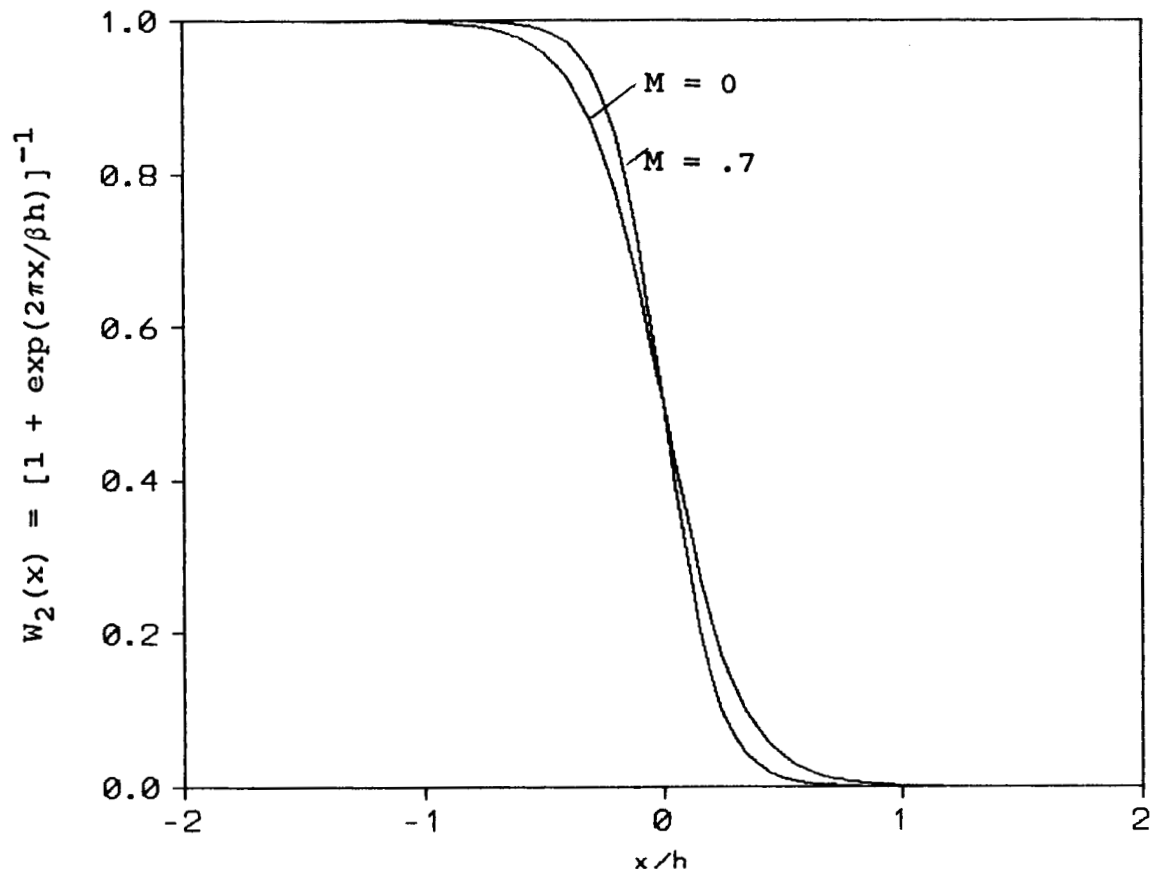


Figure 3: Variation of the weighting function $W_2(x)$ for angle of attack correction (See equation 21).

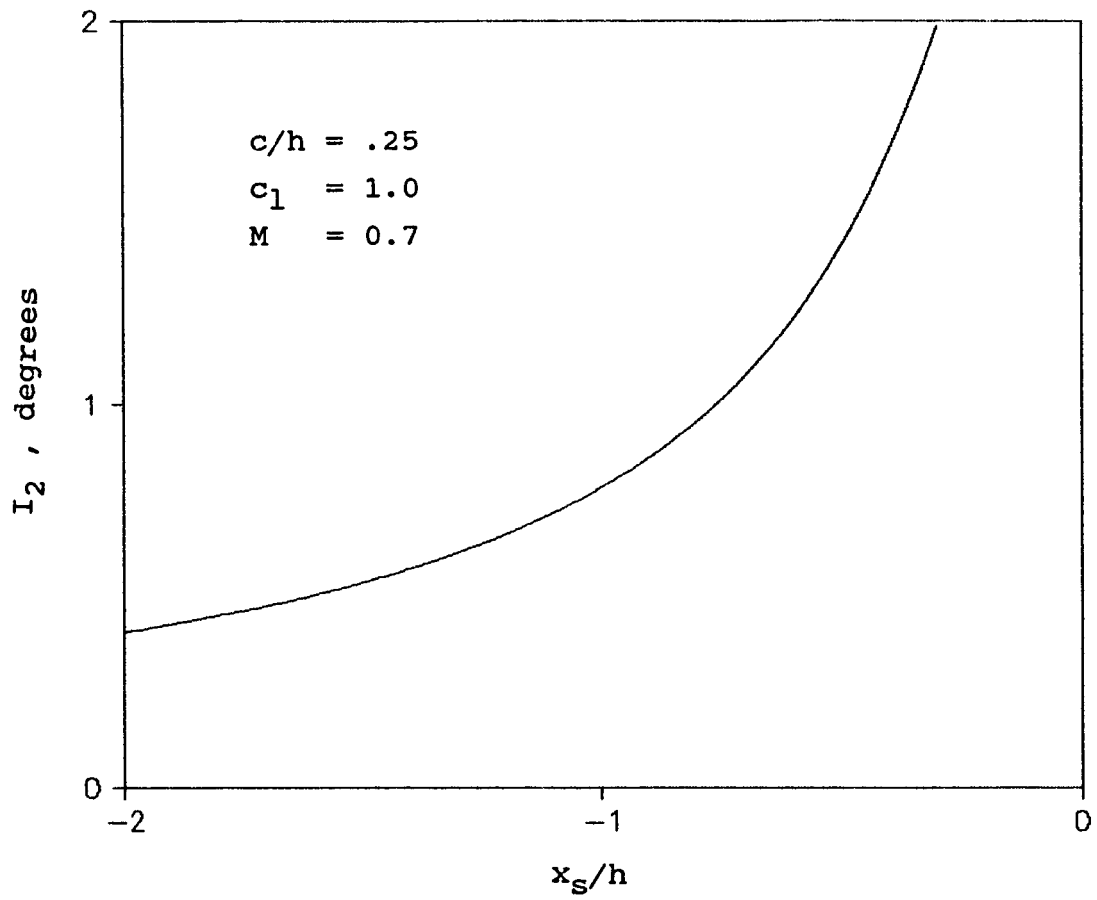


Figure 4: Contribution to angle of attack due to vortex from negative infinity to x_s (See equation 32).

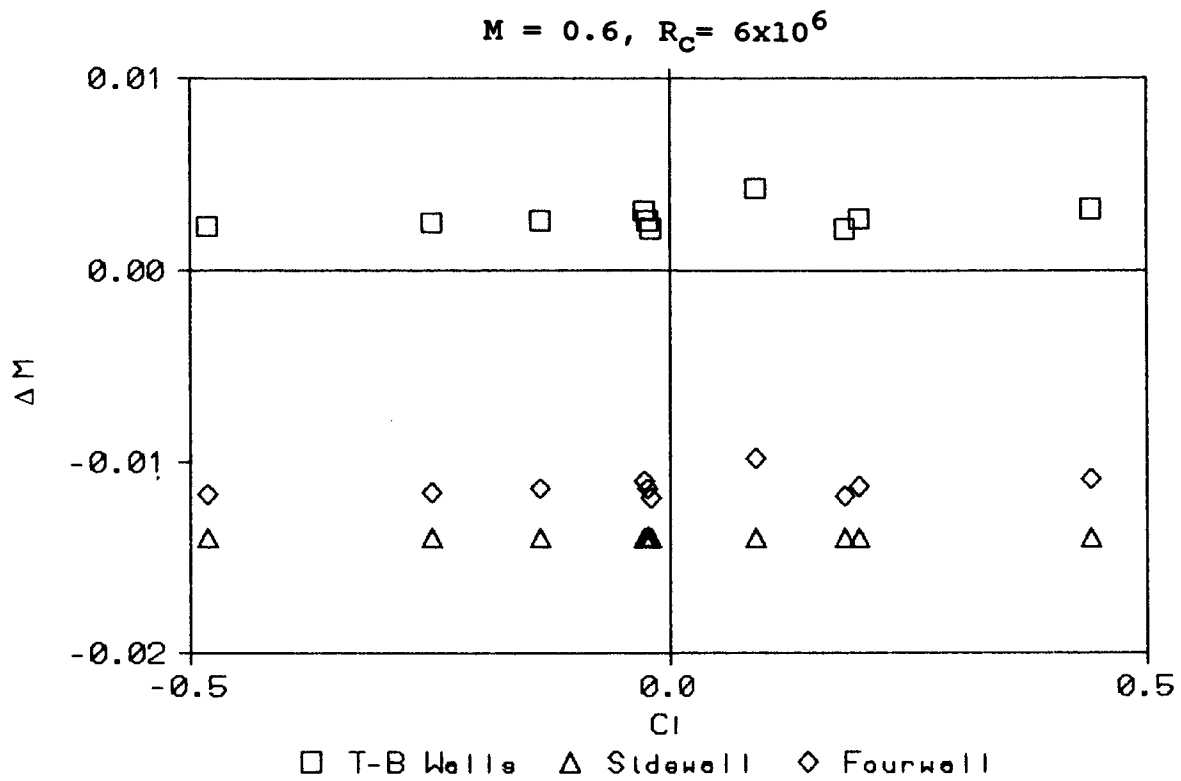


Figure 5: Calculated blockage correction for the symmetrical supercritical airfoil.

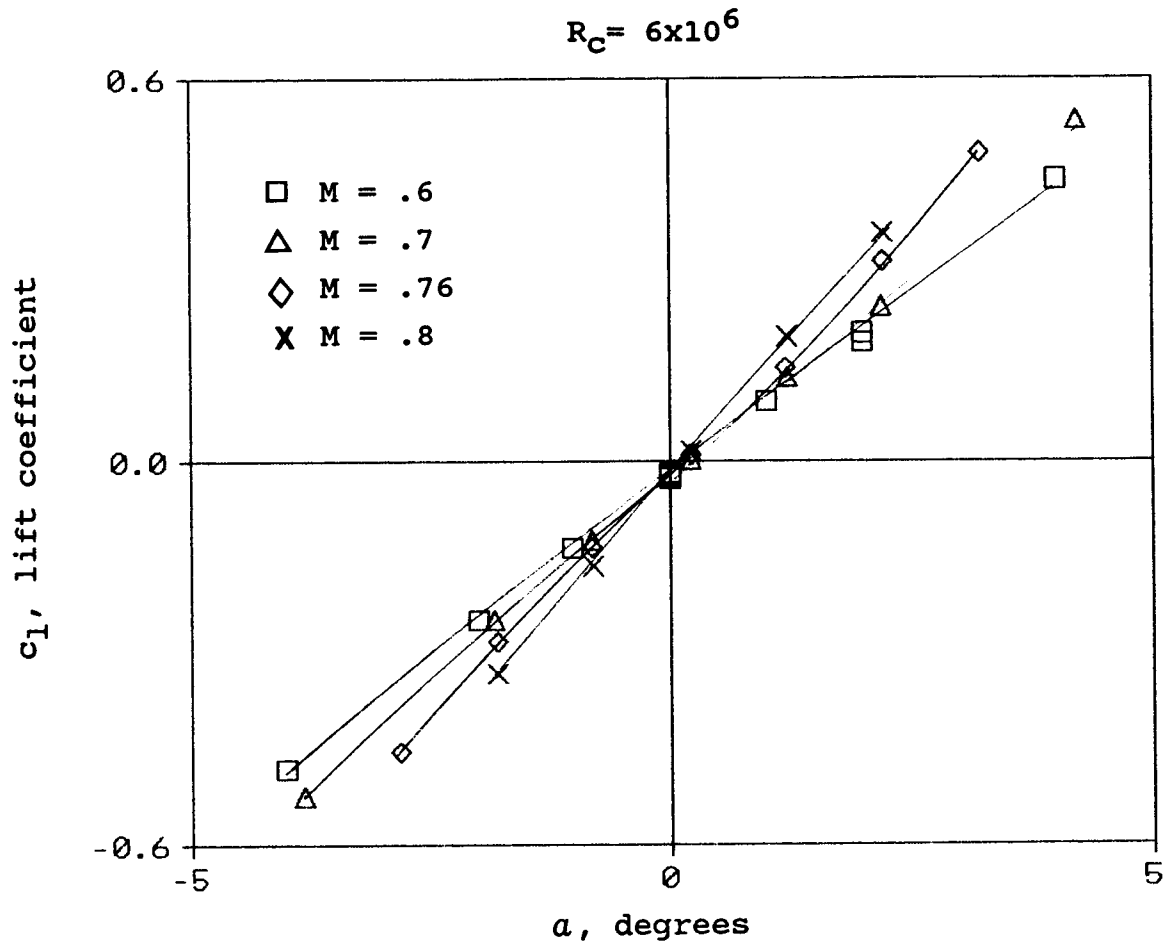


Figure 6: Variation of lift coefficient with angle of attack for the symmetric supercritical airfoil

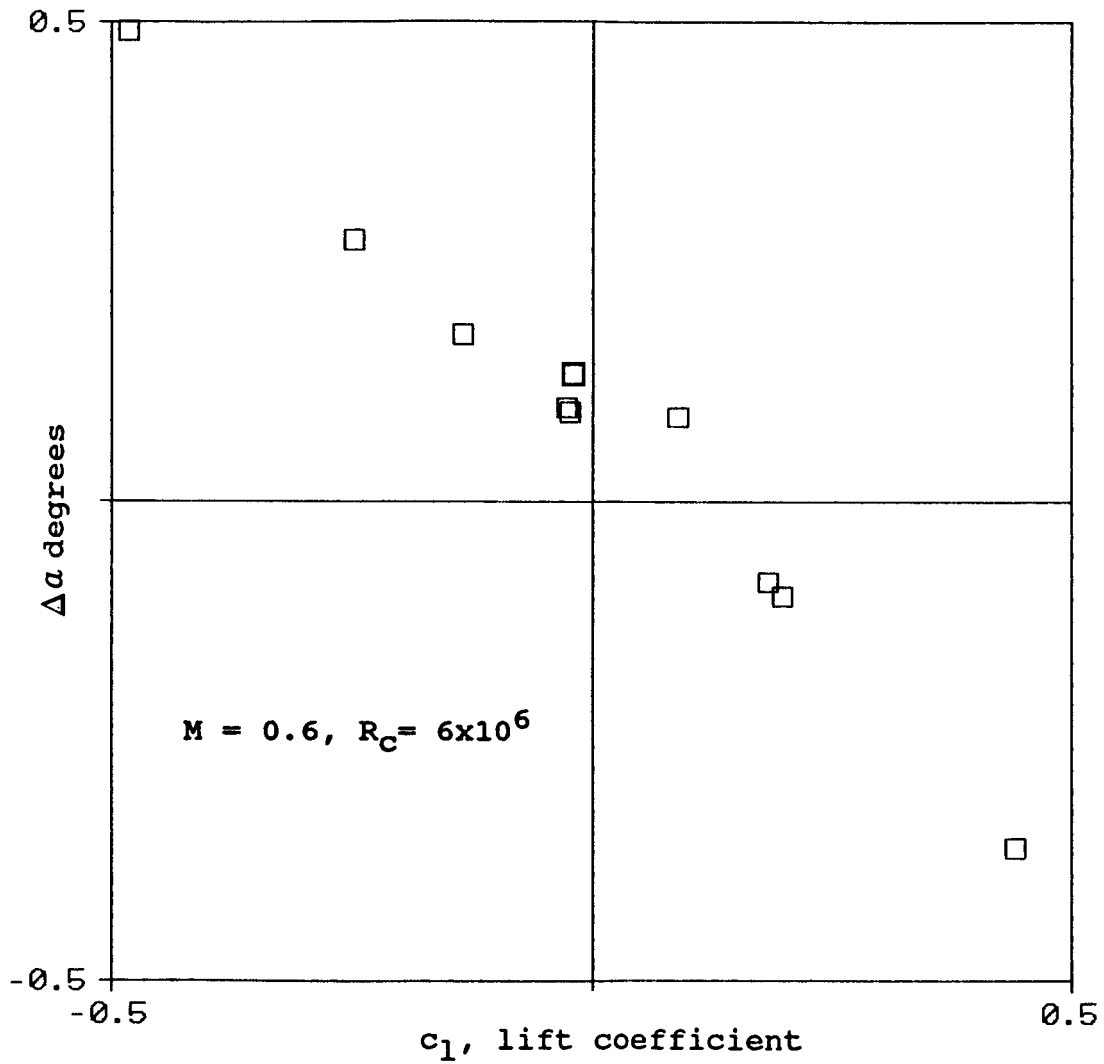


Figure 7: Calculated correction for the angle of attack for the symmetrical supercritical airfoil.

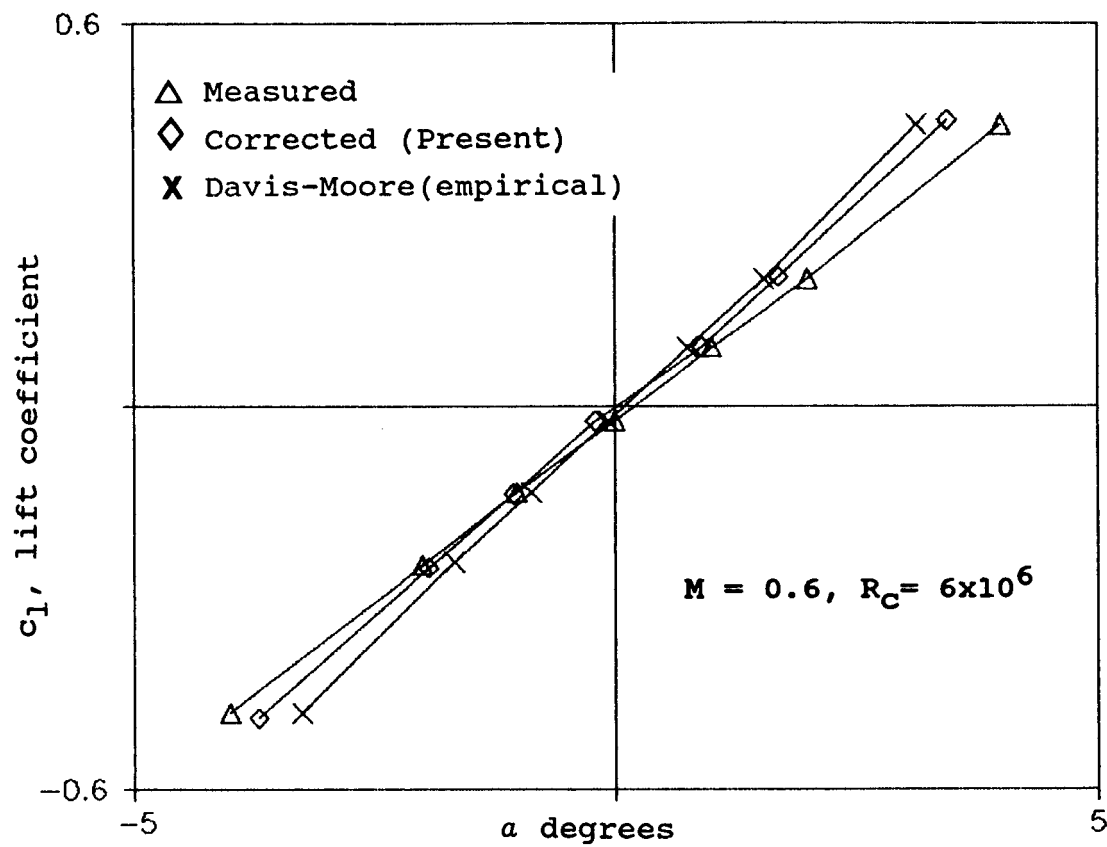


Figure 8: Corrected and measured lift coefficients for the symmetrical supercritical airfoil.

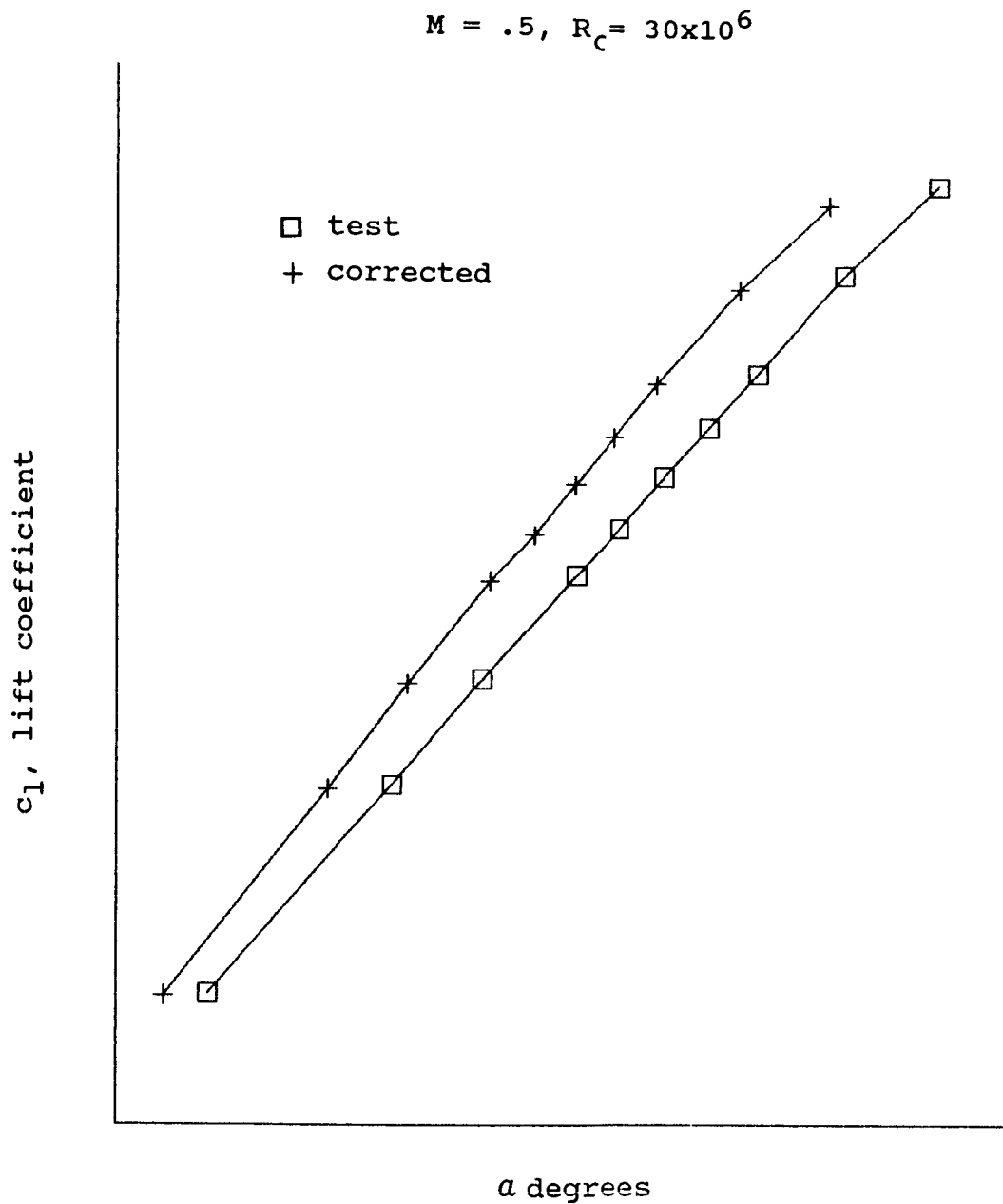


Figure 9: Application of the present method to a cambered airfoil test (subcritical case).

$$M = .73, R_C = 30 \times 10^6$$

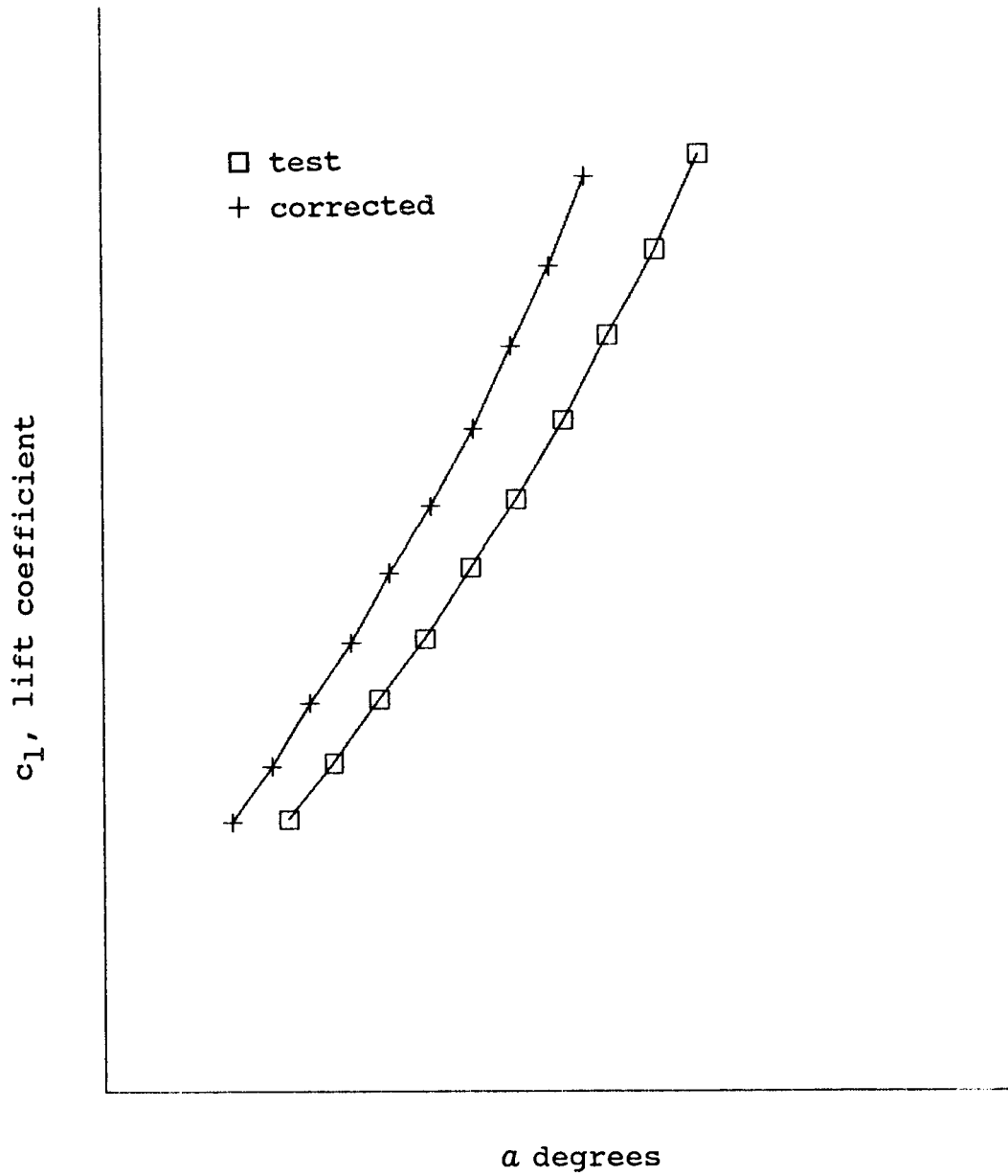


Figure 10: Application of the present method to a cambered airfoil test (supercritical case).

APPENDIX A: PROGRAM INPUT DETAILS

Option 1: Calculations for a given Test.

Namelist VALUS

```
Record 1. 00 (Columns 1-2); Input data for wall pressures
           and airfoil force/pressure
           coefficients read from test
           data files.
Record 2   Test number(I3),Run Number(I2),DS(F10.6),SH(F10.6)
Record 3   -- , , --
etc.,
Last      00000 (Columns 1-5), DS, SH (2F10.6)
/EOR
```

Option 2: Calculations for a given case.

Namelist VALUS

```
Record 1. 01 (Columns 1 -2)
Record 2. TITLE (Columns 1-80)
Record 3. $IDAT (From Column 2)
/EOR
```

Option 3: Calculations for Check Case (NAE Data)

```
Record 1: 02 (Columns 1-2)
/EOR
```

Parameters in Namelist VALUS

(default values of the parameters are shown in paranthesis)

XSTART : Upstream value of x for integration of wall pressures (-24.5)
XEND : Downstream value of x for integration of wall pressures (23.5)
XINCR : Value of increment for X interpoalting the intermediate values (2.0)
AREA : Cross-Sectional area of airfoil (3.0 sq")
WIDTH : Width of the tunnel (8.0")
H : Distance between the top and bottom walls (24")
CHORD : Airfoil Chord (6.0")
XL : Distance of airfoil leading edge from turntable center (2.16")
IAR : 1, for including aspect ratio effects (Default)
0, aspect ratio effects not included
WVL : Length scale representing airfoil chord. Required if aspect ratio correction is made. (2)
ISWL : =0, No sidewall boundary-layer correction.
=1, Murthy's Correction method. (Default option)
=2, Barnwell-Sewall correction method.
IEXTR : =1, Upstream most top and bottom wall pressures are extrapolated to infinity. (Default option)
=0, No extrapolation of wall pressures.
ISKIPT : No. of upper wall ports to be skipped (Max. 5)
ISKIPB : No. of lower wall ports to be skipped (Max. 5)
IT(5) : Array, Port numbers to be skipped on top wall (0)
IB(5) : Array, Port numbers to be skipped on bottom wall (0)
IREND : Last Run number on the data files (100)
IPEND : Last Point number on thedata files (100)
ITB : =0, No top/bottom wall corrections applied
#0, top/bottom wall correction applied (default)

Parameters in Namelist IDAT

EM : Test Mach number
ALPHD : Angle of Attack (Deg.)
CL : Lift Coefficient
CD : Drag Coefficient
DS : Sidewall boundary-layer thickness ($2\delta^*/b$)
SH : Sidewall boundary-layer shape factor
RE : Chord Reynolds number
NUAF : No. of orifices on airfoil upper surface(Max.60)*
NLAF : No. of orifices on airfoil lower surface(Max.60)*
NU : No. of orifices on the top wall (Max. 60)
NL : No. of orifices on the bottom wall (Max. 60)
XAFU(60) : x/c location of orifices on airfoil upper surface*
XAFL(60) : x/c location of orifices on airfoil lower surface*
XWU(60) : x/c location of orifices on top wall
XWL(60) : x/c location of orifices on bottom wall
CPAFU(60): *Cp values on airfoil upper surface*
CPAFL(60): Cp values on airfoil lower surface*
CPWU(60) : Cp values on top wall
CPWL(60) : Cp values on bottom wall

* Not used in the program.

Appendix B

Example of file for Array Numbers for Test Parameters

```
C   ARRAY NUMBERS RELEVANT TO THE TEST ARE INSERTED HERE
C   ARRAY NUMBERS FOR TEST190 (ASH)
NP( 1)= 1076
NP( 2)= 1078
NP( 3)= 1079
NP( 4)= 1065
NP( 5)= 1220
NP( 6)= 1066
NP( 7)= 1067
NP(12)=  45
C   NOU,NOL:    NO. OF ORIFICES ON AIRFOIL UPPER,LOWER SURFACES
C   NOT,NOB:    NO. OF ORIFICES ON TUNNEL TOP AND BOTTOM WALLS
C   ISTX,ICPST: STARTING ARRAY NUMBER FOR X AND CP, (TOP WALL)
C   ISBX,ICPSB: STARTING ARRAY NUMBER FOR X AND CP, (TOP WALL)
C   IUSX,ICPUS: STARTING ARRAY NUMBER FOR X AND CP, (AIRFOIL US)
C   ILSX,ICPLS: STARTING ARRAY NUMBER FOR X AND CP, (AIRFOIL LS)
C
NOU=25 $ NOL=28 $ NOT=26 $ NOB=26
ISTX=1829 $ ICPST= 570
ISBX=1566 $ ICPSB= 596
IUSX=1983 $ ICPUS= 492
ILSX=1350 $ ICPLS= 517
```

TEST
RUN
POINT
ALPHD
MINF
RINF
CL
CD

ORIGINAL PAGE IS
OF POOR QUALITY

Appendix C

Input Data for the Sample Case (Ref. NASA CR-3777)

\$VALUS XSTART=-26.5, XEND=23.5, XINCR=2.0, IAR=0, ISWL=2, \$END

01

DATA FROM NASA CR-3777, P-24, TWINTN4: REF:WILLIAM B KEMP, JR.
\$IDAT EM=.701, CL=.2204, CD=.0076, DS=0.01543, SH=1.5042, RE=6, ALPHD=0.0,
NU=26, NL=28, NUAUF=24, NLAF=24,
CPWU(1)= -.54861E-02,
-.12283E-02, -.98122E-03, .62431E-03, -.52061E-03, .86244E-03, .11078E-03,
.13516E-02, -.37153E-02, -.84227E-02, -.19627E-01, -.36989E-01, -.48082E-01,
-.60229E-01, -.59275E-01, -.50005E-01, -.50088E-01, -.32147E-01, -.33204E-01,
-.28056E-01, -.32320E-01, -.36963E-01, -.37117E-01, -.36747E-01, -.39867E-01,
-.39552E-01,
CPWL(1)= -.22372E-01,
.69173E-03, -.35306E-02, .47236E-02, .14234E-01, .98306E-02, .13424E-01,
.22097E-01, .18123E-01, .22969E-01, .97888E-02, -.56598E-02, .21510E-02,
.20283E-03, .14175E-02, .84934E-03, -.88307E-03, -.23261E-02, -.70418E-02,
-.92554E-02, -.15335E-01, -.16095E-01, -.18531E-01, -.18062E-01, -.18691E-01,
-.18373E-01, -.17930E-01, -.45142E-01,
XWU(1)= -26.5, -24.5, -22.5, -20.5, -18.5, -16.5, -14.5, -12.5,
-10.5, -8.5, -6.5, -4.5, -2.5, -0.5, 1.5, 3.5,
5.5, 7.5, 9.5, 11.5, 13.5, 15.5, 17.5, 19.5,
21.5, 23.5,
XWL(1)= -26.5, -24.5, -22.5, -20.5, -18.5, -16.5, -14.5, -12.5,
-10.5, -8.5, -6.5, -4.5, -2.5, -0.5, 1.5, 3.5,
5.5, 7.5, 9.88, 11.88, 13.88, 15.88, 17.88, 19.88,
20.88, 22.88, 24.88, 26.88, 28.88,
XAFU(1)= .22477E-03,
.14361E-01, .28221E-01, .52970E-01, .77977E-01, .10296E+00, .15231E+00,
.20155E+00, .25228E+00, .30200E+00, .35197E+00, .40145E+00, .45146E+00,
.50149E+00, .55082E+00, .60089E+00, .65075E+00, .70067E+00, .74982E+00,
.80091E+00, .85039E+00, .89945E+00, .94878E+00, .987503 ,
CPAFU(1)= .10741E+01,
-.32689E+00, -.61743E+00, -.83530E+00, -.92300E+00, -.97980E+00, -.94881E+00,
-.84726E+00, -.70543E+00, -.60428E+00, -.53857E+00, -.48697E+00, -.42540E+00,
-.37318E+00, -.31092E+00, -.26626E+00, -.22483E+00, -.17602E+00, -.12971E+00,
-.74062E-01, -.20218E-01, .44718E-01, .12041E+00, .21364 ,
XAFL(1)= .22477E-03,
.11718E-01, .24341E-01, .49936E-01, .74166E-01, .98549E-01, .14860E+00,
.19846E+00, .24811E+00, .29807E+00, .34861E+00, .39795E+00, .44826E+00,
.49806E+00, .54869E+00, .59798E+00, .64853E+00, .69885E+00, .74836E+00,
.79859E+00, .84924E+00, .89914E+00, .94766E+00, .987503 ,
CPAFL(1)= .10741E+01,
.49190E+00, .17864E+00, -.10019E+00, -.21237E+00, -.29413E+00, -.36746E+00,
-.38417E+00, -.37348E+00, -.34969E+00, -.32701E+00, -.30194E+00, -.26462E+00,
-.23905E+00, -.20599E+00, -.17514E+00, -.15402E+00, -.11758E+00, -.85763E-01,
-.40814E-01, -.83148E-02, .29585E-01, .11052E+00, .255044 ,
\$END

Results for the Sample Case

DATA FROM NASA CR-3777, P-24, TWINTN4:

REF: WILLIAM B KEMP, JR.

BARNWELL/SEWALL CORR (DOES NOT ACCOUNT FOR AR)

DELTA M	-.0139
D ALPHA	0.0000
M CORR	.6871
CL CORR	.2234
CD CORR	.007702
AL CORR	0.0000

TOP-BOT WALL CORRECTION ONLY

DELTA M	.0041
D ALPHA	-.2588
M CORR	.7051
CL CORR	.2186
CD CORR	.007539
AL CORR	-.2588

BOTH SIDEWALL & TOP-BOT WALL CORRECTION

DELTA M	.0042
D ALPHA	-.2516
M CORR	.6913
CL CORR	.2215
CD CORR	.007637
AL CORR	-.2516

Appendix D

Control Cards and Input for a typical 0.3-m TCT Test Program

```
FOURADX,T1000,CM170000.
USER,USERNUM,PASSWOR.
CHARGE,XXXXXX,XXX.
GET,FETCH/UN=474750C.
GET,J190001/UN=USERNUM.
FETCH(TAPE1)
GET,FOURADX,ARRAY190.
XE,FOURADX.
FTN,I=FOURADX,L=0,PL=3000.
ATTACH(FTNMLIB/UN=LIBRARY,NA)
LDSET(LIB=FTNMLIB,PRESETA=INDEF)
LGO.
REPLACE,TAPE10=OUPTFLN.
DELIVER.XXXXXXX XXXXXX
GET,OUPTFLN.
COPY,OUPTFLN,OUTPUT.
EXIT.
REPLACE,TAPE10=ERRADX.
GET,ERRADX.
COPY,ERRADX,OUTPUT.
/EOR
J190001
/EOR
DEL;
L/IDAT=00/;READ ARRAY190;T;D/%/*;E
/EOR
$VALUS IT(1)=10,ISKIPT=1,ISKIPL=1,IL(1)=1,ITB=1,IAR=0,IEND=1,IPEND=12,$END
00
19001 -.0206 1.4448
00000 .0000 .0000
/EOF
```

Typical output for a 0.3-m TCT Test

```
$VALUS
XSTART = -.245E+02,
XINCR  = .2E+01,
XEND   = .235E+02,
AREA   = .3E+01,
H      = .24E+02,
XL     = .216E+01,
CHORD  = .6E+01,
ISKIPT = 1,
ISKIPL = 1,
WIDTH  = .8E+01,
IAR    = 0,
WVL    = .2E+01,
ISWL   = 1,
ITB    = 1,
IUAF   = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
ILAF   = 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0,
ISKPAFU = 15,
ISKPAFL = 15,
DS     = .2E-01,
SH     = .14E+01,
IREND  = 1,
IPEND  = 12,
IT     = 10, 0, 0, 0, 0,
IL     = 1, 0, 0, 0, 0,
IEXTR  = 1,
$END
```

contd/

TEST	190.	190.	190.	190.	190.	190.
RUN	1.	1.	1.	1.	1.	1.
POINT	1.	2.	3.	4.	5.	6.

MEASURED VALUES

ALPHAD	.0102	1.0122	2.0060	2.0060	4.0120	.0000
MACH NO.	.6018	.6013	.6006	.6005	.6026	.6015
REX10-6	5.9873	5.9956	5.9882	5.9863	5.9934	5.9856
CL	-.0260	.0926	.1857	.2005	.4425	-.0197
CD1	.007225	.007197	.007345	.007331	.009376	.007220

SIDEWALL BL PARAMETERS (CALCULATED)

2DS/B	.0207	.0207	.0207	.0207	.0207	.0207
H	1.4457	1.4457	1.4457	1.4457	1.4457	1.4457

SIDEWALL BL CORRECTION (MURTHY)

DELTA M	-.0140	-.0140	-.0140	-.0140	-.0140	-.0140
D ALPHA	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
M CORR	.5878	.5873	.5867	.5866	.5886	.5876
CL CORR	-.0266	.0948	.1901	.2053	.4530	-.0201
CD CORR	.007397	.007368	.007519	.007505	.009598	.007391
AL CORR	.0102	1.0122	2.0060	2.0060	4.0120	.0000

TOP-BOT WALL CORRECTION ONLY

DELTA M	.0031	.0043	.0022	.0027	.0032	.0022
D ALPHA	.0957	.0955	-.0684	-.0825	-.3253	.1308
M CORR	.6049	.6055	.6028	.6032	.6058	.6037
CL CORR	-.0258	.0917	.1846	.1991	.4390	-.0195
CD CORR	.007169	.007120	.007304	.007281	.009301	.007180
AL CORR	.1058	1.1077	1.9376	1.9235	3.6868	.1308

BOTH SIDEWALL & TOP-BOT WALL CORRECTION

DELTA M	.0030	.0042	.0022	.0027	.0031	.0021
D ALPHA	.0983	.0888	-.0835	-.0989	-.3618	.1333
M CORR	.5909	.5915	.5888	.5892	.5917	.5897
CL CORR	-.0264	.0938	.1890	.2038	.4493	-.0200
CD CORR	.007339	.007288	.007477	.007453	.009520	.007350
AL CORR	.1085	1.1009	1.9225	1.9071	3.6503	.1333

contd./

TEST	190.	190.	190.	190.
RUN	1.	1.	1.	1.
POINT	7.	10.	11.	12.

MEASURED VALUES

ALPHAD	-1.0081	-1.9958	-3.9917	.0000
MACH NO.	.6011	.6003	.6010	.5997
REX10-6	5.9826	5.9917	5.9997	5.9923
CL	-.1351	-.2489	-.4808	-.0228
CD1	.007425	.007872	.009376	.007370

SIDEWALL BL PARAMETERS (CALCULATED)

2DS/B	.0207	.0207	.0207	.0207
H	1.4457	1.4457	1.4457	1.4457

SIDEWALL BL CORRECTION (MURTHY)

DELTA M	-.0140	-.0140	-.0140	-.0139
D ALPHA	0.0000	0.0000	0.0000	0.0000
M CORR	.5871	.5863	.5870	.5857
CL CORR	-.1384	-.2548	-.4922	-.0234
CD CORR	.007601	.008059	.009599	.007545
AL CORR	-1.0081	-1.9958	-3.9917	.0000

TOP-BOT WALL CORRECTION ONLY

DELTA M	.0026	.0025	.0023	.0026
D ALPHA	.1628	.2516	.4498	.0917
M CORR	.6037	.6027	.6033	.6023
CL CORR	-.1342	-.2473	-.4780	-.0227
CD CORR	.007375	.007823	.009321	.007321
AL CORR	-.8453	-1.7442	-3.5419	.0917

BOTH SIDEWALL & TOP-BOT WALL CORRECTION

DELTA M	.0026	.0024	.0023	.0026
D ALPHA	.1744	.2726	.4904	.0939
M CORR	.5897	.5887	.5893	.5883
CL CORR	-.1374	-.2532	-.4892	-.0232
CD CORR	.007550	.008008	.009541	.007494
AL CORR	-.8337	-1.7233	-3.5013	.0939

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16. Abstract A simplified fourwall interference assessment method has been described, and a computer program developed to facilitate correction of the airfoil data obtained in the Langley 0.3-m Transonic Cryogenic Tunnel (TCT). The procedure adopted is to first apply a blockage correction due to sidewall boundary-layer effects by various methods. The sidewall boundary-layer corrected data are then used to calculate the top and bottom wall interference effects by the method of Capallier, Chevallier and Bouinol, using the measured wall pressure distribution and the model force coefficients. The interference corrections obtained by the present method have been compared with other methods and found to give good agreement for the experimental data obtained in the TCT with slotted top and bottom walls.					
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