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Experimental Verification of a Wall Interference Correction Method with Interface Measurements

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A wall interference assessment and correction method for two-dimensional subsonic wind-tunnel testing is presented. Pressure coefficient and angle-of-attack correction are calculated using velocity measurements on interfaces inside the wind tunnel. A mathematical representation of the test article and tunnel wall boundary conditions is not required. Available experimental data of an NACA 0012 airfoil tested at a Mach number of 0.70 and at two different angle of attack in a solid wall wind tunnel are applied to the method. Blockage corrections are computed and corrected surface pressure coefficients compare favorably to free-air flowfield data if the tunnel flowfield is subsonic. The present wall interference correction method can determine blockage corrections in transonic wind-tunnel flowfields with restrictions. The computed angle-of-attack correction is negligible for the given experimental data.

Nomenclature

c	=	chord length
c_p^*	=	critical pressure coefficient
$c_{p_i}(x, 0)$	=	pressure coefficient correction
Δc_{p_i}	=	error of pressure coefficient correction
$c_{p_T}(x, 0)$	=	pressure coefficient on the centerline of the wind tunnel
$c_{p_T}(x, h_1)$	=	pressure coefficient on first interface
$c_{p_\infty}(x, 0)$	=	pressure coefficient in unconfined flow
h	=	tunnel semiheight
h_1	=	y coordinate of first interface
h_2	=	y coordinate of second interface
l_1, l_2	=	measurement interval boundaries
M	=	Mach number
$u_a(x, y)$	=	antisymmetric axial velocity component
$u_i(x, 0)$	=	axial interference velocity
$u_s(x, y)$	=	symmetric axial velocity component
$u_T(x, y)$	=	axial velocity component in tunnel flowfield
$v_a(x, y)$	=	antisymmetric vertical velocity component
$v_i(x, 0)$	=	vertical interference velocity
$v_s(x, y)$	=	symmetric vertical velocity component
$v_T(x, y)$	=	measured vertical velocity component in the wind tunnel
x	=	x coordinate
y	=	y coordinate
α_i	=	angle-of-attack correction
α_T	=	angle of attack in wind-tunnel flowfield
α_∞	=	angle of attack in unconfined flow
β	=	$\sqrt{1 - M^2}$

Introduction

PRESSURE coefficient and angle-of-attack correction in subsonic wind-tunnel testing can be obtained by a wall interference assessment and correction (WIAC) method which uses interference functions[1-3] in combination with velocity measurements on interfaces.

This method does not require the mathematical modeling of the tunnel wall configuration and the representation of the test article which would be necessary if classical wall interference correction methods are applied.

Wall interference assessment and correction methods based on interference functions were successfully investigated in the past using limited experimental data and numerical flowfield simulations.[1,2] Interference functions appear in the form of one- and two-interface method equations. These equations are based upon velocity measurements on one or two interfaces, respectively. An experimental verification of the suggested WIAC method is urgently needed to gain confidence of the method.

A specific form of interference function based on a two-interface method equation is presented in this article. This function is applicable in solid wall wind tunnels and requires only axial velocity measurements on one interface.

Experimental data[4] of an NACA 0012 airfoil tested at a Mach number of 0.70 and angle-of-attack of 0 and 2 deg are supplied by Harbin Aerodynamic Research Institute, Harbin, China, through the NASA/CAE Wind Tunnel Interference Cooperative Program. Pressure coefficient and angle-of-attack correction are calculated using interface measurements recorded during the wind-tunnel experiment. The pressure coefficient correction is applied to pressure measurements on the test article surface and compared to experimental results in the near free-air flow condition of Amick[5] and Vidal et al.[6]

Interference Prediction

Interference functions in the form of one- and two-interface method equations[1-3] use velocity measurements on interfaces to calculate a wall interference correction on the test article at the centerline of a two-dimensional wind tunnel. Different types of two-interface method equations are conceivable and were investigated in the past. A new type of two-interface method equation is presented which uses measurements of axial velocity components on the first interface and vertical velocity components on the second interface. Figure 1 shows the location of the test article and interfaces inside a wind tunnel.

For a small disturbance subsonic flowfield, c_{p_i} due to wall interference on the tunnel centerline can be calculated. The pressure coefficient on the test article surface in unconfined flow $c_{p_\infty}(x, 0)$ is obtained if the measured pressure coefficient $c_{p_T}(x, 0)$ is corrected as follows:

$$c_{p_\infty}(x, 0) = c_{p_T}(x, 0) - c_{p_i}(x, 0) \tag{1a}$$

where

$$c_{p_i}(x, 0) = -2 \cdot u_i(x, 0) \tag{1b}$$

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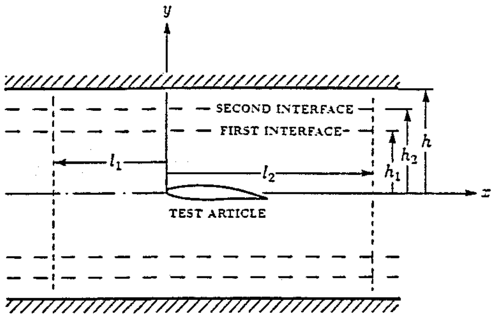

Fig. 1 Location of test article and interfaces in two-dimensional wind tunnel.

The component $u_i(x, 0)$ is given by a corresponding two-interface method equation. This equation is obtained similarly to previous derivations,[2] and has the following form:

$$u_i(x, 0) = \frac{2}{\pi}\cdot\left[\frac{-1}{\beta}\cdot\int_{-\infty}^{\infty} v_s(\eta, h_2)\cdot H_1(\eta)\,\mathrm{d}\eta + \int_{-\infty}^{\infty} u_s(\eta, h_1)\cdot H_2(\eta)\,\mathrm{d}\eta\right] \tag{2a}$$

where

$$v_s(\eta, h_2) = \{[v_T(\eta, h_2) - v_T(\eta, -h_2)]/2\} \tag{2b}$$

$$u_s(\eta, h_1) = \{[u_T(\eta, h_1) + u_T(\eta, -h_1)]/2\} \tag{2c}$$

$$H_1(\eta) = \sum_{k=1}^{\infty} F_1 \tag{2d}$$

$$H_2(\eta) = \sum_{k=1}^{\infty} F_2 \tag{2e}$$

$$F_1 = \frac{(-1)^{k-1}\cdot(x-\eta)}{(x-\eta)^2 + [\beta h_1 + (2k-1)\beta(h_2-h_1)]^2} \tag{2f}$$

$$F_2 = \frac{(-1)^{k-1}\cdot[\beta h_2 + (2k-1)\beta(h_2-h_1)]}{(x-\eta)^2 + [\beta h_2 + (2k-1)\beta(h_2-h_1)]^2} \tag{2g}$$

A solid wall tunnel is now considered and the wall is selected as the second interface. Vertical velocity components on the second interface are practically zero if the boundary layer is uniformly distributed along the wall. The first interface is located outside of the wall boundary layer. Interface location h_2 equals h and Eqs. (2) are simplified as

$$u_i(x, 0) = \frac{2}{\pi}\cdot\int_{-\infty}^{\infty} u_s(\eta, h_1)\cdot H_2(\eta)\,\mathrm{d}\eta \tag{3a}$$

where

$$u_s(\eta, h_1) = [u_T(\eta, h_1) + u_T(\eta, h_1)]/2 \tag{3b}$$

$$H_2(\eta) = \sum_{k=1}^{\infty} F_2 \tag{3c}$$

$$F_2 = \frac{(-1)^{k-1}\cdot[\beta h + (2k-1)\beta(h-h_1)]}{(x-\eta)^2 + [\beta h + (2k-1)\beta(h-h_1)]^2} \tag{3d}$$

An angle-of-attack correction α_i can be calculated if $v_i(x, 0)$ on the tunnel centerline is known. The unconfined flow value of the angle-of-attack α_∞ can be obtained based on the given value of the angle-of-attack α_T in the wind tunnel as follows:

$$\alpha_\infty = \alpha_T - \alpha_i \tag{4a}$$

where

$$\alpha_i \approx \frac{1}{c}\cdot\int_0^c v_i(\eta, 0)\,\mathrm{d}\eta \tag{4b}$$

The vertical interference velocity component $v_i(x, 0)$ can be expressed similar to Eqs. (2). The corresponding two-interface method equation is given as

$$v_i(x, 0) = \frac{2}{\pi}\cdot\left[\int_{-\infty}^{\infty} v_a(\eta, h_2)\cdot L_1(\eta)\,\mathrm{d}\eta + \beta\cdot\int_{-\infty}^{\infty} u_a(\eta, h_1)\cdot L_2(\eta)\,\mathrm{d}\eta\right] \tag{5a}$$

where

$$v_a(\eta, h_2) = [v_T(\eta, h_2) + v_T(\eta, -h_2)]/2 \tag{5b}$$

$$u_a(\eta, h_1) = [u_T(\eta, h_1) - u_T(\eta, -h_1)]/2 \tag{5c}$$

$$L_1(\eta) = \sum_{k=1}^{\infty} G_1 \tag{5d}$$

$$L_2(\eta) = \sum_{k=1}^{\infty} G_2 \tag{5e}$$

$$G_1 = \frac{(-1)^{k-1}\cdot[\beta h_1 + (2k-1)\beta(h_2-h_1)]}{(x-\eta)^2 + [\beta h_1 + (2k-1)\beta(h_2-h_1)]^2} \tag{5f}$$

$$G_2 = \frac{(-1)^{k-1}\cdot(x-\eta)}{(x-\eta)^2 + [\beta h_2 + (2k-1)\beta(h_2-h_1)]^2} \tag{5g}$$

The vertical velocity $v_i(x, 0)$ reduces for a solid wall tunnel to

$$v_i(x, 0) = \frac{2\beta}{\pi}\cdot\int_{-\infty}^{\infty} u_a(\eta, h_1)\cdot L_2(\eta)\,\mathrm{d}\eta \tag{6a}$$

where

$$u_a(\eta, h_1) = [u_T(\eta, h_1) - u_T(\eta, -h_1)]/2 \tag{6b}$$

$$L_2(\eta) = \sum_{k=1}^{\infty} G_2 \tag{6c}$$

$$G_2 = \frac{(-1)^{k-1}\cdot(x-\eta)}{(x-\eta)^2 + [\beta h + (2k-1)\beta(h-h_1)]^2} \tag{6d}$$

The application of Eqs. (3a) and (6a) to experimental data requires the approximation of an improper integral using finite integration limits. In our case, experimental data were taken in the interval (l_1, l_2), and so we get

$$u_i(x, 0) \approx \frac{2}{\pi}\cdot\int_{l_1}^{l_2} u_s(\eta, h_1)\cdot H_2(\eta)\,\mathrm{d}\eta \tag{7a}$$

$$v_i(x, 0) \approx \frac{2\beta}{\pi}\cdot\int_{l_1}^{l_2} u_a(\eta, h_1)\cdot L_2(\eta)\,\mathrm{d}\eta \tag{7b}$$

The interference functions given by Eqs. (3a) and (6a) require only the measurement of axial velocity components on the first interface. Axial velocity components can be measured using a static pipe. This setup was installed in the wind tunnel of Harbin Aerodynamic Research Institute.

Nonlifting Case

In the first part of the experimental study an NACA 0012 airfoil was tested at a Mach number of 0.70 and 0-deg angle

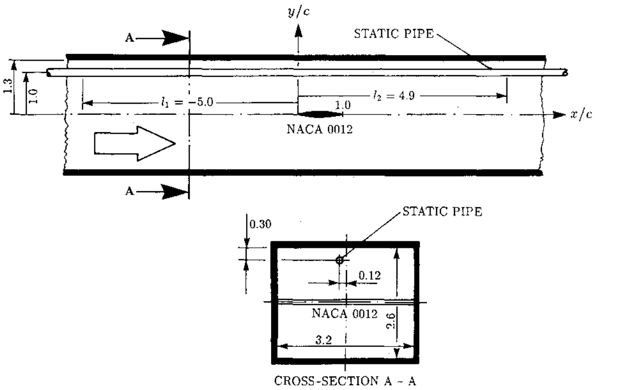

Fig. 2 Geometry of wind tunnel at Harbin Aerodynamic Research Institute.

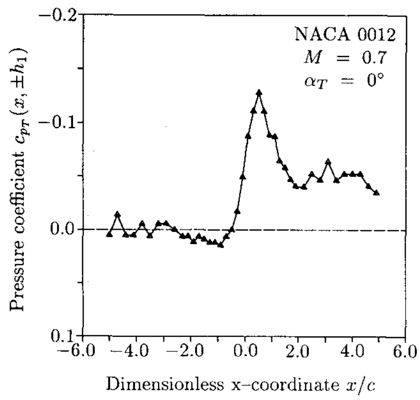

Fig. 3 Pressure coefficient measurement at interface location $h_1(\alpha_T = 0$ deg).

of attack in a wind tunnel of Harbin Aerodynamic Research Institute. Figure 2 shows the geometry of test article and wind tunnel. The model blockage, i.e., the ratio of projected model cross-sectional area to wind-tunnel cross-sectional area, is 4.6% so that substantial wall interference is expected. Pressure coefficients on the surface of the test article are recorded. A static pressure pipe with 41 orifices is installed at a distance of one chord length parallel to the tunnel centerline. The static pipe is located outside of the wall boundary layer, and measures pressure coefficients on the selected interface location.

The influence of the side wall boundary layers on the pressure coefficient measurements is negligible as measurements on the test article surface, and on the interface location are taken close to the plane defined by the middle span of the airfoil as shown in Fig. 2. Top and bottom wall boundary layers seem to be uniformly distributed in the neighborhood of the middle span of the test article location. The velocity component normal to the boundary layer is assumed to be practically zero.

Figure 3 shows recorded pressure coefficients $c_{p_T}(x, h_1)$ on the first interface which are related to axial velocities $u_T(x, h_1)$ as follows:

$$u_T(x, \pm h_1) = c_{p_T}(x, \pm h_1)/-2 \tag{8a}$$

The angle-of-attack α_T equals zero, and the symmetric airfoil is mounted at the tunnel centerline. Therefore, we can assume that

$$u_T(x, h_1) = u_T(x, -h_1) \tag{8b}$$

Combining Eqs. (3b) and (8b), we get

$$u_s(\eta, h_1) = u_T(\eta, h_1) \tag{8c}$$

Combining Eqs. (6b) and (8b), we get

$$u_a(\eta, h_1) = 0.0 \tag{8d}$$

$c_{p_i}(x, 0)$ is calculated based on Eqs. (1b), (3c), (3d), (7a), (8a), and (8c). Table 1 shows results of this calculation.

$c_{p_T}(x, 0)$ on the airfoil surface were recorded as well during testing of a NACA 0012 airfoil at Harbin Aerodynamic Research Institute. Values of $c_{p_T}(x, 0)$ are depicted using the diamond symbol in Fig. 4. The calculated $c_{p_i}(x, 0)$ is applied to these measurements using Eq. (1a). Corrected surface pressures $c_{p_\infty}(x, 0)$ are depicted using the star symbol in Fig. 4. These values compare favorably to data of Amick[5] (circle symbol) and Vidal et al.[6] (square symbol). Amick conducted tests in a wind tunnel where model blockage is 3.3% compared to 4.6% of the tunnel at Harbin Aerodynamic Research Institute. Therefore, less wall interference is expected. Vidal et al.[6] obtained pressure measurements with minimum wall interference effects testing a 6-in. chord NACA 0012 section in the Calspan 8-ft transonic wind tunnel. In this case the model blockage is 0.8%.

Two major sources of error have to be considered if Eqs. (1b) and (3a) are applied to experimental data: 1) errors due to inaccurate velocity measurement on interfaces, and 2) errors due to the approximation of an improper integral using finite integration limits.

An analysis[7] of the present experimental conditions in the vicinity of the test article location has shown that the upper bound of these errors is in the order of the error of pressure coefficient measurement, i.e., Δc_{p_i} ±0.005, on interfaces.

Combining Eqs. (4b), (6c), (6d), (7b), and (8d) we see that $v_i(x, 0)$ is zero anywhere on the tunnel centerline. Therefore, no angle-of-attack correction is necessary.

Table 1 Two-interface method, $\alpha_T = 0$ deg

x/c	$c_{p_i}(x, 0)$
0.0	−0.0377
0.1	−0.0404
0.2	−0.0429
0.3	−0.0451
0.4	−0.0469
0.5	−0.0484
0.6	−0.0494
0.7	−0.0502
0.8	−0.0505
0.9	−0.0506
1.0	−0.0502

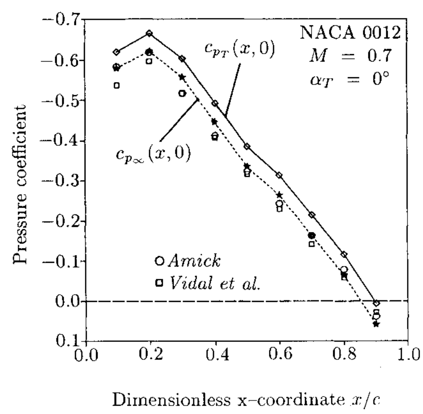

Fig. 4 Comparison of surface pressure measurements $c_{p_T}(x, 0)$ and corrected surface pressure measurements $c_{p_\infty}(x, 0)$ with free-air measurements of Amick[5] and Vidal et al.[6] ($\alpha_T = 0$ deg).

Lifting Case

In the second part of the experimental study an NACA 0012 airfoil was tested at a Mach number of 0.70 and an angle of attack of 2 deg. Model blockage is approximately 6.0% for the given experimental condition.

A single static pressure pipe is used to measure pressure coefficients at the interface location $+h_1$ above the airfoil. Pressure measurements at the interfaces for +2-deg and −2-deg angle of attack are utilized in the following analysis. The interface pressure distribution above the airfoil at $+h_1$ for −2-deg angle of attack is equivalent to the pressure distribution below the airfoil at $-h_1$ for +2-deg angle-of-attack, since the airfoil is symmetric and mounted at the tunnel centerline.

Figure 5 shows recorded pressure coefficients $c_{p_T}(x, \pm h_1)$ on interfaces above and below the airfoil.

$c_{pi}(x, 0)$ is calculated applying Eqs. (1b), (3b–3d), (7a) and (8a) to interface measurements $c_{p_T}(x, \pm h_1)$. Results of this calculation are given in Table 2.

Surface pressure coefficients $c_{p_T}(x, 0)$ are recorded during the Harbin experiment. These values are depicted in Fig. 6 using the square symbol. Computed $c_{p_i}(x, 0)$ are applied to these surface pressure measurements using Eq. (1a) to obtain corrected values $c_{p_\infty}(x, 0)$ (star symbol in Fig. 6).

Vidal et al.[6] tested an NACA 0012 airfoil at a Mach number of 0.65 and an angle of attack of 1.88 deg. Surface pressure coefficients were recorded and the model blockage was 1.0% during their experiment. The Prandtl-Glauert rule is applied to Vidal's measurements to obtain corresponding surface pressure coefficients for a Mach number of 0.70. These corrected values can be used for comparison with the present experimental data. Vidal's data are plotted in Fig. 6 using the circle symbol.

A comparison of pressure coefficients plotted in Fig. 6 shows that corrected results of the Harbin experiment and Vidal's data agree favorably on those model surface locations where the local Mach number is less than one. Small discrepancies between expected and corrected pressure coefficient distribution originate from several different sources: the selected angle of attack is not exactly the same in both experiments, i.e., 2 deg compared to 1.88 deg; the circulation of the airfoil inside of the wind tunnel and in free-air flow is assumed to be identical; errors may be introduced by different manufacturing accuracy of the airfoil model.

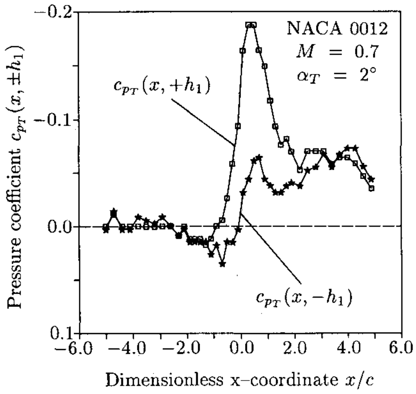

Fig. 5 Pressure coefficient measurement at interface location $\pm h_1(\alpha_T = 2$ deg).

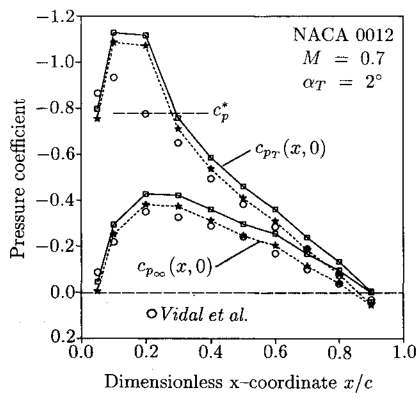

Fig. 6 Comparison of surface pressure measurements $c_{p_T}(x, 0)$ and corrected surface pressure measurements $c_{p_\infty}(x, 0)$ with free-air measurements of Vidal et al.[6] (α_T = 2 deg).

Table 2 Two-interface method, α_T = 2 deg

x/c	$c_{pi}(x, 0)$	$v_i(x, 0)$
0.0	−0.0390	−0.00310
0.1	−0.0419	−0.00254
0.2	−0.0443	−0.00191
0.3	−0.0467	−0.00127
0.4	−0.0485	−0.00062
0.5	−0.0502	+0.00004
0.6	−0.0512	+0.00067
0.7	−0.0522	+0.00130
0.8	−0.0525	+0.00187
0.9	−0.0528	+0.00244
1.0	−0.0526	+0.00292

c_p^* for a Mach number of 0.70 is −0.78. A supersonic pocket obviously existed in the Harbin experiment, considering the original pressure distribution on the upper surface given in Fig. 6. Corrected and expected surface pressures do not agree in this area. These discrepancies come from the fact that Eqs. (2) are derived assuming a subsonic and not a transonic flowfield. The present correction method is obviously not applicable if the local Mach number on the model surface is greater than one. However, experimental results indicate that the present correction technique can still be applied successfully to parts of the model surface where the local Mach number is less than one.

$v_i(x, 0)$ is calculated based on Eqs. (6b–6d), (7b), and (8a) considering only measurements in the interval (l_1, l_2). Results are given in Table 2.

An angle-of-attack correction α_i can be obtained applying Eq. (4b). Based on values given in Table 2, we get that α_i is equal to -1×10^{-5}, rad, or -6×10^{-4}, deg, and is therefore negligible under present conditions.

Conclusions

A two-dimensional subsonic wall interference assessment and correction method is presented which uses interface measurements of axial velocities. Experimental data were used to calculate pressure coefficient and angle-of-attack corrections. Corrected and predicted pressure coefficient on the surface of a test article in subsonic flow compare favorably to verify the method. Experimental results indicate that the present method is applicable to transonic tunnel flowfields, with some restrictions. Testing equipment in existing wind tunnels can easily be modified if the present method is utilized. Only static pipes parallel to the tunnel centerline have to be installed. In the future, it will be necessary to study the lifting case again if additional experimental data are available for the calculation of the angle-of-attack correction.

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