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Lift-interference and blockage corrections for two-dimensional subsonic flow in ventilated and closed wind-tunnels

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LIFT-INTERFERENCE AND BLOCKAGE CORRECTIONS FOR TWO-DIMENSIONAL SUBSONIC FLOW IN VENTILATED AND CLOSED WIND-TUNNELS

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LIFT-INTERFERENCE AND BLOCKAGE CORRECTIONS FOR TWO-DIMENSIONAL SUBSONIC FLOW IN VENTILATED AND CLOSED WIND-TUNNELS

1. NOTATION AND UNITS

		SI	British
A	area of aerofoil section	m^2	ft^2
A_e	equivalent area of aerofoil section (see Section 5.1)	m^2	ft^2
a	width of slot (see Sketch 3.1)	m	ft
b	breadth of tunnel	m	ft
C_D	drag coefficient in constrained flow, $(\text{drag})/\frac{1}{2}\rho_\infty U_\infty^2 c$		
C_L	lift coefficient in constrained flow, $(\text{lift})/\frac{1}{2}\rho_\infty U_\infty^2 c$		
$C_{m^{1/4}}$	pitching-moment coefficient in constrained flow, about quarter-chord axis, $(\text{pitching-moment})/\frac{1}{2}\rho_\infty U_\infty^2 c^2$, positive nose up		
c	chord of aerofoil	m	ft
d	mean periodic spacing of slots (see Equation (3.9))	m	ft
F	slotted-tunnel geometry parameter (see Section 3.3)		
G	ratio of corrected to uncorrected kinetic pressures		
h	height of tunnel	m	ft
K	function defined by Equation (5.19)		
l	aerodynamic loading, $(p_l - p_u)/\frac{1}{2}\rho_\infty U_\infty^2$		
M_∞	Mach number of undisturbed tunnel-stream		
N	effective number of full-width slots (see Section 3.3)		
P	wall porosity parameter (see Section 3.2)		
p	local static pressure	N/m^2	lbf/ft^2
p_∞	static pressure of undisturbed tunnel-stream	N/m^2	lbf/ft^2
δp	pressure drop across ventilated wall	N/m^2	lbf/ft^2
$\partial p/\partial x$	longitudinal pressure gradient due to blockage	N/m^3	lbf/ft^3

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q	dummy variable of integration		
R	Reynolds number of undisturbed tunnel-stream, $\rho_{\infty} U_{\infty}^2 c / \mu_{\infty}$		
T_{∞}	static temperature of undisturbed stream	K	K
t	aerofoil maximum thickness	m	ft
U_{∞}	velocity of undisturbed tunnel-stream	m/s	ft/s
w_i	vertical velocity induced by tunnel walls	m/s	ft/s
w_n	vertical velocity at ventilated walls	m/s	ft/s
x	longitudinal co-ordinate of tunnel	m	ft
x_L	longitudinal co-ordinate of leading edge of aerofoil	m	ft
z	vertical co-ordinate of tunnel	m	ft
α	incidence with respect to tunnel axis (assumed to be direction of undisturbed stream)	radian *	radian *
β	Prandtl-Glauert compressibility parameter, $(1 - M_{\infty}^2)^{1/2}$		
γ	ratio of specific heat capacity at constant pressure to specific heat capacity at constant volume, taken to be 1.4 for air		
Δ	prefix denoting correction increment		
δ_0	lift-interference parameter associated with stream direction		
δ_1	lift-interference parameter associated with streamline curvature		
ε	blockage factor, $\Delta U_{\infty} / U_{\infty}$		
θ	chordwise parameter, see Equation (4.5)	radian	radian
μ_{∞}	viscosity of undisturbed tunnel-stream	kg/m s	slug/ft s
ρ_{∞}	density of undisturbed tunnel-stream	kg/m ³	slug/ft ³
ϕ	perturbation velocity potential	m ² /s	ft ² /s
ϕ_i	perturbation velocity potential induced by tunnel-wall constraints	m ² /s	ft ² /s
ϕ_m	perturbation velocity potential due to model in unconstrained flow	m ² /s	ft ² /s

For footnote see end of Notation Section.

Ω ratio of ventilated-wall to closed-wall values of blockage factors

Subscripts

B denotes total-blockage values

c denotes closed-wall values

f denotes free-air (*i.e.* corrected) values of aerodynamic coefficients based on corrected kinetic pressure, $\frac{1}{2}\rho_{\infty}U_{\infty}^2 + \Delta(\frac{1}{2}\rho_{\infty}U_{\infty}^2)$

l denotes aerofoil lower-surface values

R denotes lift resolution correction values

s denotes solid-blockage values

u denotes aerofoil upper-surface values

* Except where stated as degree

2. INTRODUCTION

This Item gives correction formulae, obtained from Derivation 1, for wind-tunnel flow and model measurements for a two-dimensional aerofoil spanning and centrally placed in a rectangular wind-tunnel with closed, longitudinally-slotted or perforated[†] roof and floor and solid side-walls, when the flow over the aerofoil is wholly subsonic and fully attached.

Such corrections are necessary, as the flow past a model in a wind tunnel is different from that which occurs in free air because of the constraints imposed on the flow by the tunnel walls. Measurements made in the tunnel have therefore to be corrected to free-air values to allow for changes in flow speed, direction and streamwise gradient. For a model that is fairly small compared to the tunnel height, the corrections can be calculated theoretically by first-order linearised potential flow theory, in which the changes to the stream direction and the streamline curvature are referred to as lift interference and the changes in stream velocity and longitudinal gradient are referred to as blockage interference. The lift interference arises from changes induced by the tunnel walls in the circulation or vorticity around the model and is assumed to be independent of the blockage effect, which is associated with changes in the velocity potential of the doublet and source representing the volume occupied by the aerofoil and its wake.

In this Item, as in Derivation 1, the lift interference is treated through the use of the parameter δ_0 , which represents the effect of changes in stream direction, and δ_1 , which represents the effect of changes in stream-line curvature.

The blockage interference is treated in terms of the total blockage factor, ε_B , which is the sum of the solid blockage factor, ε_s , associated with the aerofoil volume, and the wake blockage factor ε_w , associated with the volume of the wake. The streamwise gradient of blockage interference gives rise to a longitudinal

[†] By an array of straight or inclined holes with circular or other cross-sectional shapes or by transverse slots.

buoyancy force on the aerofoil which is allowed for by a correction to the drag if measured by a balance. When ventilated tunnels are used, the solid and wake blockages are expressed as ratios, Ω_s and Ω_w , of the corresponding factors for the closed tunnel.

The functions δ_0 , δ_1 , Ω_s and Ω_w have been evaluated for a systematic variation of two parameters, F and β/P , that represent the characteristics of ventilated walls, and the results are presented graphically. The presentation is more comprehensive than that contained in Derivation 1 and, within the limitations of the theory, tunnel corrections for given wall boundary conditions can be made accurately for a wider range of wall characteristics than has been possible previously.

A comprehensive list of references to the many reports dealing with the wind-tunnel corrections treated in this Item is given in Derivation 1.

3. WALL CONSTRAINTS

3.1 Potential Flow Equations

The theoretical analysis of tunnel corrections is based on potential flow theory in which the perturbation velocity potential, ϕ , of an aerofoil satisfies the linearised differential equation

$$\beta^2 \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial z^2} = 0 \quad (3.1)$$

and the homogeneous wall boundary condition for ventilated walls

$$\frac{\partial \phi}{\partial x^2} \pm \frac{Fh}{2} \frac{\partial^2 \phi}{\partial x \partial z} \pm \frac{1}{P} \frac{\partial \phi}{\partial z} = 0 \quad \text{at} \quad z = \pm \frac{h}{2}, \quad (3.2)$$

as derived in Reference 4. The perturbation velocity potential is written as

$$\phi = \phi_m + \phi_i \quad (3.3)$$

where ϕ_m is the potential of the aerofoil and its wake in the absence of any wall boundary conditions and ϕ_i is the addition necessary to satisfy the boundary condition given by Equation (3.2). The potential ϕ_m comprises a vortex potential to represent lift, a doublet potential to represent the volume of the aerofoil and a source potential to represent the volume of the aerofoil wake. It is the contribution of ϕ_i to each of these three components, evaluated at the aerofoil position, that gives lift-interference, solid-blockage and wake-blockage corrections, respectively. Solving Equations (3.1) to (3.3) for ϕ_i yields the following interference parameters at the model position

$$\delta_0 = \frac{h}{U_\infty c C_L} \frac{\partial \phi_i}{\partial z}, \quad (3.4)$$

$$\delta_1 = \frac{\beta h^2}{U_\infty c C_L} \frac{\partial^2 \phi_i}{\partial x \partial z} \quad (3.5)$$

and
$$\varepsilon_B = \frac{1}{U_\infty} \frac{\partial \phi_i}{\partial x}. \quad (3.6)$$

These depend on the non-dimensional parameters F and P appearing in Equation (3.2), which are discussed in Sections 3.2 to 3.4.

3.2 Perforated Tunnel

For a perforated wall $F = 0$, and the parameter P is a measure of the pressure difference across the wall. To first order in ϕ , and in incompressible flow, the pressure difference is

$$\delta p = -\rho_\infty U_\infty \frac{\partial \phi}{\partial x} = \frac{\rho_\infty U_\infty w_n}{P}, \quad (3.7)$$

where $w_n (= \pm \partial \phi / \partial z \text{ at } z = \pm h/2)$ is the velocity normal to the wall, and the boundary condition is a special case of Equation (3.7). The same value of P is assumed to apply to roof and floor[†].

The value of P for a particular wall can be established experimentally by measuring δp for various values of $\rho_\infty w_n$. The interference parameters and blockage factors are found to be functions of β/P which, to a rough approximation, is generally assumed to be independent of Mach number. In specific cases, however, there may be some variation of β/P with Mach number and some guidance on this point may be obtained from Reference 6.

3.3 Slotted Tunnel

The parameter F is a unique function of the geometry of a slotted tunnel and is defined by

$$^\ddagger F = \frac{2d}{\pi h} \log_e \operatorname{cosec} \left(\frac{\pi a}{2d} \right), \quad (3.8)$$

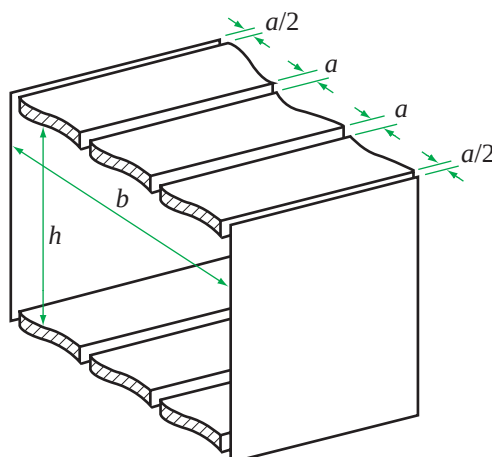
where a is the slot width and d is the mean periodic spacing of the slots. For a tunnel of breadth b with N slots of width a , d is given by

$$d = \frac{b}{N}. \quad (3.9)$$

Slotted tunnels sometimes have half-width slots adjacent to the side walls and in such cases the two half-width slots are considered as a single full-width slot. In Sketch 3.1, for example, there are two slots of width a and two slots of width $a/2$ adjacent to the side walls, so that $N = 3$.

[†] Reference 7 discusses an experiment where different values of P were assigned to roof and floor.

[‡] As noted in Derivation 1, Equation (3.8) was derived assuming vanishingly small slot depth, l . Reference 9 suggests that for attached flow through the slots a further term $2dl/ha$ should be added to F in Equation (3.8). For separated flow this term is omitted and the wall porosity term in Equation (3.2) is introduced to allow for the effects of viscosity.



Sketch 3.1

In practice, the slots of a tunnel are often tapered in the longitudinal direction and the value taken for a should be the slot width at the aerofoil position. Conventionally, the ratio a/d is known as the open area ratio of the tunnel.

For a slotted tunnel, the quantity P appears in the full homogeneous boundary condition to allow for viscous effects in the slots. In the case of an ideal slotted wall, when there are no viscous effects, $P \rightarrow \infty$ and the last term on the left-hand side of Equation (3.2) vanishes.

3.4 Special Cases

It should be noted that for the ideal slotted tunnel ($P \rightarrow \infty$) integration of Equation (3.2) leads to

$$\phi \pm \frac{Fh}{2} \frac{\partial \phi}{\partial z} = 0 \quad \text{at } z = \pm \frac{h}{2}. \quad (3.10)$$

Thus the open-wall condition, $\phi = 0$, is obtained in the limit as $a/d \rightarrow \infty$ and $F = 0$.

The closed-wall condition, $\partial \phi / \partial z = 0$, can be recovered in two ways. It follows from Equation (3.10), for the ideal slotted tunnel as $a/d \rightarrow 0$ and $F \rightarrow \infty$. Alternatively, it is the limiting form of Equation (3.2) as the porosity term dominates and $P \rightarrow 0$.

4. LIFT INTERFERENCE

4.1 General Case of Ventilated Walls

Lift interference induces an upwash velocity, w_i , which varies along the tunnel and necessitates corrections to the aerofoil incidence, loading, lift and pitching moment. The correction to incidence, $\Delta \alpha$, represents the interference upwash at the aerofoil mid-chord and the remaining corrections allow for the residual upwash distribution over the aerofoil.

The incidence correction is given by

$$\Delta\alpha = \left(\frac{c}{h}\right)\delta_0 C_L + \left(\frac{c}{h}\right)^2 \frac{\delta_1}{\beta} \left(\frac{C_L}{4} + C_{m_{1/4}}\right), \quad (4.1)$$

where the first term is associated with the upwash at the aerofoil centre of lift (the location of the lift vortex) and the second term allows for the additional upwash at the half-chord point.

The parameters δ_0 and δ_1 are defined by Equations (3.4) and (3.5) in Section 3.1 and substitution of the appropriate velocity potential ϕ_i yields the following integral solutions in terms of the tunnel-wall parameters F and P (see Derivation 1, Chapter 6),

$$\delta_0 = -\frac{1}{2\pi} \left(\frac{\beta}{P}\right) \int_0^\infty \frac{dq}{(\sinh q + Fq \cosh q)^2 + ((\beta/P) \cosh q)^2}, \quad (4.2)$$

and

$$\delta_1 = -\frac{1}{\pi} \int_0^\infty \frac{[(1-Fq)(\sinh q + Fq \cosh q) - (\beta/P)^2 \cosh q] q e^{-q} dq}{(\sinh q + Fq \cosh q)^2 + ((\beta/P) \cosh q)^2}. \quad (4.3)$$

The choice of $\Delta\alpha$ is such that the residual loading correction, Δl , vanishes at the aerofoil leading-edge and the increment to be added to the measured loading is

$$\Delta l = -2 \left(\frac{c}{h}\right)^2 \frac{\delta_1}{\beta^2} C_L \sin \theta, \quad (4.4)$$

where θ is a parameter used to describe the chordwise distance aft from the leading edge of the aerofoil,

$$x - x_L = \frac{c}{2} (1 - \cos \theta). \quad (4.5)$$

The incremental correction to lift is obtained by integrating Δl along the aerofoil chord, giving

$$\Delta C_L = -\frac{\pi}{2} \left(\frac{c}{h}\right)^2 \frac{\delta_1}{\beta^2} C_L. \quad (4.6)$$

and the incremental correction to pitching moment is obtained by integrating $\Delta l(x_L + 0.25c - x)$ along the aerofoil chord, giving

$$\Delta C_{m_{1/4}} = \frac{\pi}{8} \left(\frac{c}{h}\right)^2 \frac{\delta_1}{\beta^2} C_L = -\frac{\Delta C_L}{4}. \quad (4.7)$$

The lift and pitching-moment coefficients appearing in Equations (4.1), (4.4), (4.6) and (4.7) are uncorrected and based on the uncorrected kinetic pressure, $\frac{1}{2}\rho_\infty U_\infty^2$.

The parameters δ_0 and δ_1 have been calculated from Equations (4.2) and (4.3) by evaluating the integrals numerically (see Derivation 3) for the ranges $0 \leq F \leq 1.2$ and $0 \leq \beta/P \leq 5.0$, and are plotted in Figures 1 and 2 as carpets[†] in F and β/P .

4.2 Particular Wall Conditions

For four particular wall conditions δ_0 and δ_1 can often be expressed in simplified form, as set out below in Table 4.1. Where there is no simple form, the appropriate Figure is referenced.

TABLE 4.1

Wall condition	δ_0	δ_1
Perforated walls ($\beta/P \neq 0, F = 0$)	$-\frac{1}{2\pi} \cot^{-1}\left(\frac{\beta}{P}\right)$	$\frac{\pi}{24} - \frac{1}{2\pi} \left[\cot^{-1}\left(\frac{\beta}{P}\right) \right]^2$
Ideal slotted walls ($\beta/P = 0, F \neq 0$)	$-\frac{1}{4(1+F)}$	Figure 2
Closed walls ($\beta/P \rightarrow \infty, F \rightarrow \infty$)	0	$\frac{\pi}{24}$
Open jet ($\beta/P = 0, F = 0$)	$-\frac{1}{4}$	$-\frac{\pi}{12}$

5. BLOCKAGE EFFECTS

5.1 General Case of Ventilated Walls

The change in longitudinal velocity caused by blockage varies along the tunnel, but for a small aerofoil it is calculated only at the locations of the doublet and source representing ϕ_m , which give rise to solid and wake blockage respectively. Associated with each of these velocity increments there is a streamwise buoyancy force on the aerofoil which would be absent in free air and which necessitates a correction to balance-measured drag-forces, as described in Section 5.4.

The blockage caused by the model and its wake are added to give the total blockage factor

$$\frac{\Delta U_\infty}{U_\infty} = \varepsilon_B = \varepsilon_s + \varepsilon_w. \quad (5.1)$$

For ventilated walls the values of ε_s and ε_w are obtained by factoring the closed-wall blockage factors by the quantities Ω_s and Ω_w , respectively. The total blockage factor can therefore be written as

$$\varepsilon_B = \Omega_s \varepsilon_{sc} + \Omega_w \varepsilon_{wc}. \quad (5.2)$$

The blockage factors are defined by Equation (3.6) in Section 3.1 and substitution of the appropriate velocity potential ϕ_i yields the following results for a closed-wall tunnel,

$$\varepsilon_{sc} = \frac{\pi A_e}{6\beta^3 h^2}, \quad (5.3)$$

[†] The expressions for δ_0 and δ_1 have been evaluated by a different method in Derivation 2 where the integrals are expressed in infinite power series expansions; the values obtained by the numerical integration agree with the power series summations.