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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, (drag)/$\frac{1}{2}\rho_\infty U_\infty^2 c$		
C_L	lift coefficient in constrained flow, (lift)/$\frac{1}{2}\rho_\infty U_\infty^2 c$		
$C_{m\frac{1}{4}}$	pitching-moment coefficient in constrained flow, about quarter-chord axis, (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, $(1-M_\infty^2)^{½}$		
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

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

and the homogeneous wall boundary condition for ventilated walls

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

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

$$\phi = \phi_m + \phi_i \tag{3.3}$$

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

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

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

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

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

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

where w_n $(= \pm\partial\phi/\partial z$ 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 $\rho_\infty \omega_n$. 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

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

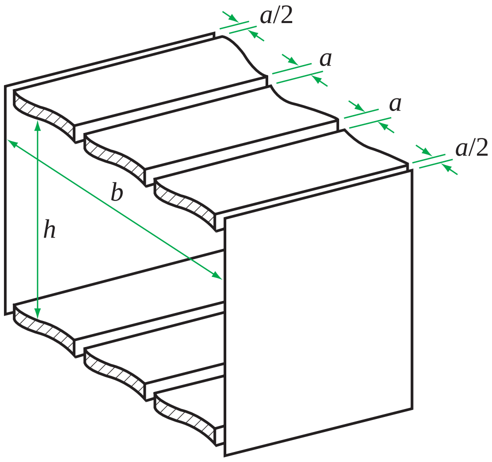
where a is the slot width and d is the mean periodic spacing of the slots. For a tunnel of breadth b with N slots of width a, d is given by

$$d = \frac{b}{N}. \tag{3.9}$$

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, $P \to \infty$ 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 $(P \to \infty)$ integration of Equation (3.2) leads to

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

Thus the open-wall condition, $\phi = 0$, is obtained in the limit as $a/d \to \infty$ 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 $a/d \to 0$ and $F \to \infty$. Alternatively, it is the limiting form of Equation (3.2) as the porosity term dominates and $P \to 0$.

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

$$\Delta\alpha = \left(\frac{c}{h}\right)\delta_0 C_L + \left(\frac{c}{h}\right)^2 \frac{\delta_1}{\beta}\left(\frac{C_L}{4} + C_{m¼}\right), \tag{4.1}$$

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),

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

and

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

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

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

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

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

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

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

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

$$\Delta C_{m¼} = \frac{\pi}{8}\left(\frac{c}{h}\right)^2 \frac{\delta_1}{\beta^2} C_L = -\frac{\Delta C_L}{4}. \tag{4.7}$$

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, $½\rho_\infty U_\infty^2$.

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 $0 \le F \le 1.2$ and $0 \le \beta/P \le 5.0$, 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 ($\beta/P \ne 0,\ F = 0$)	$-\frac{1}{2\pi}\cot^{-1}\left(\frac{\beta}{P}\right)$	$\frac{\pi}{24} - \frac{1}{2\pi}\left[\cot^{-1}\left(\frac{\beta}{P}\right)\right]^2$
Ideal slotted walls ($\beta/P = 0,\ F \ne 0$)	$-\frac{1}{4(1+F)}$	Figure 2
Closed walls ($\beta/P \to \infty,\ F \to \infty$)	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

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

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

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

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,

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

† 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.

where A_e is an equivalent area for the aerofoil section, and

$$\varepsilon_{wc} = \tfrac{1}{4}\left(\frac{c}{h}\right)\frac{C_D}{\beta^2}, \tag{5.4}$$

where, if drag measurements are made by a wake traverse method, C_D is simply the uncorrected drag coefficient based on the uncorrected kinetic pressure $\tfrac{1}{2}\rho_\infty U_\infty^2$, and if drag measurements are made by a balance, C_D is the balance-measured drag coefficient based on the uncorrected kinetic pressure and corrected for stream rotation by the addition of the resolved lift component correction $(c/h)\delta_0 C_L^2$ (see Section 6).

In Derivation 1 it is pointed out that improved agreement with experimental results is obtained if ε_{sc} and ε_{wc} are modified on the basis of more elaborate theories. Thus ε_{sc} contains an incidence effect factor and A_e is replaced by $A[1 + 1.2\beta(t/c)]$, and ε_{wc} contains an extra compressibility factor which multiplies β^{-2}. The recommended formulae for the blockage factors are then

$$\varepsilon_{sc} = \frac{\pi A}{6\beta^3 h^2}\left[1 + 1.2\beta\left(\frac{t}{c}\right)\right]\left[1 + 1.1\left(\frac{c}{t}\right)\alpha^2\right] \tag{5.5}$$

and

$$\varepsilon_{wc} = \tfrac{1}{4}\left(\frac{c}{h}\right)\frac{[1 + 0.4M_\infty^2]}{\beta^2}C_D. \tag{5.6}$$

The blockage factor ratios Ω_s and Ω_w are obtained by substituting the appropriate value of ϕ_i in Equation (3.6) and using Equations (5.2) to (5.4), which gives the following integral solutions in terms of the tunnel-wall parameters F and P,

$$\Omega_s = -\frac{6}{\pi^2}\int_0^\infty \frac{[[1 - F^2q^2 - (\beta/P)^2] + [(1 - Fq)^2 + (\beta/P)^2]e^{-2q}]q\,dq}{(\cosh q + Fq\sinh q)^2 + ((\beta/P)\sinh q)^2}, \tag{5.7}$$

and

$$\Omega_w = -\frac{2}{\pi}\left(\frac{\beta}{P}\right)\int_0^\infty \frac{dq}{(\cosh q + Fq\sinh q)^2 + ((\beta/P)\sinh q)^2}.^{\dagger} \tag{5.8}$$

The parameters Ω_s and Ω_w have been calculated from Equations (5.7) and (5.8) by evaluating the integrals numerically (see Derivation 3) for the ranges $0 \le F \le 1.2$ and $0 \le \beta/P \le 5.0$, and are plotted in Figures 3 and 4 as carpets[‡] in F and β/P.

5.2 Particular Wall Conditions

For four particular wall conditions Ω_s and Ω_w can often be expressed in simplified form, as set out in Table 5.1. Where there is no simple form, the appropriate Figure is referenced.

† It should be noted that Equation (5.8) is not the same as that given in Derivation 1 or in earlier texts. It has been shown in Derivation 2 that an error in the early work on this subject was perpetuated by later workers and that Equation (5.8) is the correct form for Ω_w.

‡ The expressions for Ω_s and Ω_w 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.

TABLE 5.1

Wall condition	Ω_s	Ω_w
Perforated walls ($\beta/P \neq 0$, $F = 0$)	$\frac{6}{\pi^2}[\tan^{-1}(\beta/P)]^2 - ½$	$-\frac{2}{\pi}\tan^{-1}(\beta/P)$
Ideal slotted walls ($\beta/P = 0$, $F \neq 0$)	Figure 3	0
Closed walls (by definition)	1	1
Open jet ($\beta/P = 0$, $F = 0$)	– ½	0

5.3 Corrections to Stream Quantities

Because blockage changes the stream longitudinal velocity, the static pressure, density and static temperature of the stream also change. The incremental corrections to be added to the undisturbed stream values to allow for these changes, and the associated incremental corrections to the derived flow quantities, Mach number, kinetic pressure and Reynolds number, are defined through the following equations,

$$\frac{\Delta U_\infty}{U_\infty} = \varepsilon_B = \frac{\Omega_s \pi A}{6\beta^3 h^2}\left[1 + 1.2\beta\left(\frac{t}{c}\right)\right]\left[1 + 1.1\left(\frac{c}{t}\right)\alpha^2\right] + \frac{\Omega_w}{4}\left(\frac{c}{h}\right)\frac{[1 + 0.4M_\infty^2]C_D}{\beta^2},^{\dagger} \tag{5.9}$$

$$\frac{\Delta p_\infty}{p_\infty} = -1.4M_\infty^2\varepsilon_B \;(\Delta p_\infty = -\rho_\infty U_\infty^2\varepsilon_B \text{ in compressible flow}), \tag{5.10}$$

$$\frac{\Delta\rho_\infty}{\rho_\infty} = -M_\infty^2\varepsilon_B, \tag{5.11}$$

$$\frac{\Delta T_\infty}{T_\infty} = -0.4M_\infty^2\varepsilon_B, \tag{5.12}$$

$$\frac{\Delta M_\infty}{M_\infty} = (1 + 0.2M_\infty^2)\varepsilon_B, \tag{5.13}$$

$$\frac{\Delta(½\rho_\infty U_\infty^2)}{½\rho_\infty U_\infty^2} = (2 - M_\infty^2)\varepsilon_B \tag{5.14}$$

and

$$\frac{\Delta R}{R} = (1 - 0.7M_\infty^2)\varepsilon_B, \tag{5.15}$$

where it has been assumed that $\gamma = 1.4$. The Reynolds number correction involves the further assumption that the viscosity of the stream is proportional to $T_\infty^{0.75}$; in practice $\Delta R/R$ is very small and R is seldom corrected.

† See comment after Equation (5.4) concerning C_D.

5.4 Drag Corrections Due to Blockage Gradients

The variation in longitudinal velocity caused by blockage is not symmetrical forward and aft of the aerofoil mid-chord, and consequently there is a longitudinal buoyancy force on the aerofoil which would be absent in free air. Balance measurements of drag record this buoyancy force and therefore have to be corrected in order to correspond to free-air values by the addition of an incremental coefficient ΔC_{DB} as described below. However, if the aerofoil drag is obtained by wake traverse measurements downstream of the model, this buoyancy correction should not be applied.

The interference pressure gradient due to the longitudinal blockage gradient is

$$\left(\frac{\partial p}{\partial x}\right)_B = -\rho_\infty U_\infty^2\left(\frac{\partial \varepsilon_s}{\partial x} + \frac{\partial \varepsilon_w}{\partial x}\right), \tag{5.16}$$

which leads to an incremental correction to the balance-measured drag coefficient,

$$\Delta C_{DB} = \frac{A_e\left(\frac{\partial p}{\partial x}\right)_B}{½\rho_\infty U_\infty^2 c} = -\frac{2A_e}{c}\left(\frac{\partial \varepsilon_s}{\partial x} + \frac{\partial \varepsilon_w}{\partial x}\right). \tag{5.17}$$

The solid blockage gradient is given by

$$\frac{\partial \varepsilon_s}{\partial x} = \frac{A_e K}{\beta^4 h^3}, \tag{5.18}$$

where

$$K = -\frac{4}{\pi}\left(\frac{\beta}{P}\right)\int_0^\infty \frac{q^2 \mathrm{d}q}{(\cosh q + Fq\sinh q)^2 + ((\beta/P)\sinh q)^2}. \tag{5.19}$$

The wake blockage gradient is closely related to the solid blockage at the model, so that

$$\frac{\partial \varepsilon_w}{\partial x} = \frac{cC_D\varepsilon_s}{2A_e}, \tag{5.20}$$

where C_D is the balance-measured drag coefficient based on the uncorrected stream kinetic pressure, $½\rho_\infty U_\infty^2$, and corrected for stream rotation by the addition of the resolved lift component correction $(c/h)\delta_0 C_L^2$, (see Section 6).

Therefore, from Equation (5.16),

$$\Delta C_{DB} = \frac{-2A_e^2 K}{c\beta^4 h^3} - C_D\varepsilon_s, \tag{5.21}$$

and, substituting for A_e from Equation (5.3), this can be rewritten as

$$\Delta C_{DB} = \frac{-72\beta^2 h\varepsilon_{sc}^2 K}{\pi^2 c} - C_D\Omega_s\varepsilon_{sc}, \tag{5.22}$$

where ε_{sc} is given by Equation (5.5). The function K has been calculated from Equation (5.19) by evaluating the integral numerically for the ranges $0 \le F \le 1.2$ and $0 \le \beta/P \le 5.0$, and is plotted in Figures 5a and 5b as a carpet† in F and β/P.

For a perforated wall $(\beta/P \neq 0,\ F = 0)$, K is given by

$$K = \frac{\pi}{3}\left[1 - \frac{4}{\pi^2}\left[\tan^{-1}\left(\frac{\beta}{P}\right)\right]^2\right]\tan^{-1}\left(\frac{\beta}{P}\right). \tag{5.23}$$

For the ideal (inviscid) slotted wall, the closed wall and the open jet, the solid blockage varies symmetrically about the aerofoil mid-chord and in these three cases the solid-blockage gradient is zero and

$$K = 0. \tag{5.24}$$

5.5 Zero Solid Blockage

One of the advantages of a ventilated tunnel is that a suitable choice of slotted-tunnel and porosity parameters can result in zero solid blockage. From Equation (5.7) it is possible to relate F and β/P at $\Omega_s = 0$ for tunnel-wall conditions varying from the ideal slotted wall $(\beta/P = 0)$ to the perforated wall ($F = 0$). This relationship has been evaluated numerically in Derivation 2, in which the integral was expressed in terms of infinite power series expansions, and the results are reproduced in Figure 6 where F is plotted against β/P for $\Omega_s = 0$. As F is a given function of the tunnel geometry, the value of the porosity parameter P can be estimated from Figure 6 if a tunnel operating condition is known to correspond to zero solid blockage. References 5 and 8 discuss how this condition may be determined experimentally.

At $\Omega_s = 0$ the drag correction due to the wake blockage gradient vanishes from Equation (5.22). The drag contribution from the solid blockage gradient is still present, however, and is important because it happens that $\partial\varepsilon_s/\partial x$ increases as ε_s tends to zero.

6. CORRECTION OF AERODYNAMIC COEFFICIENTS

The lift-interference and blockage effects have been considered separately in Sections 4 and 5 and their interaction needs to be treated with care.

The interference correction to balance-measured drag coefficients differs in two respects from the procedure for correcting drag coefficients determined by wake traverse. The drag force recorded by the balance includes the longitudinal buoyancy force and requires the correction ΔC_{DB}, as described in Section 5.4, and there is also a resolved component of lift due to the change in streamwise direction at the centre of lift which requires the incremental correction

$$\Delta C_{DR} = \left(\frac{c}{h}\right)\delta_0 C_L^2, \tag{6.1}$$

where C_L is the uncorrected lift coefficient based on the uncorrected stream kinetic pressure. Neither of these corrections applies when the drag force is obtained by wake traverse.

It is recommended that the aerodynamic coefficients determined from tunnel measurements and based on the uncorrected stream kinetic pressure are corrected to free-air values by

† The expressions for K 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.

(i) adding to the measured values, of l, C_L and $C_{m¼}$, the lift-interference corrections Δl, ΔC_L and $\Delta C_{m¼}$ (Equations (4.4), (4.6) and (4.7)) and, in the case of balance measurements of drag only, adding to C_D the corrections ΔC_{DB} (Equation (5.22)) and ΔC_{DR} (Equation (6.1))

(ii) and then factoring the results by G, the ratio of the uncorrected kinetic pressure to the corrected kinetic pressure.

The free-air values of aerodynamic coefficients, based on the corrected kinetic pressure, are then given by

$$(l)_f = (l + \Delta l)G, \tag{6.2}$$

$$(C_L)_f = (C_L + \Delta C_L)G, \tag{6.3}$$

$$(C_{m¼})_f = (C_{m¼} + \Delta C_{m¼})G, \tag{6.4}$$

and $$(C_D)_f = C_D G \quad \text{(for wake traverse measured drag coefficients)}, \tag{6.5}$$

or $$(C_D)_f = (C_D + \Delta C_{DB} + \Delta C_{DR})G \quad \text{(for balance-measured drag coefficients)} \tag{6.6}$$

where $$G = \frac{½\rho_\infty U_\infty^2}{½\rho_\infty U_\infty^2 + \Delta(½\rho_\infty U_\infty^2)} = \frac{1}{1 + (2 - M_\infty^2)\varepsilon_B}, \tag{6.7}$$

and ε_B is given by Equation (5.9).

The corrected coefficients are appropriate to a free-air incidence $\alpha + \Delta\alpha$ and to a free-air Mach number $M_\infty + \Delta M_\infty$, where $\Delta\alpha$ is obtained from Equation (4.1) and ΔM_∞ from Equation (5.13).

7. APPLICABILITY

The interference and blockage factors that are presented apply to a two-dimensional aerofoil spanning and centrally placed in a rectangular wind-tunnel with closed, slotted or perforated roof and floor and solid side walls.

Most of the equations presented are derived by linearised potential flow theory and the resulting interference corrections apply only to attached, subcritical flow. In practice they are used over the whole range of conditions in two-dimensional tunnel tests where $M_\infty < 1$, even for slightly supercritical flow or flow with some degree of separation, but in these conditions they should clearly be used with caution.

The equations are also limited, by the theory, to cases where the aerofoil chord is fairly small compared to tunnel height. They are, however, commonly used for values of c/h up to 0.35.

In practice, it is difficult to establish a precise value of the parameter β/P and it is shown in Derivation 3 that the possible error in correcting measured values of lift-curve slope, for example, can be significant due to uncertainty in the value of β/P to be used in Figures 1 to 5. It is particularly important that the value taken for β/P should be as accurate as possible when β/P is less than about 1.5 as some of the curves presented in Figures 1 to 5 vary rapidly in this region.

8. DERIVATION AND REFERENCES

Derivation

The Derivation lists selected sources that have assisted in the preparation of this Item.

1.	GARNER, H.C. ROGERS, E.W.E. ACUM, W.E.A. MASKELL, E.C.	Subsonic wind-tunnel wall corrections. AGARDograph 109, NATO, October 1966.
2.	CATHERALL, D.	On the evaluation of wall interference in two-dimensional ventilated wind tunnels by subsonic linear theory. RAE tech. Rep. 76134, 1976.
3.	BLOCKLEY, R.H. HODGES, M.D.	Comparisons between selected experimental data and current first-order viscous theory for subcritical viscous flow over two-dimensional aerofoils. S&T Memo -2-78 (BR 65595), 1978.

References

The References are sources of information supplementary to that in this Item.

4.	BALDWIN, B.S. TURNER, J.B. KNECHTEL, E.D.	Wall interference in wind tunnels with slotted and porous boundaries at subsonic speeds. NACA tech. Note 3176, 1954.
5.	PEARCE, H.H. SINNOTT, C.S. OSBORNE, J.	Some effects of wind-tunnel interference observed in tests on two-dimensional aerofoils at high subsonic and transonic speeds. AGARD Rep. 296, March 1959.
6.	GOETHERT, B.H.	Transonic wind tunnel testing. AGARDograph 49, Pergamon Press, 1961.
7.	MOKRY, M. PEAKE, D.J. BOWKER, A.J.	Wall interference on two-dimensional supercritical airfoils, using wall pressure measurements to determine the porosity factors for tunnel floor and ceiling. NRC Aero Rep. LR 575, February 1974.
8.	LOCK, R.C.	A proposal for co-operative aerofoil tests in Commonwealth transonic wind tunnels. CAARC, C.C. 729 Tech. 30, March 1975.
9.	BERNDT, S.B. SÖRENSÉN, H.	Flow properties of slotted walls for transonic test sections. Paper 17 in wind-tunnel design and testing techniques. AGARD CP-174, October 1975.

9. EXAMPLE

An aerofoil has been tested in three two-dimensional tunnels with solid side-walls and, respectively, slotted, perforated and closed roof and floor. The slotted tunnel operated at two conditions, the ideal condition (*i.e.* no viscous effects in the slots), and the zero solid-blockage condition $(\Omega_s = 0)$. The porosity parameter for the perforated tunnel was the same as that of the slotted tunnel at $(\Omega_s = 0)$. The lift, pitching-moment and drag coefficients were measured at two Mach numbers, $M_\infty = 0.75$ and $M_\infty = 0.40$, and two geometric incidences, $\alpha = 2.0°$ and $\alpha = -1.0°$. The drag coefficient was measured by a wake-traverse method. Compare the corrections required in each case to convert the measured data (given in Tables 9.1 to 9.4) to free-air values.

[*As the calculation procedure is similar in all cases, the evaluation of corrected values is presented in detail for only a single case and the results are tabulated for the remainder.*]

9.1 Correction of Data at $M_\infty = 0.75$, $\alpha = 2.0°$ for the Ideal Slotted Tunnel ($\beta/P = 0$)

Tunnel Geometry and Wall Parameters

The slotted tunnel has a height, h, of 0.45 m, a breadth, b, of 0.40 m and four slots of width $a = 1.4 \times 10^{-3}$ m.

The aerofoil has a chord, c, of 0.130 m, a section area, A, of 1.58×10^{-3} m^2 and a thickness chord ratio, t/c of 0.14.

The set of measured values to be corrected are $M_\infty = 0.75$, $\alpha = 2.0°$, $C_L = 0.331$, $C_{m_{1/4}} = 0.0374$ and $C_D = 7.97 \times 10^{-3}$.

Equation (3.9) gives the mean periodic spacing of the slots

$$d = \frac{b}{N} = \frac{0.40}{4} = 0.10 \text{ m},$$

and Equation (3.8) gives the slotted-tunnel geometry parameter

$$F = \frac{2d}{\pi h} \log_e \operatorname{cosec}\left(\frac{\pi a}{2d}\right) = \frac{2 \times 0.10}{\pi \times 0.45} \log_e \operatorname{cosec}\left(\frac{\pi \times 1.4 \times 10^{-3}}{2 \times 0.10}\right) = 0.540.$$

As the tunnel is assumed ideal, $\beta/P = 0$ (but also note from Figure 6 that with $F = 0.540$ the tunnel has zero solid blockage when $\beta/P = 1.09$).

Lift Interference

At $M_\infty = 0.75$, $\beta = (1 - M_\infty^2)^{1/2} = (1 - 0.75^2)^{1/2} = 0.661$.

The parameter δ_0 is obtained from Table 4.1 for an ideal tunnel, so

$$\delta_0 = \frac{-1}{4(1+F)} = \frac{-1}{4(1+0.540)} = -0.162.$$

The parameter δ_1 is obtained from Figure 2 with $\beta/P = 0$ and $F = 0.540$, giving

$$\delta_1 = -0.098.$$

The lift-interference corrections to α, C_L and $C_{m_{1/4}}$ are given by Equations (4.1), (4.6) and (4.7), as follows

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

$$= \frac{0.130}{0.45} \times (-0.162) \times 0.331 + \left(\frac{0.130}{0.45}\right)^2 \frac{(-0.098)}{0.661}\left(\frac{0.331}{4} + 0.0374\right)$$

$$= -0.0170 \text{ radians } (-0.973 \text{ degrees}),$$

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

$$= -\frac{\pi}{2}\left(\frac{0.130}{0.45}\right)^2 \frac{(-0.098)}{0.661^2} 0.331$$

$$= 9.73 \times 10^{-3},$$

and

$$\Delta C_{m\frac{1}{4}} = -\frac{\Delta C_L}{4}$$

$$= -\frac{9.73}{4} \times 10^{-3} = -2.43 \times 10^{-3}.$$

Blockage Effects

The closed-wall blockage factors are given by Equations (5.5) and (5.6),

$$\varepsilon_{sc} = \frac{\pi A}{6\beta^3 h^2}\left[1 + 1.2\beta\left(\frac{t}{c}\right)\right]\left[1 + 1.1\left(\frac{c}{t}\right)\alpha^2\right]$$

$$= \frac{\pi \times 1.58 \times 10^{-3}}{6 \times 0.661^3 \times 0.45^2}\left[1 + 1.2 \times 0.661 \times 0.14\right]\left[1 + 1.1 \times \left(\frac{1}{0.14}\right)\left(\frac{2.0}{57.3}\right)^2\right]$$

$$= 0.0159,$$

and

$$\varepsilon_{wc} = \frac{1}{4}\left(\frac{c}{h}\right)\frac{[1 + 0.4M_\infty^2]C_D}{\beta^2}$$

$$= \frac{1}{4}\left(\frac{0.130}{0.45}\right)\frac{[1 + 0.4 \times 0.75^2]}{0.661^2} 7.97 \times 10^{-3}$$

$$= 0.00161.$$

The blockage-factor ratio Ω_s is obtained from Figure 3 with $\beta/P = 0$ and $F = 0.540$, giving

$$\Omega_s = -0.18,$$

and Ω_w is obtained from Table 5.1 for a ideal slotted tunnel, so

$$\Omega_w = 0.$$

Thus, from Equation (5.2)

$$\varepsilon_B = \Omega_s \varepsilon_{sc} + \Omega_w \varepsilon_{wc}$$

$$= -0.18 \times 0.0159 + 0 \times 0.00161$$

$$= -2.86 \times 10^{-3}.$$

The correction to the test Mach number is obtained from Equation (5.13)

$$\frac{\Delta M_\infty}{M_\infty} = (1 + 0.2 M_\infty^2)\varepsilon_B ,$$

so

$$\Delta M_\infty = (1 + 0.2 \times 0.75^2)(-2.86 \times 10^{-3}) \times 0.75$$
$$= -2.39 \times 10^{-3} .$$

The ratio of corrected to uncorrected kinetic pressures, G, is obtained from Equation (6.7),

$$G = \frac{1}{1 + (2 - M_\infty^2)\varepsilon_B}$$
$$= \frac{1}{1 + (2 - 0.75^2)(-2.86 \times 10^{-3})}$$
$$= 1.0041.$$

As the aerofoil drag was measured by a wake traverse method there is no correction to C_D due to longitudinal buoyancy or resolved lift component.

Correction of Measured Data to Free-air Values

The free-air values corresponding to the set of measured values at $M_\infty = 0.75$, $\alpha = 2.0°$ are given by Equations (6.3), (6.4) and (6.5),

$$(C_L)_f = (C_L + \Delta C_L)G$$
$$= (0.331 + 9.73 \times 10^{-3})1.0041$$
$$= 0.342,$$

$$(C_{m1/4})_f = (C_{m1/4} + \Delta C_{m1/4})G$$
$$= (0.0374 - 2.43 \times 10^{-3})1.0041$$
$$= 0.0351,$$

and

$$(C_D)_f = C_D G$$
$$= 7.97 \times 10^{-3} \times 1.0041$$
$$= 8.00 \times 10^{-3} ,$$

and these corrected values are appropriate to a free-air incidence

$$\alpha + \Delta\alpha = 2.0 - 0.973 = 1.027 \text{ degrees}$$

and a free-air Mach number

$$M_\infty + \Delta M_\infty = 0.75 - 2.39 \times 10^{-3} = 0.748 .$$

9.2 Comparison of Tunnel Corrections

The correction of data at other Mach numbers and incidences, and for the different tunnels, follows the method set out above and the results are summarised in Tables 9.1 to 9.4. In order to appreciate the relative magnitudes of corrections in different tunnels and at different Mach numbers it is instructive to study the lift-curve slope, $\partial C_L/\partial\alpha$, and the aerodynamic centre, $\partial C_{m1/4}/\partial C_L$, of the aerofoil in free air and constrained flow. These parameters are evaluated in the Tables and are contrasted in Sketches 9.1 and 9.2. It may be noted that the closed wall tunnel gives a lift-curve slope higher than the free-air values whereas all the ventilated tunnels give lift-curve slopes less than the free-air value.

TABLE 9.1 Ideal Slotted Tunnel

Tunnel properties		*Aerofoil geometry*		*Lift-interference and blockage parameters*		
h	0.45 m	c	0.130 m	δ_0	(Table 4.1)	–0.162
b	0.40 m	A	1.58×10^{-3} m^2	δ_1	(Figure 2)	–0.098
F	(Equation (3.8)) 0.540	t/c	0.14	Ω_s	(Figure 3)	–0.18
β/P	0			Ω_w	(Table 5.1)	0

MEASURED VALUES

M_∞	0.75		0.40	
α (degrees)	2.0	–1.0	2.0	–1.0
C_L	0.331	0.000	0.265	0.000
$C_{m1/4}$	0.0374	0.0350	0.0360	0.0350
C_D	7.97×10^{-3}	7.97×10^{-3}	7.48×10^{-3}	7.48×10^{-3}
$\partial C_L/\partial\alpha$ (per radian)	6.32		5.06	
$\partial C_{m1/4}/\partial C_L$	7.25×10^{-3}		3.77×10^{-3}	

BLOCKAGE FACTORS

ε_{sc}	(Equation (5.5))	0.0159	0.0158	0.00617	0.00613
ε_{wc}	(Equation (5.6))	0.00161	0.00161	6.84×10^{-4}	6.84×10^{-4}
ε_B	(Equation (5.2))	-2.86×10^{-3}	-2.84×10^{-3}	-1.11×10^{-3}	-1.10×10^{-3}
G	(Equation (6.7))	1.0041	1.0041	1.0020	1.0020

CORRECTIONS

ΔM_∞	(Equation (5.13))	-2.39×10^{-3}	-2.37×10^{-3}	-4.58×10^{-4}	-4.54×10^{-4}
$\Delta\alpha$ (degrees)	(Equation (4.1))	–0.973	–0.0248	–0.763	–0.0179
ΔC_L	(Equation (4.6))	0.00973	0.000	0.00405	0.000
$\Delta C_{m1/4}$	(Equation (4.7))	–0.00243	0.000	–0.00101	0.000

FREE-AIR VALUES

$M_\infty + \Delta M_\infty$		0.748		0.400	
$\alpha + \Delta\alpha$ (degrees)		1.027	–1.0248	1.237	–1.0179
$(C_L)_f$	(Equation (6.3))	0.342	0.000	0.270	0.000
$(C_{m1/4})_f$	(Equation (6.4))	0.0351	0.0351	0.0351	0.0351
$(C_D)_f$	(Equation (6.5))	8.00×10^{-3}	8.00×10^{-3}	7.49×10^{-3}	7.49×10^{-3}
$(\partial C_L/\partial\alpha)_f$ (per radian)		9.55		6.86	
$(\partial C_{m1/4}/\partial C_L)_f$		0		0	

TABLE 9.2 Slotted Tunnel at $\Omega_s = 0$

Tunnel properties		*Aerofoil geometry*		*Lift-interference and blockage parameters*		
h	0.45 m	c	0.130 m	δ_0	(Figure 1)	–0.093
b	0.40 m	A	1.58×10^{-3} m^2	δ_1	(Figure 2)	0.040
F	(Equation (3.8)) 0.540	t/c	0.14	Ω_s	(Figure 3 (or 6))	0
β/P	1.09			Ω_w	(Figure 4)	–0.435

MEASURED VALUES

M_∞	0.75		0.40	
α (degrees)	2.0	–1.0	2.0	–1.0
C_L	0.404	0.000	0.307	0.000
$C_{m1/4}$	0.0338	0.0350	0.0345	0.0350
C_D	7.99×10^{-3}	7.99×10^{-3}	7.50×10^{-3}	7.50×10^{-3}
$\partial C_L/\partial\alpha$ (per radian)	7.72		5.86	
$\partial C_{m1/4}/\partial C_L$	-2.97×10^{-3}		-1.63×10^{-3}	

BLOCKAGE FACTORS

ε_{sc}	(Equation (5.5))	0.0159	0.0158	0.00617	0.00613
ε_{wc}	(Equation (5.6))	0.00162	0.00162	0.000685	0.000685
ε_B	(Equation (5.2))	-7.05×10^{-4}	-7.05×10^{-4}	-2.98×10^{-4}	-2.98×10^{-4}
G	(Equation (6.7))	1.0010	1.0010	1.0005	1.0005

CORRECTIONS

ΔM_∞	(Equation (5.13))	-5.88×10^{-4}	-5.88×10^{-4}	-1.23×10^{-4}	-1.23×10^{-4}
$\Delta\alpha$ (degrees)	(Equation (4.1))	–0.583	0.0101	–0.449	0.00730
ΔC_L	(Equation (4.6))	–0.00485	0.000	–0.00191	0.000
$\Delta C_{m1/4}$	(Equation (4.7))	0.00121	0.000	0.00479	0.000

FREE-AIR VALUES

$M_\infty + \Delta M_\infty$		0.749		0.400	
$\alpha + \Delta\alpha$ (degrees)		1.417	–0.990	1.551	–0.993
$(C_L)_f$	(Equation (6.3))	0.400	0.000	0.305	0.000
$(C_{m1/4})_f$	(Equation (6.4))	0.0350	0.0350	0.0350	0.0350
$(C_D)_f$	(Equation (6.5))	8.00×10^{-3}	8.00×10^{-3}	7.50×10^{-3}	7.50×10^{-3}
$(\partial C_L/\partial\alpha)_f$ (per radian)		9.52		6.87	
$(\partial C_{m1/4}/\partial C_L)_f$		0		0	

TABLE 9.3 Perforated Tunnel

Tunnel properties		*Aerofoil geometry*		*Lift-interference and blockage parameters*		
h	0.45 m	c	0.130 m	δ_0	(Table 4.1)	–0.118
b	0.40 m	A	1.58×10^{-3} m^2	δ_1	(Table 4.1)	0.0432
F	(Section 3.2) 0	t/c	0.14	Ω_s	(Table 5.1)	–0.0828
β/P	1.09			Ω_w	(Table 5.1)	–0.527

MEASURED VALUES

M_∞	0.75		0.40	
α (degrees)	2.0	–1.0	2.0	–1.0
C_L	0.384	0.000	0.295	0.000
$C_{m^1\!/_4}$	0.0337	0.0349	0.0345	0.0350
C_D	7.98×10^{-3}	7.98×10^{-3}	7.49×10^{-3}	7.49×10^{-3}
$\partial C_L/\partial\alpha$ (per radian)	7.33		5.63	
$\partial C_{m^1\!/_4}/\partial C_L$	-3.13×10^{-3}		-1.69×10^{-3}	

BLOCKAGE FACTORS

ε_{sc}	(Equation (5.5))	0.0159	0.0158	0.00617	0.00613
ε_{wc}	(Equation (5.6))	0.00162	0.00162	0.000684	0.000684
ε_B	(Equation (5.2))	-2.17×10^{-3}	-2.16×10^{-3}	-8.71×10^{-4}	-8.68×10^{-4}
G	(Equation (6.7))	1.0031	1.0031	1.0016	1.0016

CORRECTIONS

ΔM_∞	(Equation (5.13))	-1.81×10^{-3}	-1.80×10^{-3}	-3.60×10^{-4}	-3.58×10^{-4}
$\Delta\alpha$ (degrees)	(Equation (4.1))	–0.709	0.0109	–0.552	0.00788
ΔC_L	(Equation (4.6))	–0.00497	0.000	–0.00199	0.000
$\Delta C_{m^1\!/_4}$	(Equation (4.7))	0.00124	0.000	0.000498	0.000

FREE-AIR VALUES

$M_\infty + \Delta M_\infty$		0.748		0.400	
$\alpha + \Delta\alpha$ (degrees)		1.291	–0.989	1.448	–0.992
$(C_L)_f$	(Equation (6.3))	0.380	0.000	0.293	0.000
$(C_{m^1\!/_4})_f$	(Equation (6.4))	0.0350	0.0350	0.0351	0.0351
$(C_D)_f$	(Equation (6.5))	8.00×10^{-3}	8.00×10^{-3}	7.50×10^{-3}	7.50×10^{-3}
$(\partial C_L/\partial\alpha)_f$ (per radian)		9.55		6.88	
$(\partial C_{m^1\!/_4}/\partial C_L)_f$		0		0	

TABLE 9.4 Closed Tunnel

Tunnel properties		*Aerofoil geometry*		*Lift-interference and blockage parameters*		
h	0.45 m	c	0.130 m	δ_0	(Table 4.1)	0
b	0.40 m	A	1.58×10^{-3} m^2	δ_1	(Table 4.1)	0.131
F	(Section 3.4)	t/c	0.14	Ω_s	(Table 5.1)	1
β/P	$\beta/P \to \infty$ or $F \to \infty$			Ω_w	(Table 5.1)	1

MEASURED VALUES

M_∞	0.75		0.40	
α (degrees)	2.0	–1.0	2.0	–1.0
C_L	0.557	0.000	0.381	0.000
$C_{m_{1/4}}$	0.0304	0.0359	0.0335	0.0354
C_D	8.21×10^{-3}	8.21×10^{-3}	7.59×10^{-3}	7.59×10^{-3}
$\partial C_L/\partial\alpha$ (per radian)	10.64		7.28	
$\partial C_{m_{1/4}}/\partial C_L$	-9.87×10^{-3}		-4.99×10^{-3}	

BLOCKAGE FACTORS

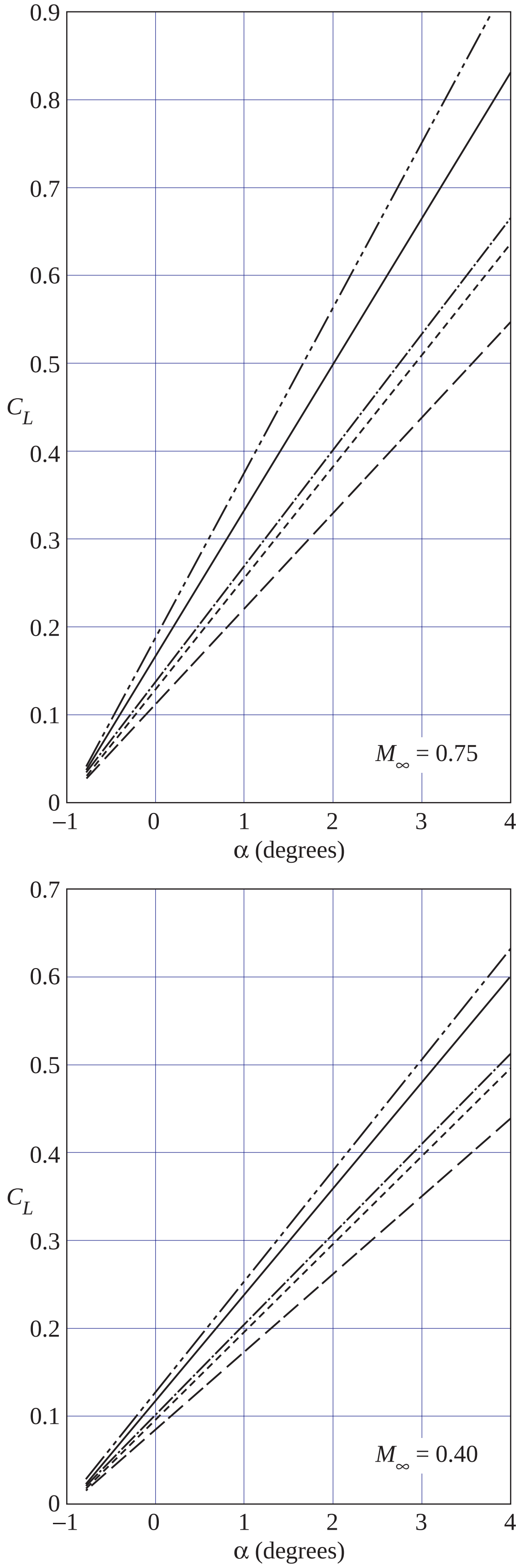
ε_{sc}	(Equation (5.5))	0.0159	0.0158	0.00617	0.00613
ε_{wc}	(Equation (5.6))	0.00166	0.00166	0.000694	0.000694
ε_B	(Equation (5.2))	1.76×10^{-2}	1.75×10^{-2}	6.86×10^{-3}	6.82×10^{-3}
G	(Equation (6.7))	0.9753	0.9755	0.9875	0.9876

CORRECTIONS

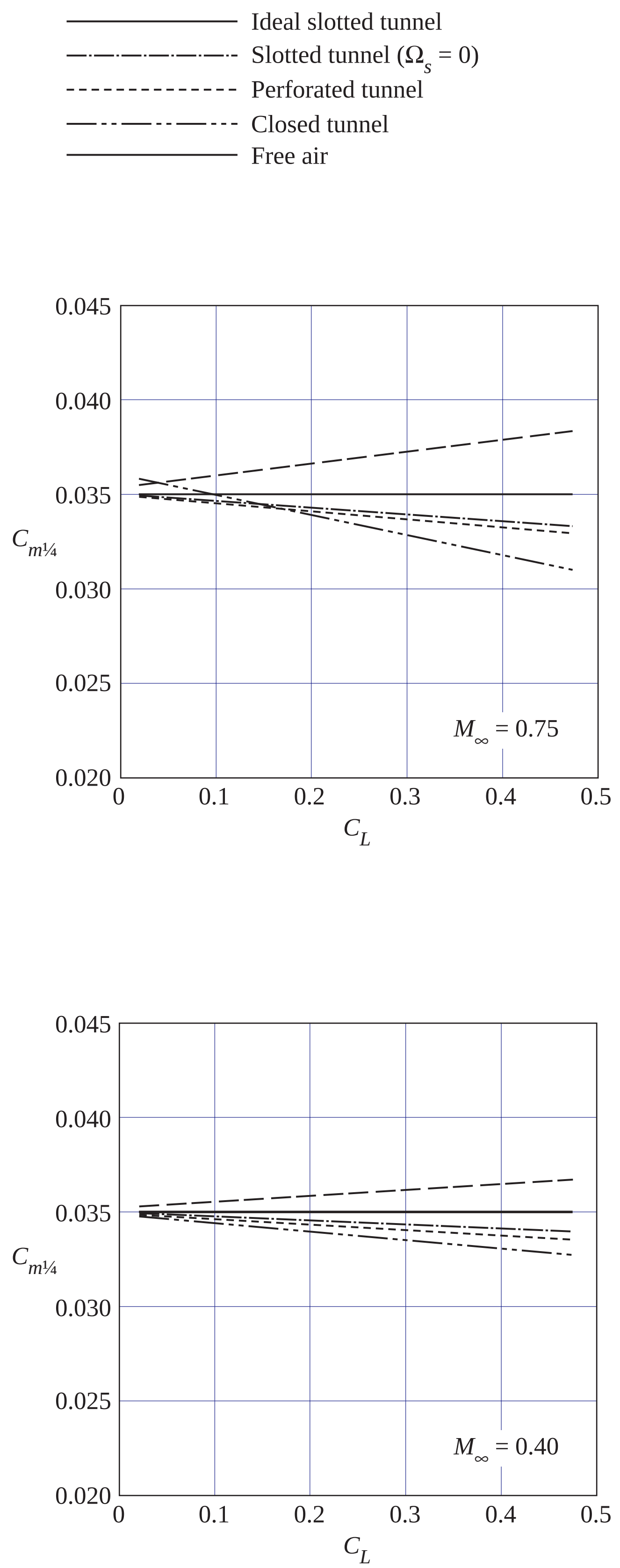
ΔM_∞	(Equation (5.13))	1.47×10^{-2}	1.46×10^{-2}	2.83×10^{-3}	2.82×10^{-3}
$\Delta\alpha$ (degrees)	(Equation (4.1))	0.161	0.0340	0.0880	0.0242
ΔC_L	(Equation (4.6))	–0.0219	0.000	–0.00778	0.000
$\Delta C_{m_{1/4}}$	(Equation (4.7))	0.00548	0.000	0.00195	0.000

FREE-AIR VALUES

$M_\infty + \Delta M_\infty$		0.765		0.403	
$\alpha + \Delta\alpha$ (degrees)		2.161	–0.966	2.088	–0.976
$(C_L)_f$	(Equation (6.3))	0.522	0.000	0.369	0.000
$(C_{m_{1/4}})_f$	(Equation (6.4))	0.0350	0.0350	0.0350	0.0350
$(C_D)_f$	(Equation (6.5))	8.01×10^{-3}	8.01×10^{-3}	7.50×10^{-3}	7.50×10^{-3}
$(\partial C_L/\partial\alpha)_f$ (per radian)		9.57		6.90	
$(\partial C_{m_{1/4}}/\partial C_L)_f$		0		0	



Sketch 9.1 Comparison of lift-curve slopes



Sketch 9.2 Comparison of aerodynamic centres

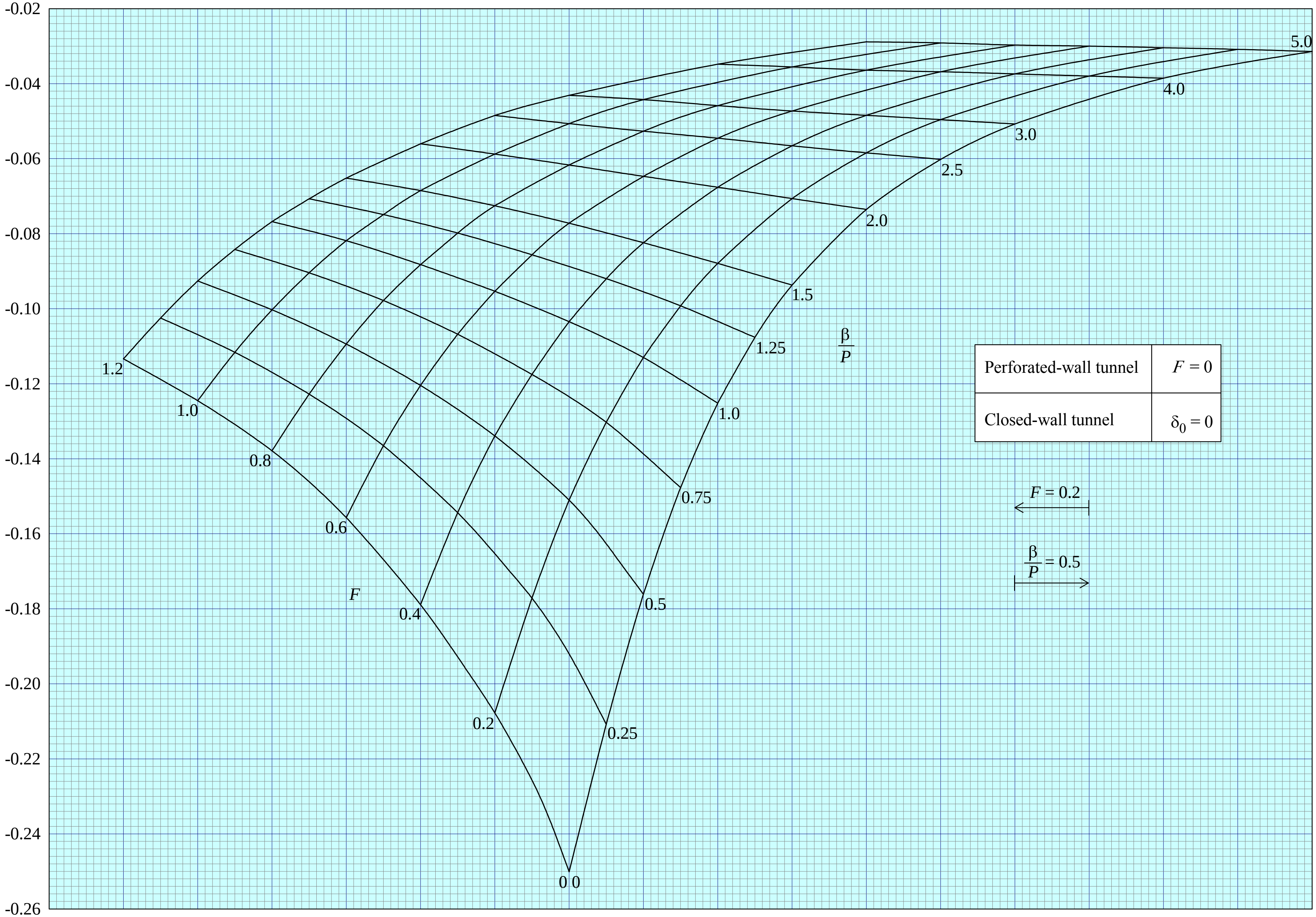


FIGURE 1 LIFT INTERFERENCE PARAMETER δ_0

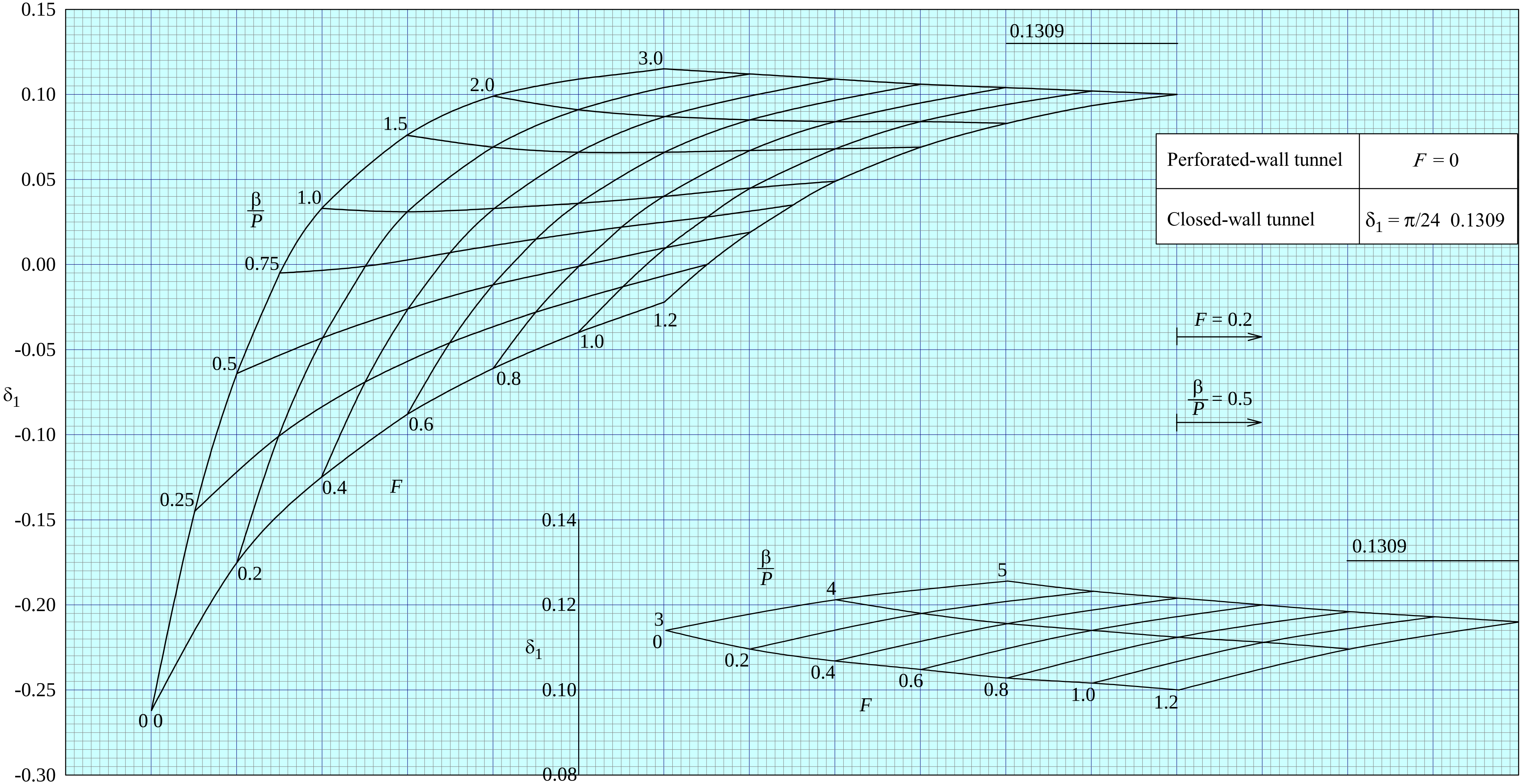


FIGURE 2 LIFT INTERFERENCE PARAMETER δ_1

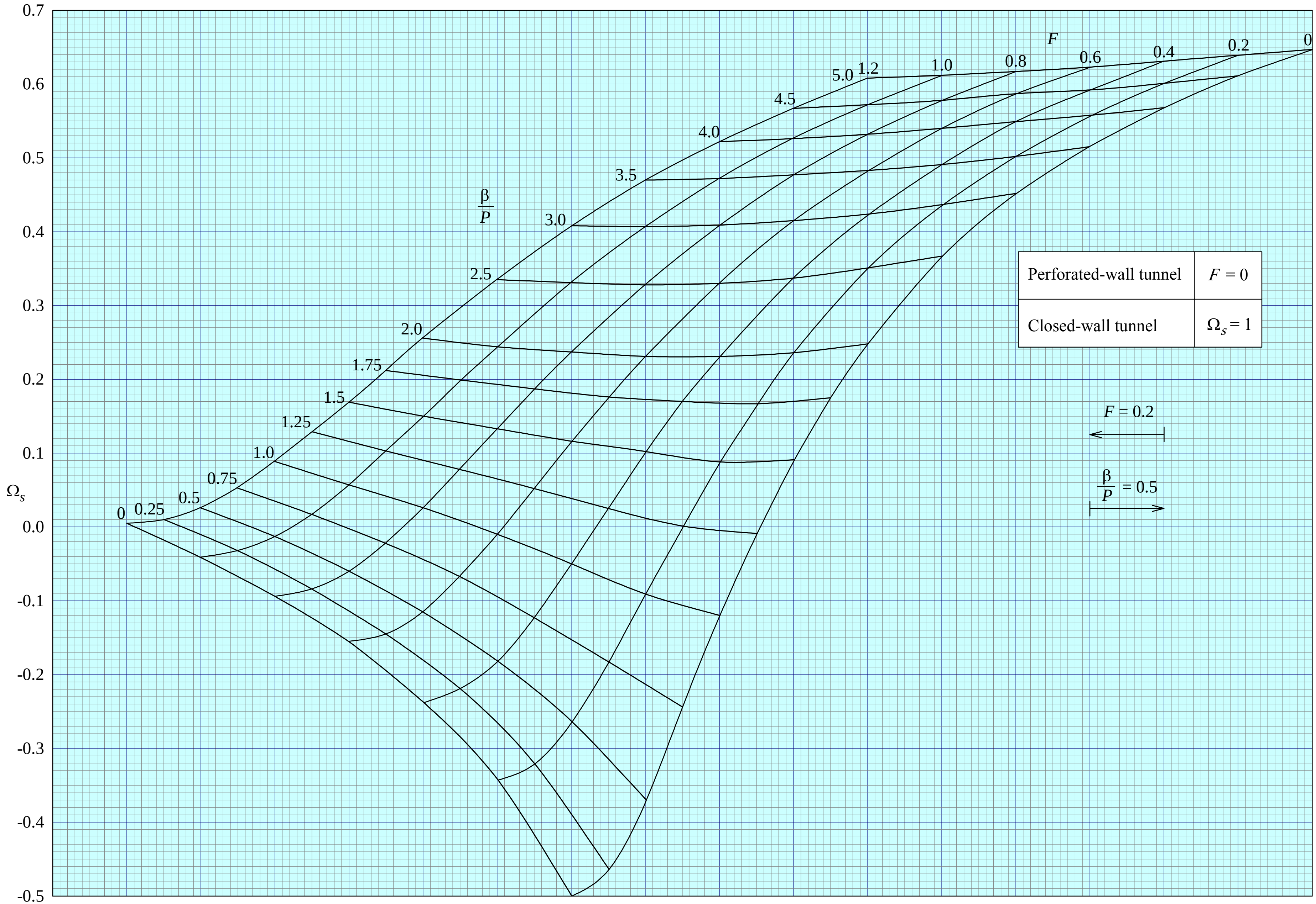


FIGURE 3 SOLID – BLOCKAGE FACTOR RATIO Ω_s

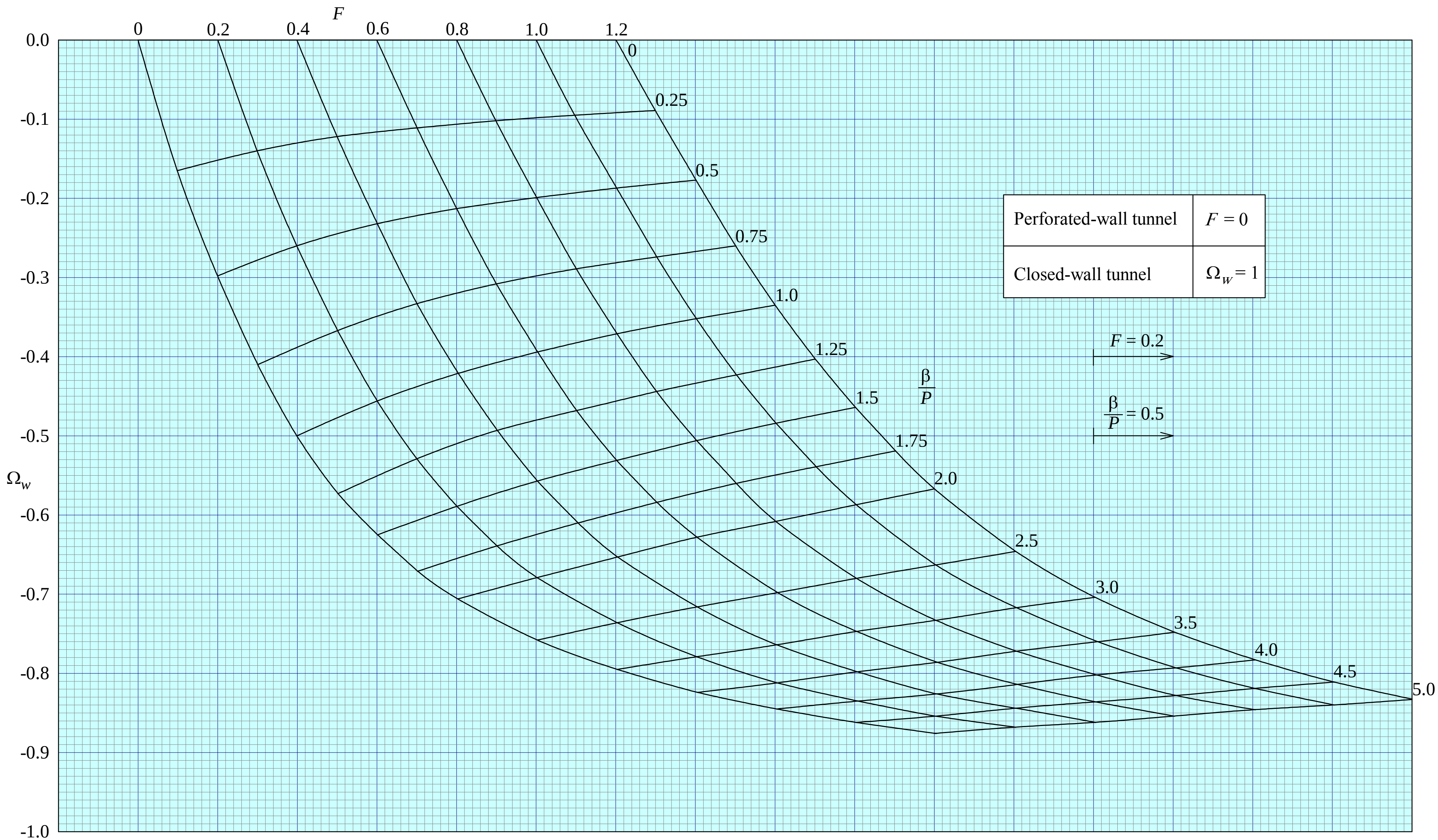


FIGURE 4 WAKE – BLOCKAGE FACTOR RATIO Ω_w

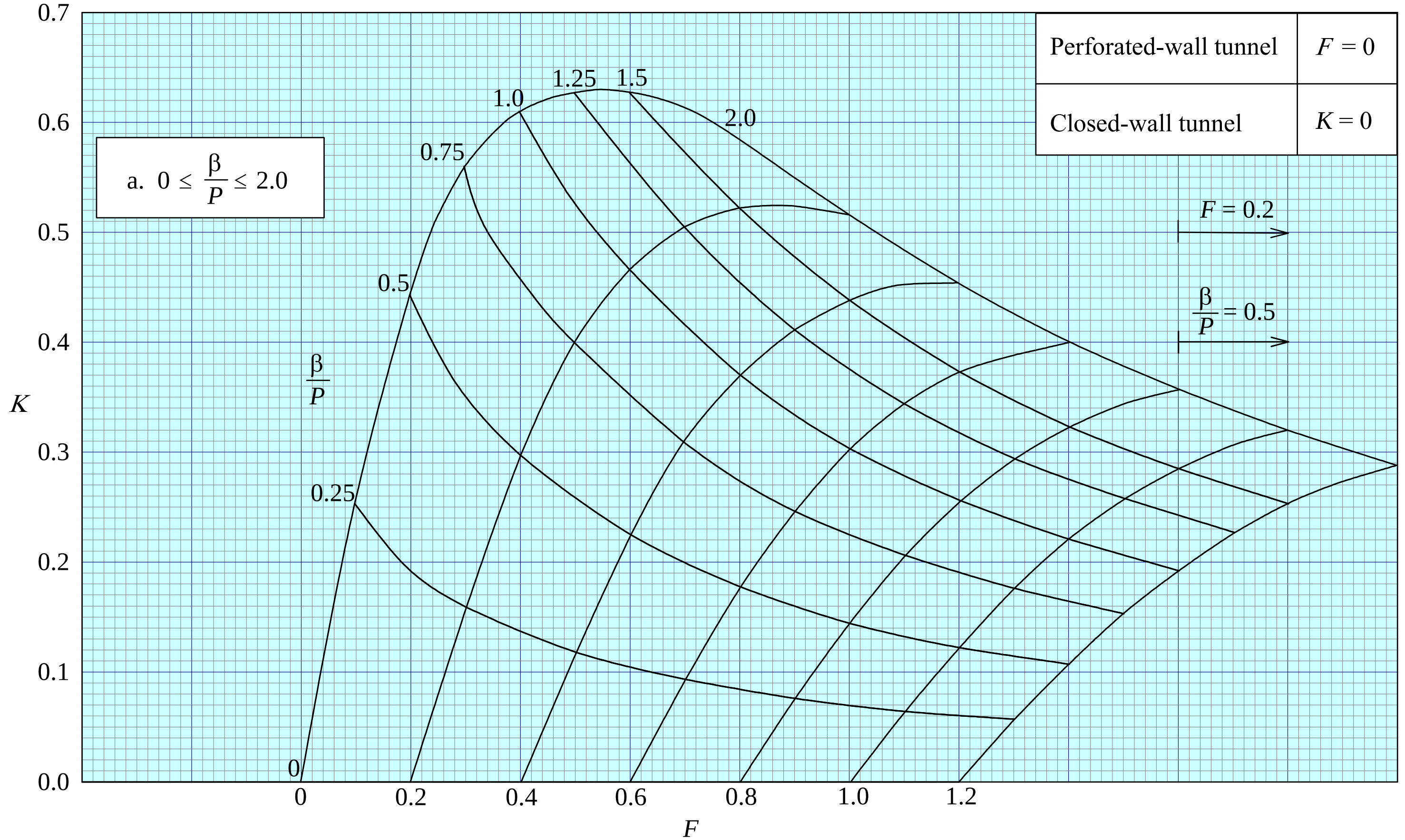


FIGURE 5a SOLID – BLOCKAGE GRADIENT FACTOR, $0 \le \beta / P \le 2.0$

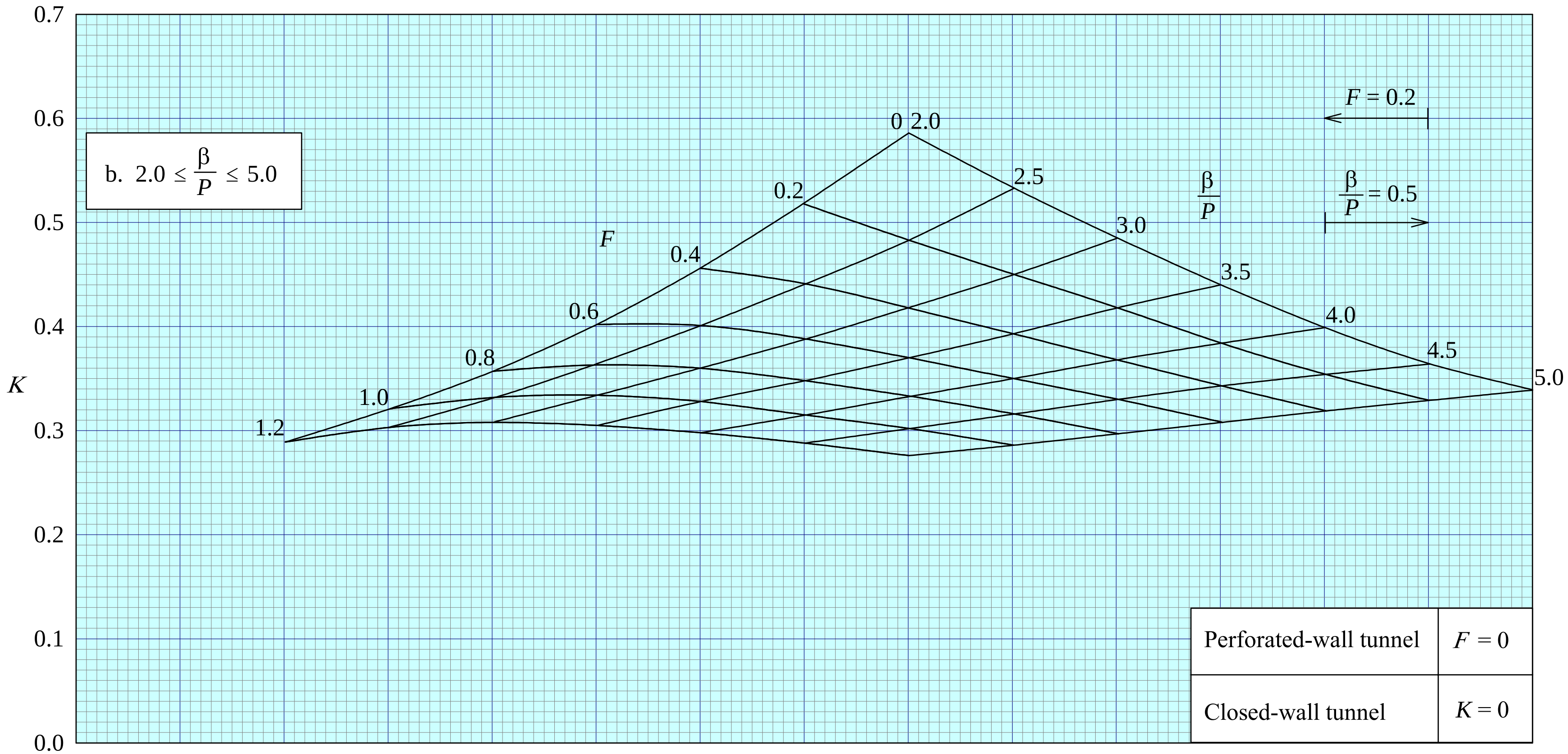


FIGURE 5b SOLID – BLOCKAGE GRADIENT FACTOR, $2.0 \le \beta / P \le 5.0$

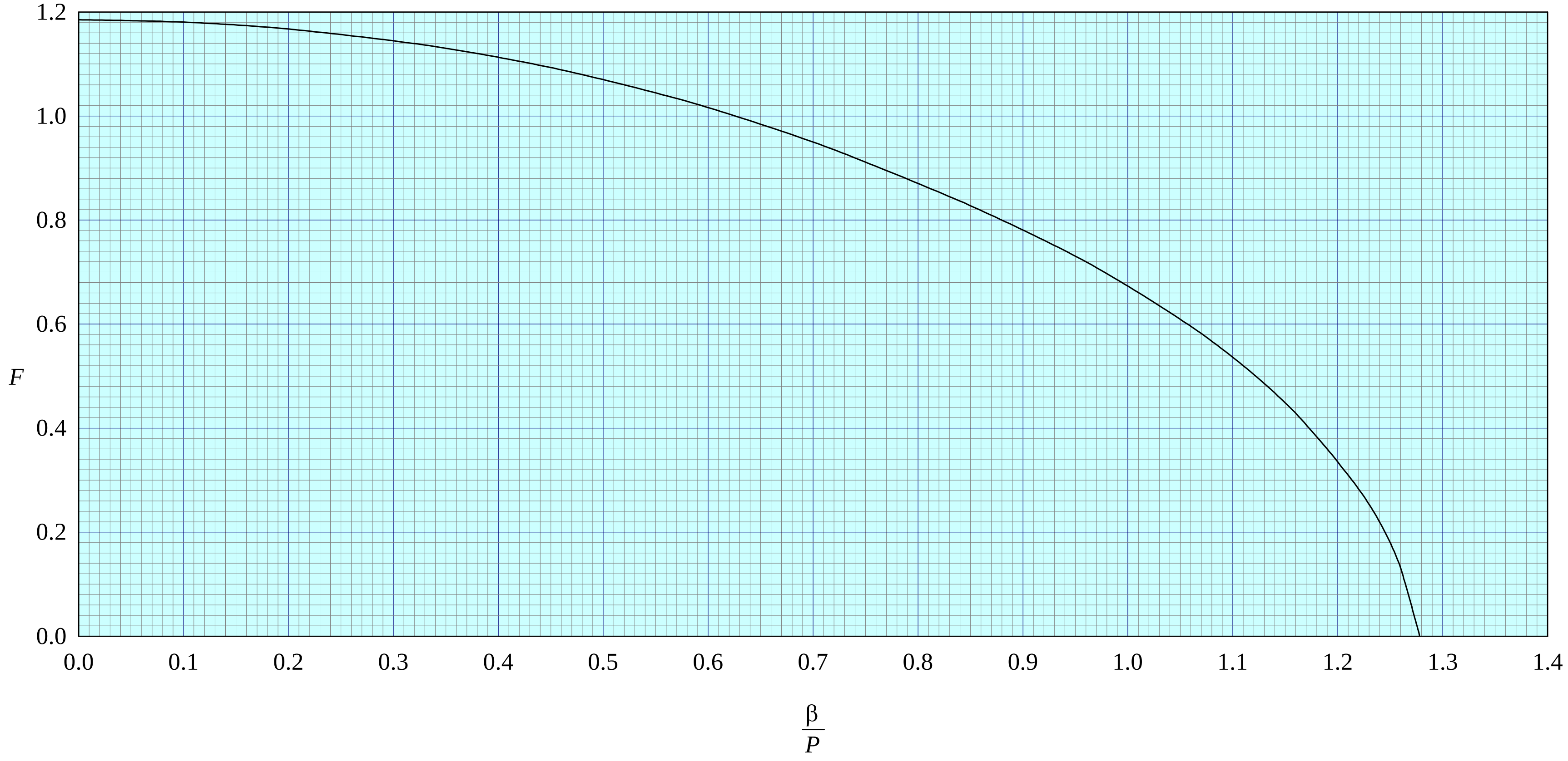


FIGURE 6 CONDITIONS FOR ZERO SOLID – BLOCKAGE (Ω_s = 0)

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