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A V/STOL Wind-Tunnel Wall Interference Study

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An integrated theoretical and experimental study of slotted wall tunnels is described. Theoretical calculations based on a modification of the point-matching method with equivalent homogeneous boundary conditions have been used to show the relationship between the lift- and blockage-interference factors and wall porosity. Experimental interference factors are obtained by comparing lift coefficient vs angle of attack data obtained in a 30 × 45 in. tunnel with those from a 7 × 10 ft tunnel. Theoretical results indicate that the lift interference for conventional models is insensitive to the porosity of the vertical walls for a height to width ratio less than 0.8. It is shown that certain combinations of vertical and horizontal wall slots give simultaneous zero lift and blockage interference. The discrepancy between theoretical and experimental results may be caused by nonhomogeneous slots and viscous effects.

Nomenclature

a = width of slot
A_m, B_m = series coefficient constants
b = tunnel semiwidth
C = cross-sectional area of tunnel
C_L = lift coefficient
h = tunnel semiheight
I_m = modified Bessel function of the first kind of order m
K_0, K_1 = modified Bessel function of the second kind of order 0 and 1, respectively
k = geometric slot parameter, $l/\pi \ln(\csc \pi a/2l)$
l = slot spacing
M_r = doublet strength
n = normal outward at the wall
P = nondimensional slot parameter, $(l + k/h)^{-1}$
R = viscosity parameter
S = wing area
s = wing span
U = freestream velocity
u = interference velocity in longitudinal direction

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V_R = ratio of model jet velocity to freestream velocity
w_∞, w_2 = interference velocity
x,y,z = Cartesian coordinate system (Fig. 1)
α = Fourier transform parameter or model angle of attack
$\Delta\alpha$ = angle of attack correction
Γ = circulation about a wing
δ = lift interference factor, $\delta_0 + \delta_2$
δ_0 = lift interference at the plane of a wing
ϵ_{sb} = blockage factor
λ = tunnel height-to-width ratio
τ_r = model volume
ρ,θ = polar coordinate system (Fig. 1)
ρ_∞ = density of freestream
ϕ = perturbation velocity potential, $\phi_i + \phi_m$
ϕ_i = interference velocity potential
ϕ_m = disturbance potential
ϕ_m^* = disturbance potential for the far downstream wake, Eq. (8)
$\bar{\phi}_i, \bar{\phi}_m$ = Fourier transform of ϕ_i and ϕ_m, respectively

Subscripts

H = horizontal walls
V = vertical walls

Introduction

A NUMBER of investigations[1,2] both theoretical and experimental, have been undertaken to determine an optimum test section configuration of a wind tunnel for Vertical/Short Take Off and Landing (V/STOL) model testing. Although a wall configuration which gives zero interference has not yet been determined, all results indicate that a test section with mixed boundaries offers the most promise as a configuration which will allow testing in an acceptable environment. The wall interference for a conventional model in a ventilated tunnel at subsonic speeds has been thoroughly reviewed in Refs. 3 and 4. In some recent investigations, a vortex lattice network has been applied to calculate wall interference in a ventilated test section.[5,6] Another approach is the utilization of an electrical analogy to obtain solutions of a finite difference formulation.[7]

This paper describes an integrated theoretical and experimental program at the Arnold Engineering Development Center to develop V/STOL wind-tunnel walls. The basic philosophy which is being followed in the study is first to consider the case of a conventional lifting wing; then to extend the problem to the case of a moderate value of the downwash; and finally, to consider the case where the downwash has a large value characteristic of VTOL transition flight.

As a first step in the theoretical study of the interference problem, a method has been developed[8] to calculate the interference induced by tunnel walls of arbitrary boundary conditions for the case of a conventional lifting wing, which is one limiting case of V/STOL configurations. The point-matching method is used to calculate the two-dimensional interference of any slotted wall test section with a homogeneous boundary condition. A modification of the method is used to calculate the three-dimensional interference of slotted and porous walls. Comparisons are made to examine the agreement between the results obtained by the point-matching method and some available classic analytical and/or electric analogy solutions. The attractive feature of using the point-matching method is that it is applicable to a tunnel with an arbitrary cross section and arbitrary wall configuration with the model located anywhere inside the test section. The ability to obtain solutions for diverse configurations permits a theoretical search to be made for a set of zero interference wall configurations by variation of the distribution of slot openings in the tunnel walls. Several optimum distributions of slot opening obtained from the theoretical computation are presented herein.

In the experimental program, tests are being conducted with a jet-in-fuselage model in a 30 × 45 in. wind tunnel. The force data which are considered interference free were obtained in the Ling-Temco-Vought 7 × 10 ft wind tunnel. The difference between theory and experiment is explained by the possibilities of the small span assumption in the theory, nonhomogeneous slots and viscous effects on the flow through the slots. Finally, some questions are raised concerning the definition of the lift interference factor for a V/STOL model in a wind tunnel.

Theoretical Calculations

The flowfield of an inviscid, incompressible fluid in terms of the potential function Φ is governed by Laplace's equation. In terms of the perturbation velocity potential ϕ and the uniform freestream velocity U, the potential is

$$\Phi = Ux + \phi \tag{1}$$

The perturbation potential is considered to be composed of two parts

$$\phi = \phi_m + \phi_i \tag{2}$$

where

ϕ_m = the disturbance potential caused by a lifting wing or a body of revolution in free air, and
ϕ_i = the interference potential induced by the tunnel walls

The mathematical model used for the disturbance potential is a single horseshoe vortex for a wing or a doublet for a body of revolution. Since these singularities satisfy Laplace's equation, the differential equation for the interference potential is

$$\nabla^2\phi_i = 0 \tag{3}$$

where

$$\nabla^2 = \partial^2/\partial\rho^2 + (1/\rho)(\partial/\partial\rho) + 1/\rho^2(\partial^2/\partial\theta^2) + \partial^2/\partial x^2 \tag{4}$$

It is assumed that there are longitudinal slots along the wind-tunnel wall. For simplicity, an equivalent homogeneous boundary condition can be introduced to satisfy all points on a uniformly slotted wall. The boundary condition, based on periodic slots of width a and spacing l is given[9] by

$$\phi + k\frac{\partial\phi}{\partial n} = 0 \tag{5}$$

where k is the geometric slot parameter

$$k = l/\pi \ln[\csc(\pi a/2l)] \tag{6}$$

and a/l is the open area ratio as shown in Fig. 1.

The solution to this boundary value problem is obtained by direct application of the point-matching method[8] to calculate the lift interference at the plane of a wing (two-dimensional) in a test section with slotted walls. A modification of the point-matching method is used to calculate the lift and blockage interferences along the longitudinal axis of the test section.

Two-Dimensional Interference

In the present analysis, the potential for a wing with circulation Γ and of zero span s defined such that

$$\lim_{s\to 0} \Gamma s = \text{const}$$

with the wing located at the center of the tunnel, is represented by a single horseshoe vortex.[10] Thus,

$$\phi_m = (\Gamma s/4\pi)(\sin\theta/\rho)[1 + x/(\rho^2 + x^2)^{1/2}] \tag{7}$$

The potential for the wake far downstream from the wing is

$$\phi_m{}^* = \lim_{x \to \infty} \phi_m = (\Gamma s / 2\pi)(\sin\theta/\rho) \tag{8}$$

which is independent of x and represents the basic disturbance potential when no walls are present. If the slot configuration is also made independent of x, then the interference potential is independent of x. The interference velocity at the wing is by symmetry half of that far downstream. Therefore, the classical interference factor at the plane of the wing can be determined by

$$\delta_0 = C\Delta w_\infty / 4\Gamma s \tag{9}$$

where

Δw_∞ = interference velocity far downstream
C = wind-tunnel cross-sectional area

The essence of the point-matching method is to begin with an exact particular solution and a homogeneous series solution for the governing linear partial differential equation. The boundary conditions are then matched at discrete points which permit the solution of problems having irregular mixed boundaries. The undetermined coefficients of the series solution are calculated from the system of algebraic equations which are obtained by satisfying the linear boundary conditions at discrete boundary points.

The results of computations of the lift interference factor for a rectangular tunnel with four walls slotted are presented in Fig. 2. The nondimensional slot parameter in Fig. 2 is defined as $P = (1 + k/h)^{-1}$. The value of $P = 0$ corresponds to solid walls and $P = 1.0$ to open walls. The interference factor for the particular configuration shown in Fig. 2 has not been previously obtained analytically. The only available solution is that obtained by an electrical analogy technique.[7] It can be seen that the present solutions agree quite well with the electrical analogy results.

The nature of the point-matching method permits a search for an optimum configuration where the slots are not uniformly distributed around the tunnel walls. If it is assumed that the slot parameter of the horizontal walls P_H may be different from that of the vertical walls P_V then wall configurations with certain combinations of P_H and P_V are found to have zero interference. Figure 3 shows the relationship between the slot parameters on the horizontal and vertical walls required for zero lift interference for various values of tunnel height-width ratio. It can be seen that the lift interference is relatively insensitive to the porosity of the vertical walls, with the exception of the square tunnel. Therefore, the initial efforts of the experimental program, to be described later, have been concerned with solid vertical and slotted horizontal walls.

Three-Dimensional Interference

Lift interference

In the previous section, the upwash at the plane of the wing was found. In order to find the upwash at any tail position, one must know the upwash distribution along the longitudinal

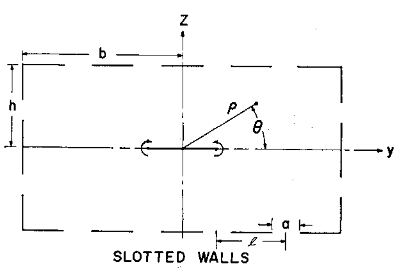

Fig. 1 Coordinate system and geometry of wind-tunnel cross section.

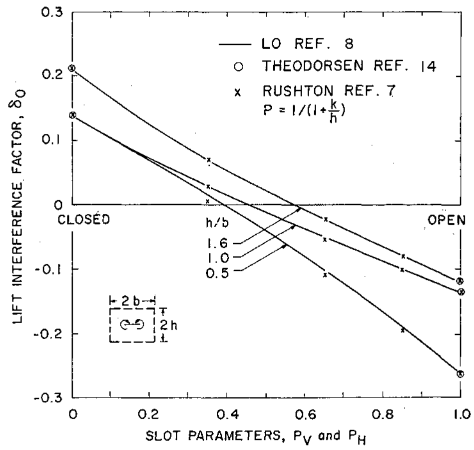

Fig. 2 Lift interference factor for rectangular tunnels with four walls slotted, $P_V = P_H$ (Ref. 14).

axis of the tunnel. It is apparent that the potential, ϕ_m and ϕ_i, must depend upon the variable x as well as the variables ρ and θ. The disturbance potential for a horseshoe vortex of zero span, Eq. (7), can be split into two parts as

$$\phi_m = \phi_{m1}(\rho,\theta) + \phi_{m2}(\rho,\theta,x) \tag{10}$$

where

$$\phi_{m1} = (\Gamma s/4\pi)(\sin\theta/\rho) = \tfrac{1}{2}\phi_m{}^* \tag{11}$$

$$\phi_{m2} = (\Gamma s/4\pi)(\sin\theta/\rho)x/(\rho^2 + x^2)^{1/2} \tag{12}$$

Since the differential equation and boundary conditions of the interference potential are linear, ϕ_i may also be split into two parts as

$$\phi_i = \phi_{i1}(\rho,\theta) + \phi_{i2}(\rho,\theta,x) \tag{13}$$

where ϕ_{i1} is independent of x and induced by $\phi_{m1}(\rho,\theta)$, and ϕ_{i2} is induced by $\phi_{m2}(\rho,\theta,x)$.

By substituting Eqs. (10) and (13) in the differential equation and boundary conditions, the potential ϕ_{i2} again satisfies

$$\nabla^2\phi_{i2} = 0 \tag{14}$$

with the boundary condition

$$\phi_{i2} + k(\partial\phi_{i2}/\partial n) = -[\phi_{m2} + k(\partial\phi_{m2}/\partial n)] \tag{15}$$

The direct application of the point-matching method to the three-dimensional problem, Eq. (14), is difficult, especially for a region bounded by an infinitely long cylinder since the boundary surface conditions have to be satisfied at discrete points. However, since the integral transform can reduce one variable of the equation into a transform parameter, the problem in the transformed plane becomes a two-dimensional one. The point-matching method may then be used to solve the transformed equation and finally the solution can be in-

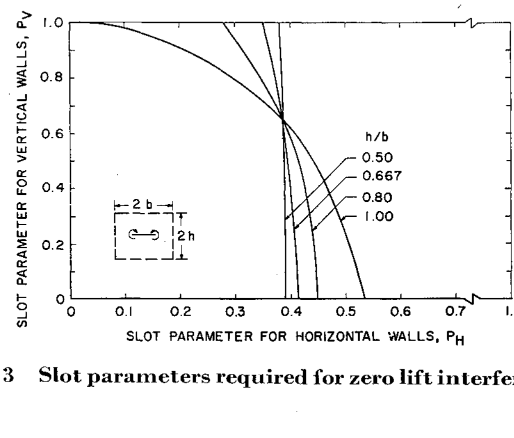

Fig. 3 Slot parameters required for zero lift interference.

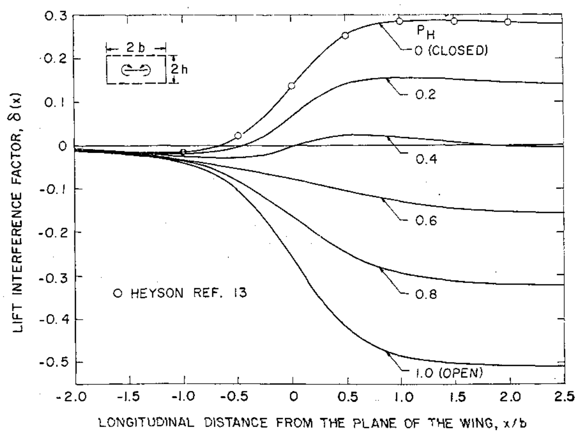

Fig. 4 Axial variation of lift interference factor, $P_V = 0, h/b = 0.5$.

verted numerically into the physical plane. The Fourier transform has been used in conjunction with the point-matching technique in this three-dimensional boundary value problem.

The Fourier sine transform is applied to solve Eq. (14) with Eq. (15), since the disturbance potential ϕ_{m_2} is asymmetric about x. Equations (14) and (15) in the transformed plane are

$$\partial^2\bar{\phi}_{i_2}/\partial\rho^2 + (1/\rho)(\partial\bar{\phi}_{i_2}/\partial\rho) + (1/\rho^2)(\partial^2\bar{\phi}_{i_2}/\partial\theta^2) - \alpha^2\bar{\phi}_{i_2} = 0 \quad (16)$$

and the boundary condition

$$\bar{\phi}_{i_2} + k(\partial\bar{\phi}_{i_2}/\partial n) = -[\bar{\phi}_{m_2} + k(\partial\bar{\phi}_{m_2}/\partial n)] \quad (17)$$

where

$$\bar{\phi}_{i_2} = \left(\frac{2}{\pi}\right)^{1/2} \int_0^\infty \phi_{i_2} \sin\alpha x dx \quad (18)$$

$$\bar{\phi}_{m_2} = \left(\frac{2}{\pi}\right)^{1/2} \int_0^\infty \phi_{m_2} \sin\alpha x dx = \left(\frac{2}{\pi}\right)^{1/2} \frac{\Gamma s}{4\pi} \sin\theta K_1(\alpha\rho) \quad (19)$$

α = Fourier transform parameter
K_1 = Modified Bessel function of the second kind of order one.

The integral of Eq. (19) is obtained from Ref. 11 which is convergent in the Cesaro sense.[12]

Now considering a rectangular wind tunnel of width $2b$ and height $2h$ with the closed vertical walls and slotted horizontal walls, a series solution of Eq. (16) is

$$\bar{\phi}_{i_2} = \sum_{m=1,3,5}^{2M-1} A_m(\alpha b) I_m(\alpha\rho) \sin m\theta \quad (20)$$

where

I_m = Modified Bessel function of the first kind of order m.

Equation (20) satisfies the properties of asymmetry about the y axis and symmetry about the z axis.

The boundary condition, Eq. (17), for the vertical solid walls becomes

$$\partial\phi_{i_2}/\partial y = -\partial\phi_{m_2}/\partial y \text{ at } y = \pm b \quad (21)$$

and for the horizontal slotted walls

$$\bar{\phi}_{i_2} \pm k_H \frac{\partial\bar{\phi}_{i_2}}{\partial z} = -\left(\bar{\phi}_{m_2} \pm k_H \frac{\partial\bar{\phi}_{m_2}}{\partial z}\right) \text{ at } z = \pm h \quad (22)$$

To determine the coefficients A_m, the series, Eq. (20) is truncated at a finite term $(2M - 1)$. A set of simultaneous linear algebraic equations is obtained by substituting Eqs. (19) and (20) into Eqs. (21) and (22) and selecting M discrete points uniformly distributed along the boundary. However, improved accuracy may be achieved by selecting more than M points along the boundary and calculating $A_m(\alpha b)$ at each specific value of αb by satisfying the boundary condition in the least squares sense.[8] All results presented herein were obtained in this manner.

Once the transformed potential $\bar{\phi}_{i_2}$ is obtained, then the interference potential in the physical plane may be determined by the inversion theorem of the Fourier transform

$$\phi_{i_2} = \left(\frac{2}{\pi}\right)^{1/2} \int_0^\infty \bar{\phi}_{i_2}(\rho,\theta,\alpha) \sin x\alpha d\alpha \quad (23)$$

The interference upwash at the centerline of the tunnel is

$$\Delta w_2|_{\rho=0} = \left.\frac{\partial\phi_{i_2}}{\partial z}\right|_{\rho=0} = \left(\frac{2}{\pi}\right)^{1/2} \frac{1}{2} \int_0^\infty A_1(\alpha b)\ \alpha \sin x\alpha d\alpha \quad (24)$$

The lift interference factor due to ϕ_{i_2} is

$$\delta_2 = C\Delta w_2(x)/2\Gamma s \quad (25)$$

Then the lift interference factor along the centerline of the tunnel can be obtained through the superposition of δ_0 due to ϕ_{i_1} and $\delta_2(x)$ due to ϕ_{i_2}. Thus,

$$\delta(x) = \delta_0 + \delta_2(x) \quad (26)$$

The lift interference factor $\delta(x)$ is presented in Fig. 4 as a function of x/b for various values of the horizontal wall slot parameter, P_H. Data for a closed tunnel, from Ref. 13 (Ref. 13 data have been divided by -4 because of different definitions) also shown in Fig. 3, are in excellent agreement with the present solution.

Solid blockage interference

The solid blockage interference is calculated using a body of revolution represented by a three-dimensional doublet with its axis aligned with the centerline of the tunnel. The potential of a doublet located at the origin of the coordinates is expressed[15] as

$$\phi_m = (M_r/4\pi)[x/(x^2 + \rho^2)^{3/2}] \quad (27)$$

The strength of the doublet M_r is related to the volume of the model τ_r by $M_r = U\tau_r$. The field equation for the interference potential ϕ_i is the Laplace equation with the homogeneous boundary condition for slotted walls as given by Eq. (5).

Consider a rectangular wind tunnel of width $2b$ and height $2h$ with four slotted walls. By applying the Fourier sine transform, the problem in the transformed plane is

$$\partial^2\bar{\phi}_i/\partial\rho^2 + (1/\rho)(\partial\bar{\phi}_i/\partial\rho) + 1/\rho^2(\partial^2\bar{\phi}_i/\partial\theta^2) - \alpha^2\bar{\phi}_i = 0 \quad (28)$$

with the boundary condition

$$\bar{\phi}_i \pm k_V \frac{\partial\bar{\phi}_i}{\partial y} = -\left(\bar{\phi}_m \pm k_V \frac{\partial\bar{\phi}_m}{\partial y}\right), y = \pm b \quad (29)$$

$$\bar{\phi}_i \pm k_H \frac{\partial\bar{\phi}_i}{\partial z} = -\left(\bar{\phi}_m \pm k_H \frac{\partial\bar{\phi}_m}{\partial z}\right), z = \pm h \quad (30)$$

where

$$\bar{\phi}_i = \left(\frac{2}{\pi}\right)^{1/2} \int_0^\infty \phi_i \sin\alpha x dx \quad (31)$$

$$\bar{\phi}_m = \left(\frac{2}{\pi}\right)^{1/2} M_r \frac{1}{4\pi} \alpha K_0(\alpha\rho) \quad (32)$$

K_0 = Modified Bessel function of the second kind of order of zero.

A series solution of Eq. (28) is

$$\bar{\phi}_i = \sum_{m=0,2,4}^{2M} B_m(\alpha b) I_m(\alpha \rho) \cos m\theta \qquad (33)$$

where, I_m = Modified Bessel function of the first kind of order m. Equation (33) satisfies the axisymmetric condition. The coefficients $B_m(\alpha b)$ are determined by the point-matching method to satisfy the boundary conditions. The solid blockage interference factor can be obtained from the transformed potential, $\bar{\phi}_i$, by the inversion theorem. The longitudinal interference velocity Δu is given by

$$\Delta u = \frac{\partial \phi_i}{\partial x} = \left(\frac{2}{\pi}\right)^{1/2} \int_0^\infty \sum_{m=0,2,4}^{2M} \alpha B_m(\alpha b) \times I_m(\alpha \rho) \cos m\theta \cos x\alpha d\alpha \qquad (34)$$

At the centerline of the tunnel, the solid blockage interference factor is

$$\epsilon_{sb} = \lim_{\rho \to 0} \frac{\Delta u}{M_r/b^3} = \frac{b^3}{M_r}\left(\frac{2}{\pi}\right)^{1/2} \int_0^\infty B_0(\alpha b)\alpha \cos x\alpha d\alpha \qquad (35)$$

The solid blockage interference factor ϵ_{sb} at the plane of the wing is plotted as a function of P_H for various values of P_V in Fig. 5. Data by Acum[16] for closed side walls are also shown in Fig. 5; it can be seen that the agreement is quite good. It may be seen from Fig. 5 that zero blockage interference can be achieved by choosing certain combinations of porosity on the horizontal and vertical walls. The variation of P_V and P_H which results in zero blockage interference for tunnel height to width ratios of 1 and 0.8 are shown in Fig. 6. The zero lift interference data from Fig. 3 are also plotted in Fig. 6 and the intersection of these sets of data gives the value of each slot parameter which simultaneously eliminates blockage and lift interference.

Experimental Study

Apparatus

Experimental work has been done in a 30 × 45 in. wind tunnel using a jet-in-fuselage model (Fig. 7). The high-disk-loading configuration was selected because of the relatively simple way of producing the required downwash while retaining the ability to separate the aerodynamic and jet forces. Further, the analytical representation of the jet wake may rely on the large amount of existing jet-in-crossflow data. The jet is provided by an air ejector which is mechanically isolated from the wing and fuselage. The model contains two balances, one measuring the force output of the ejector and its inlet and the other measuring lift, drag, and pitching moment on the wing and fuselage. The model was purposely made large, (30-in. span), so that measurable interference effects would be produced.

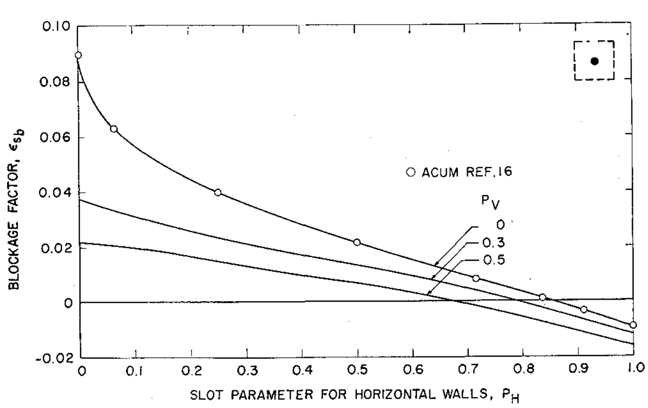

Fig. 5 Blockage interference factor for square tunnel with four walls slotted.

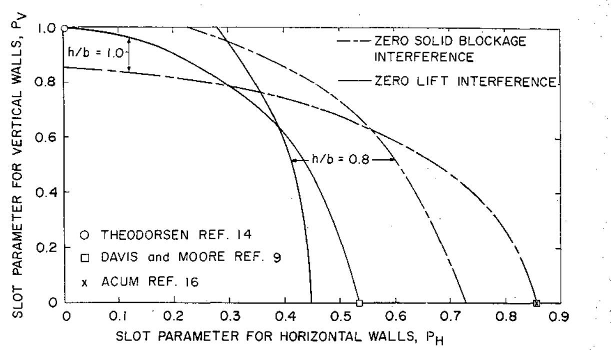

Fig. 6 Slot parameters required for zero interferences (Ref. 14).

Force data which are considered interference free were obtained on a model over a range of jet to freestream velocity ratios V_R from 0 to 30 in the Ling-Temco-Vought (LTV) low speed wind-tunnel test sections with 7 × 10 ft and 15 × 20 ft cross sections. These data are being used to ascertain the interference effect of various wall configurations in the 30 × 45 in. tunnel. To date, tests have been conducted with solid vertical walls and two series of horizontal wall configurations; the horizontal walls contained two and four slots, respectively.

Horizontal Wake Lift Interference Factor

The experimental lift interference factor has been determined from a comparison of the variation of the aerodynamic lift coefficient with angle of attack obtained in the 30 × 45 in. wind tunnel with that from the LTV wind tunnel at similar conditions. For a given configuration, the lift interference factor is determined in the least squares sense from

$$\delta_0 = \frac{C}{S}\left(N \sum_{i=1}^{N} \Delta\alpha_i C_{L_i} - \sum_{i=1}^{N} \Delta\alpha_i \sum_{i=1}^{N} C_{L_i}\right) \Bigg/ N \sum_{i=1}^{N} C_{L_i}{}^2 - \left(\sum_{i=1}^{N} C_{L_i}\right)^2 \qquad (36)$$

where C_{L_i} = a chosen value of lift coefficient, $\Delta\alpha_i$ = angle of attack from LTV data minus angle of attack from the 30 × 45 in. tunnel data at each C_{L_i}.

A comparison between the theoretical lift interference factor for the homogeneous wall and the experimental lift interference factor is presented in Figs. 8 and 9. Figure 8 shows the data for two slots in each horizontal wall; Fig. 9 for the case of four slots. Although the theoretical and experimental data have the same general trend, the agreement is not very good. Possible reasons for this lack of agreement are discussed in the next section.

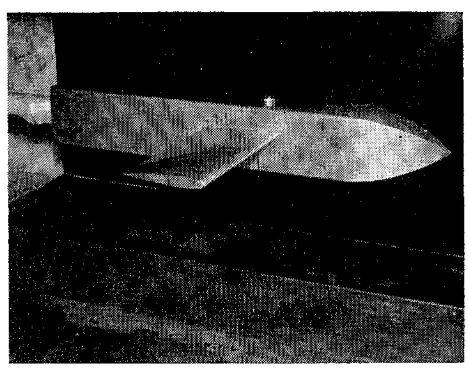

Fig. 7 Jet-in-fuselage model in the 30 × 45 in. wind tunnel.

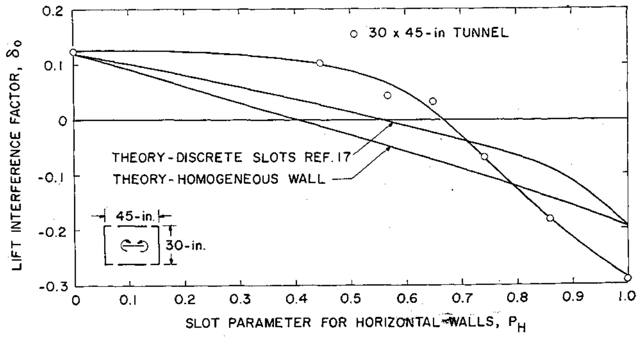

Fig. 8 Lift interference factor for two slots in each horizontal wall.

Nonhomogeneous Slots and Viscous Effects

The equivalent homogeneous boundary condition, which was the basis of the theoretical calculation described in previous sections, requires the number of slots in each wall to be sufficiently large that the effect of individual slots may be neglected. Thus, it is questionable whether the two and four slots in the experimental configuration can be considered homogeneous. Therefore, the interference factor for walls with discrete slots was computed by the method of Matthews[17] and the results also plotted in Figs. 8 and 9. The agreement is improved but the difference between theory and experiment is not completely eliminated.

Another assumption in the theoretical treatment is that the viscous effects can be completely neglected. This is obviously not the case particularly when the ratio of slot width to the wall thickness is small. To account for viscous effects in the slots, a further term R can be introduced[18] into the boundary conditions such that the boundary condition becomes

$$\partial\phi/\partial x + k(\partial^2\phi/\partial x\partial n) + (1/R)\partial\phi/\partial n = 0 \qquad (37)$$

where

$$R = -(\partial\phi/\partial n)/(\partial\phi/\partial x) = U\rho_\infty(\partial\phi/\partial n)/\Delta p$$

Reference 18 suggests that the value of R can be determined by experimentally measuring the pressure drop across a sample of a particular wall geometry at various values of the mass flow, $\rho_\infty(\partial\phi/\partial n)$.

However, the parameter, R, may be a function of several variables, for example, Reynolds number, slot geometry, dynamic pressure, lift distribution, etc. Further, the mass flow in the slot of a wind tunnel is a function of position along the longitudinal direction. Therefore, an effective value of R is required that is applicable over the length of the test section and the range of test variables. An experimental method to measure the effective value of R for a specific wall configuration is needed for its evaluation.

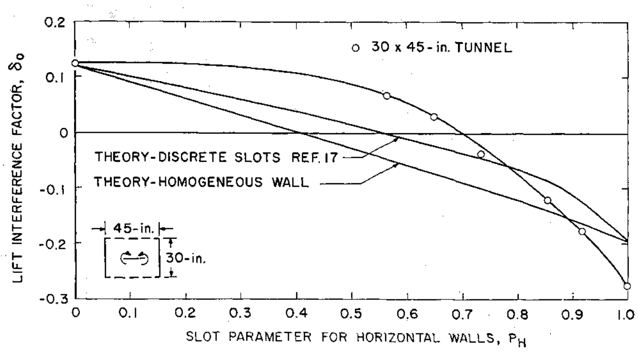

Fig. 9 Lift interference factor for four slots in each horizontal wall.

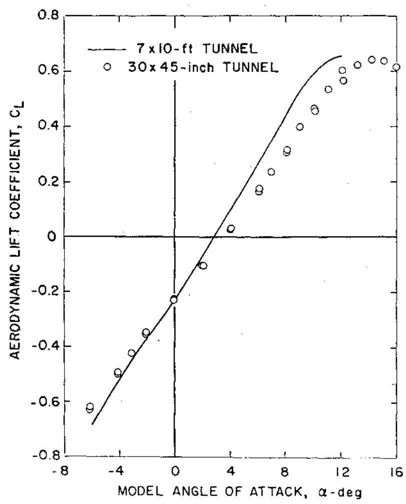

Fig. 10 Lift coefficient for jet-in-fuselage model, $V_R = 4.7$.

The theory also assumes the span of the model is small compared to the tunnel dimensions. However, in the closed tunnel, $\lambda = 0.7$, the effect of span is small and in the open jet case, increasing the span decreases the interference.[19] Even with the small span assumption, theory and experiment agree very well for the solid tunnel case which is the only case for which there is no question of the boundary condition. Thus, it would appear that the assumption of a small span is not responsible for the data discrepancy.

V/STOL Interference Factor

The discussion heretofore has been concerned with the classical lifting wing where the wake may be considered horizontal. Experimental data obtained for the V/STOL case have indicated that the application of corrections to the data in the manner of the classical case are not sufficient to bring about agreement with interference free data. The lift data correction for a wing in a wind tunnel may be considered to be an angle of attack increment,

$$\Delta\alpha = f_1(C_L, \lambda, \text{wall configuration})$$

which is due to the constraints imposed on the flow by the

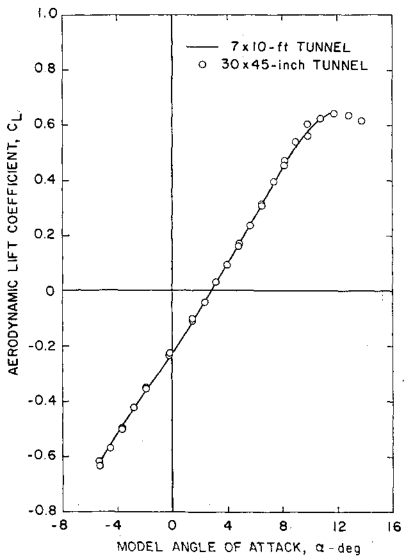

Fig. 11 Lift coefficient for jet-in-fuselage model with 30 × 45 in. tunnel data corrected by Eq. (39), $V_R = 4.7$.

tunnel boundaries. For a given tunnel geometry, the correction takes the form

$$\Delta\alpha = \delta_0(S/C)C_L \quad (38)$$

The data presented in Fig. 10 are typical of that obtained with the model configuration of this investigation operating in the VTOL transition mode. The data shown are the aerodynamic lift coefficient (jet force not included) for a velocity ratio $V_R = 4.7$ and a tunnel wall porosity of 60%. Examination of the data reveals that Eq. (38) applied to the small tunnel data will not make it coincident with that from the 7 × 10 ft tunnel; at best the data will only be parallel.

The V/STOL case differs from the classical case in that there is an additional perturbation induced in the flow-field by the downward deflected jet of a V/STOL vehicle in transition flight. The velocities induced by the jet in the wind tunnel are also influenced by the tunnel boundaries. This effect may be considered to result in an additional angle-of attack increment

$$\Delta\alpha_j = f_2(V_R, \lambda, \text{wall configuration})$$

The total angle-of-attack correction would then become

$$\Delta\alpha = \delta_0(S/C)C_L + \Delta\alpha_j \quad (39)$$

where C_L is the aerodynamic lift coefficient and does not include the brute force lift of the jet.

Since the existence of $\Delta\alpha_j$ is inferred from the experimental data, it should be noted that the testing procedures were the same in each test section. Further, the possibility of tunnel flow inclination was eliminated by testing with the model inverted. The results of the application of Eq. (39) with the experimentally determined constants $\delta_0 = -0.329$ and $\Delta\alpha_j = -0.8$ deg to the small tunnel data are shown in Fig. 11. The two sets of data, while not precisely coincident, are in agreement to within the uncertainty interval of the experimental data. The function which predicts the variation of $\Delta\alpha_j$ is still obscure. However, it appears likely that its employment is necessary.

Concluding Remarks

A method has been formulated which allows the computation of classical lift-and-blockage interference factors for any slotted wind tunnel. In order to obtain agreement between theory and experiment, it appears one must consider the effect of the simplifying assumptions used in the theory, particularly the effect of slot distribution and viscosity within the slots. An empirical constant, R, is needed to take account of the viscous effects. Experimental data have indicated that application of an angle of attack correction which is proportional to the lift coefficient, as in the classical case, is not sufficient for the case of high downwash. An addition term in the angle of attack correction is suggested.

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