A General Solution for Lift Interference in Rectangular Ventilated Wind Tunnels

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Theme

THE wind-tunnel boundary upwash interference on a symmetrical finite wing of arbitrary lift distribution is calculated in a rectangular test section with solid vertical and ventilated horizontal walls. The theory uses an image method in addition to Fourier transforms with an equivalent homogeneous boundary condition on the ventilated wall. The general solution obtained is analytically reducible, as special cases, to all available, simplified-lift-model solutions. The solution is computationally simplified by a discrete representation of the lift distribution.

Contents

The present analysis gives a completely general analytical expression for the upwash interference whereas all available previous solutions[1–5] were restricted to a combination of simplified lifting elements. The lifting wing model is mathematically represented by a surface distribution of elementary horseshoe vortices with known bound circulation distribution, $\Gamma(X, Y)$. The flowfield is considered three dimensional and is treated as steady, nonviscous and irrotational for the purpose of determining first-order tunnel wall interference corrections. The general linearized boundary value problem for the velocity potential, Φ, is shown schematically in Fig. 1. For the ventilated horizontal walls, the homogeneous boundary condition derived by Baldwin et al.[6] is used where K is a geometric slot parameter and R is a porosity parameter which accounts for the viscous effects in the slots. Closed, open, ideal slotted, and porous boundaries are included as limiting forms of the homogeneous boundary condition.[7]

The linearity of the field equation and its boundary conditions together with a Prandtl-Glauert transformation reduces the boundary value problem to the Laplace equation for an interference potential Φ_i induced by the tunnel boundaries. The solution of the transformed boundary value problem is obtained by an image system (consisting of an infinite row of lifting elements reflected in the solid vertical walls) in conjunction with Fourier transforms on the X and Y coordinates. In obtaining the solution an intermediate field function based on the X-derivative of Φ_i was used to satisfy the absolute integrability requirement for a complex Fourier transform. The omission of this requirement has created previously solutions which had to be adjusted by the superposition of a uniform upwash velocity to restore undisturbed flow at $X = -\infty$.

Classically, the upwash interference parameter, $\delta(x, y)$ is defined as a normalized value of the interference upwash velocity, $w_i(x, y)$ in the plane of the wing $(x, y, 0)$.

$$\delta(x, y) = (C/SC_L U_\infty) w_i(x, y) \tag{1}$$

where $C = 4hb$ is the cross-sectional area of the tunnel, S is the wing area, C_L the wing total lift coefficient in free air and U_∞ the freestream velocity. For the present study this is

$$\delta(x, y) = \frac{\lambda}{2\pi} \sum_{m=0}^{\infty} j \int_0^\infty [I_E \cos(\omega x) + I_G \sin(\omega x)] F_1(\omega, m) \times \cos(m\pi y) \frac{f}{\omega} d\omega + \lim_{\omega \to 0} \left(\frac{\lambda}{4} \sum_{m=0}^{\infty} j I_G F_1(\omega, m) \cos(m\pi y) \right) + \frac{\lambda}{4\pi} \sum_{\substack{k=-\infty \\ k \neq 0}}^{\infty} F_2(k) \tag{2}$$

where $\lambda = h/b$, $j = 1$ if $m = 0$ and $j = 2$ if $m \neq 0$, and $f = (\omega^2 + m^2\pi^2)^{1/2}$. Also

$$I_E = \frac{-(f/\omega)\beta/R}{\{[\sinh(\lambda f) + \lambda f F \cosh(\lambda f)]^2 + [(f/\omega)\beta/R]^2 \cosh^2(\lambda f)\}} \tag{3}$$

$$I_G = \frac{-\{(1 - f\lambda F)(\sinh(\lambda f) + \lambda f F \cosh(\lambda f)) - [(f/\omega)\beta/R]^2 \cosh(\lambda f)\}}{e^{\lambda f}\{[\sinh(\lambda f) + \lambda f F \cosh(\lambda f)]^2 + [(f/\omega)\beta/R]^2 \cosh^2(\lambda f)\}} \tag{4}$$

$$F_1(\omega, m) = \int_0^\tau \int_{\xi_1}^{\xi_2} \frac{\beta AR \gamma(\xi, \eta)}{\tau^2 C_L} \cos(\omega\xi) \cos(m\pi\eta) \, d\xi \, d\eta \tag{5}$$

and

$$F_2(k) = \int_{-\tau}^{\tau} \int_{\xi_1}^{\xi_2} \frac{\beta AR \gamma(\xi, \eta)}{\tau^2 C_L} \frac{1}{(y - \eta - 2k)^2} \times \left[1 + \frac{x - \xi}{[(x - \xi)^2 + (y - \eta - 2k)^2]^{1/2}} \right] d\xi \, d\eta \tag{6}$$

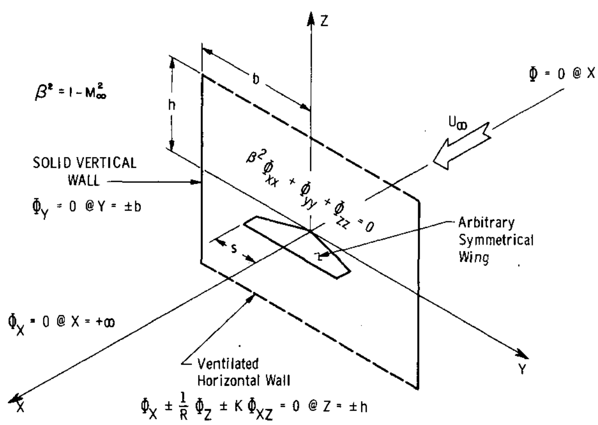

Fig. 1 Schematic of lift interference boundary value problem.

Presented as Paper 73-209 at the AIAA 11th Aerospace Sciences Meeting, Washington, D.C., January 10–12, 1973; submitted January 26, 1973; synoptic received May 29, 1973. Full paper available from AIAA Library, 750 Third Avenue, New York, N.Y. 10017. Price: Microfiche, $1.00; hard copy, $5.00. **Order must be accompanied by remittance.** The research reported herein was conducted by the Arnold Engineering Development Center, Air Force Systems Command. Research results were obtained by personnel of ARO Inc., Contract Operator at AEDC. Further reproduction is authorized to satisfy needs of the U.S. Government.

Index category: Aircraft Testing.

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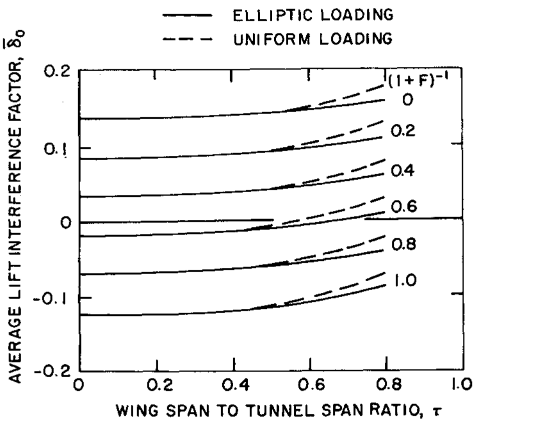

Fig. 2 Lift interference factor at the model location in a square tunnel with slotted horizontal and closed vertical walls.

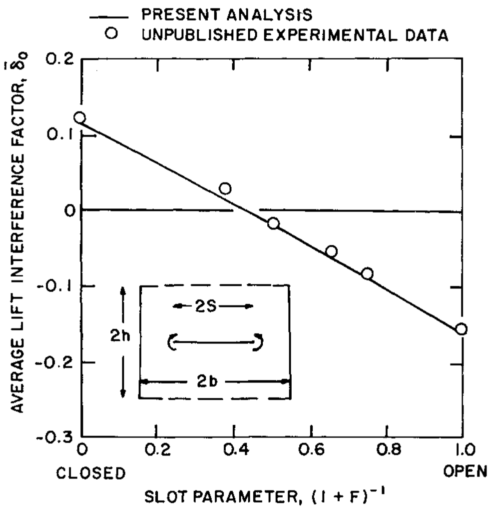

Fig. 4 Lift interference factor in a tunnel with slotted horizontal walls, $h/b = 0.667$, $s/b = 0.524$.

In the preceding, $F = K/h$, $\tau = s/b$, $\gamma = \Gamma/U_\infty b$, AR = aspect ratio, and the coordinates are normalized as $x = X/\beta b$ and $y = Y/b$. ξ_1 and ξ_2 are the wing leading and trailing edges, respectively.

Once the normalized circulation distribution, $\gamma(x, y)$, is defined Eq. (2) can be integrated to yield the upwash interference factor, $\delta(x, y)$. The mean value $\bar{\delta}(x)$ [formed by averaging $\delta(x, y)$ over the wing span] is given in Ref. 7 where the present generalized results are shown to be analytically reducible to all available simplified-lift-model solutions. Also in Ref. 7, analytic expressions are given for more sophisticated wing models such as Prandtl-Glauert lifting line and elliptically loaded wings. Increasing complexity in the mathematical wing description makes the numerical computation increasingly more difficult. In order to maintain a computational viability while allowing the increased model sophistication an influence coefficient technique was developed. For a given set of tunnel parameters, the influence coefficients need be calculated only once and then they can be easily applied to any specified wing loading distribution.[7]

Typical numerical solutions are presented in Figs. 2–4. In Fig. 2 the effect of wing span on the lift interference factor at the model location in a square tunnel with slotted floor and roof is compared for uniformly loaded and elliptically loaded wing models. One should expect that for a high aspect ratio straight wing that the calculated interference would be between the small span solution (all the lift distribution at the center) and the uniformly loaded wing (high lift distribution near the wing tips). The effect of wing span on the distribution of lift interference along the centerline of a square tunnel with perforated roof and floor for a uniformly loaded wing is shown in Fig. 3. The effects of wing span at the model location are amplified along the centerline downstream of the model. Thus, a small change in the interference at the model position will largely affect the distribution along the centerline correspondingly producing a strong effect on such aerodynamic data as the pitching moment coefficient. Finally, in Fig. 4, the present analysis is compared with some unpublished experimental data obtained on a straight wing in the Arnold Engineering Development Center 30 × 45 in. V/STOL Pilot Tunnel with slotted horizontal and closed vertical walls. The analytical results were calculated for a uniformly loaded wing with $s/b = 0.524$, the same as the physical wing. The agreement is seen to be excellent.

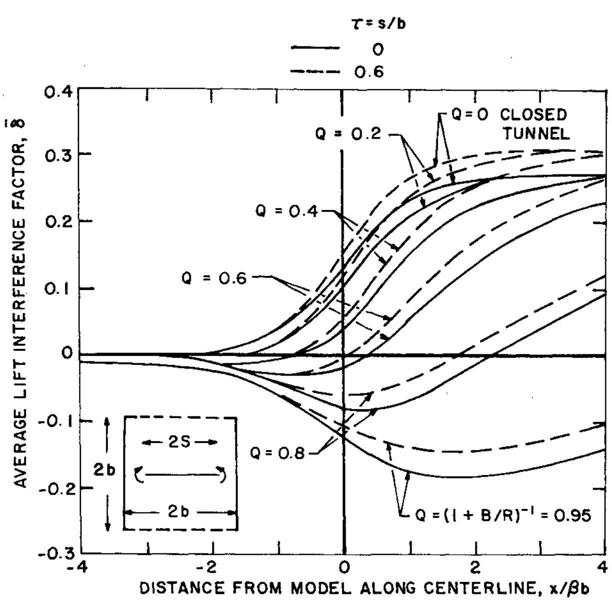

Fig. 3 Interference factor along the centerline of a square tunnel with perforated horizontal and closed side walls for a uniformly loaded wing.

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