Theoretical Aerodynamics of Over-Wing-Blowing Configurations

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Theme

A NUMERICAL method is presented for calculating the aerodynamic characteristics of over-wing-blowing (OWB) configurations. The primary lift mechanisms are identified as the jet entrainment, the wing-jet interaction due to dynamic pressure nonuniformity, and the jet flap effect if the jet intersects the wing. A new jet entrainment formula is derived, based on Kleinstein's compressible turbulent jet theory.[1] Results are compared with available experimental data.

Contents

Previous investigations on OWB aerodynamics[2,3] have been centered on the jet entrainment effect, without properly accounting for the dynamic pressure difference in the flowfield because of the presence of the jet. The predicted lift has been found to be too low as compared with experiments, in particular, when the jet is close to the wing. In this paper, the additional lift induced by the over-wing-blowing jets is attributed to the inviscid jet-wing interaction due to the higher jet dynamic pressure and the jet flap effect. The methods used in computing the jet entrainment effect and the wing-jet interaction are summarized in the following.

Existing methods for computing jet entrainment are mainly for incompressible, nonheated jets.[4] To extend the methods to compressible heated jets, Kleinstein's theory for free compressible jets is revised to include the effect of external stream, with the simplicity of his theory being retained. In this extended theory, the axial velocity is given by

$$\bar{u}_c(\xi) = \mu + (1-\mu)P_0(\xi) \tag{1}$$

$$P_0(\xi) = 1 - \exp[-1/(2\xi)] \tag{2}$$

where $\bar{u}_c$ is the ratio of jet centerline velocity u_c to the jet exit velocity u_j, and μ is the ratio of freestream velocity u_∞ to u_j. The variable ξ is related to the physical axial coordinate $\bar{x}=x/r_0$, r_0 being the initial jet radius, through the following relations:

$$2k_1(\bar{\rho}_\infty)^{1/2}(1-\mu)^{1/2}\bar{x} = \int_0^\xi \mu^{1/2} \frac{d\xi_0}{P_1(\xi_0)^{1/2}\{\ln[(1+2\mu/P_1(\xi_0))/(1+\mu/P_1(\xi_0))]\}^{1/2}} + 0.35 \tag{3}$$

where $\bar{\rho}_\infty$ is the ratio of freestream density ρ_∞ to jet exit density ρ_j and

$$k_1 = 0.0185 + 0.011\mu \tag{4}$$

$$P_1(\xi_0) = (1-\mu)[1-\exp(-1/2\xi_0)] \tag{5}$$

For a given $\bar{x}$, the corresponding ξ value can be found from Eq. (3) through Newton's method and $\bar{u}_c(\bar{x})$ then is computed from Eq. (1). The axial variation of stagnation enthalpy H_c can be found from Eq. (6):

$$\frac{H_c(\xi_h) - H_\infty}{H_j - H_\infty} = 1 - \exp[-1/(2\xi_h)] \tag{6}$$

where ξ_h is related to $\bar{x}$ through Eq. (3) with ξ replaced by ξ_h there, except k_1 is to be divided by the turbulent Prandtl number. With H_c obtained, the temperature variation can be determined from the definition of stagnation enthalpy:

$$H_c = C_p T_c + \tfrac{1}{2}u_c^2 \tag{7}$$

where C_p is the specific heat at constant pressure, and T_c is the static temperature on the jet centerline. Once the axial jet properties are obtained, the jet-entrained mass flow rate per unit distance then can be computed as

$$\frac{\partial m}{\partial x} = 2\pi \frac{\partial}{\partial x}\int_0^{r_j} (\rho u - \rho_\infty u_\infty) r\,dr \tag{8}$$

According to Abramovich's theory,[5] the sectional velocity and density profiles in the fully developed jet region may be assumed to be

$$u = u_\infty + (u_c - u_\infty)(1-\xi_1^{3/2})^2 \tag{9}$$

$$\frac{\rho}{\rho_j} = \frac{R_j T_j}{RT} = \frac{R_j T_j / R T_\infty}{[1 + (T_c/T_\infty - 1)(1-\xi_1^{3/2})]} \tag{10}$$

$$\xi_1 = r/r_j \tag{11}$$

where T is the local static temperature, T_j the jet exit static temperature, and R_j, R are the gas constants of the exit jet and the jet-air mixture, respectively. In the following applications, R_j is assumed equal to R. When Eqs. (9-11) are substituted into Eq. (8), $\partial m/\partial x$ can be expressed in terms of $u_c(\bar{x})$, $T_c(\bar{x})$, and $r_j(\bar{x})$, where $u_c(\bar{x})$ and $T_c(\bar{x})$ have been obtained previously and $r_j(\bar{x})$ is determined from the conservation of jet momentum:

$$\int_0^{r_j} \rho u r (u - u_\infty)\,dr = M \tag{12}$$

The method just described will determine the jet-entrained flow in the fully developed jet region. In the initial region, Abramovich's theory for uniform density and isothermal mixing is used to determine the jet entrained velocity at the jet exit for $\mu = 0$.

$$\frac{2r_0}{m_j}\left(\frac{\rho_j}{\rho_\infty}\right)^{1/2}\frac{\partial m}{\partial x} = 0.145 \tag{13}$$

where m_j is the jet mass flow rate. The variation of $\partial m/\partial x$ from the jet exit to the end of the potential core is assumed to be linear. For $u \neq 0$ and nonisothermal mixing, the en-

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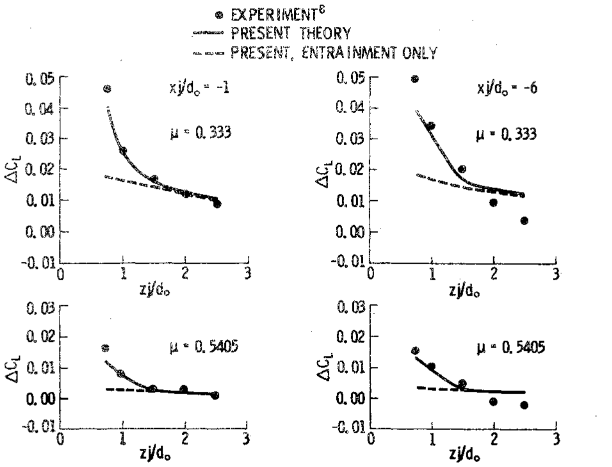

Fig. 1 Comparison of predicted results with Falk's experiment on a rectangular wing of $A\!\!R = 2$, $M_\infty = 0$, $\alpha = 0°$.

trainment at the jet exit is to be modified proportionally in the same way as that at the end of the potential core being modified relative to the freejet value (i.e., at $\mu = 0$). With the jet entrainment determined, its effect on the aerodynamic characteristics can be calculated by using a line sink distribution on the jet axis with strength equal to the entrained volume flow rate, $(\partial m/\partial x)/\rho_j$.

For the wing-jet interaction computation, an equivalent uniform jet evaluated at the midchord of the wing is obtained based on the conservation of mass, momentum, and heat content. This equivalent circular jet boundary is, in turn, replaced by an inscribed polygon on which discrete horseshoe vortices are distributed. Two vortex sheets are used on the jet boundary in order to account for the Mach number nonuniformity,[6,7] in addition to the usual wing vortex sheet. The vortex strengths are determined by satisfying the conditions of flow tangency and static pressure continuity on the jet surface, and the wing flow tangency condition.[7] These boundary conditions are linearized in the analysis, and the jet is assumed to be undistorted and remains parallel to the wing plane. It should be noted that the jet entrained flow is not included in the formulation of the flow tangency condition on the jet surface. Once the vortex strengths are determined, the wing aerodynamic characteristics can be computed as usual.

When the jet is moved toward the wing surface as to wash the wing, the jet deflection at the trailing edge relative to the wing chord would occur even if the flap angle is zero. This deflection angle is equal to or less than the airfoil trailing-edge half-angle. At present, there is no theory available to determine the magnitude of the deflection angle. From examination of available experimental data, it appears that the deflection angle for the thick jet under consideration is a function of freestream/jet velocity ratio μ, jet exit location relative to the wing leading edge x_j, and the jet axis location above the wing (z_j). The first two effects can be combined into one parameter, the equivalent velocity ratio $\bar{\mu}$ of the equivalent jet defined earlier. With $z_j = d_0$, d_0 being the initial jet diameter, correlation with three of Falk's experimental data points[8] gives the following relation for the jet deflection angle:

$$\delta_j = f\delta_e \qquad (14)$$

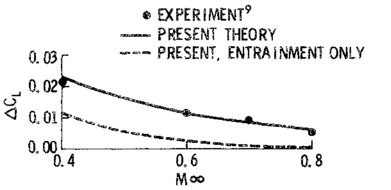

Fig. 2 Comparison of predicted results with Putnam's experiment on a 50° sweep wing of $A\!\!R = 3$, taper ratio of 0.3, $z_j/d_0 = 0.75$, $\alpha = 0°$, and the jet exit at 2.59 d_0 ahead the leading edge of mean geometric chord.

$$f = -29.5428\bar{\mu}^2 + 33.7371\bar{\mu} - 8.9148 \qquad \bar{\mu} \leq 0.6339 \qquad (15)$$

where δ_e is the airfoil trailing-edge half-angle. For $\bar{\mu} > 0.6339$, a linear interpolation between f at $\bar{\mu} = 0.6339$ and $f = 1$ at $\bar{\mu} = 1$ is used. For $z_j \leq 0.75\ d_0$, δ_j is assumed to be δ_e. Again, a linear interpolation is used for $0.75\ d_0 < z_j < d_0$. It should be noted that when this jet flap effect is present, the jet cross section is assumed to be rectangular and the computation will proceed as the upper-surface-blowing case.[7]

The foregoing theory has been applied to various configurations. Figure 1 shows the comparison with Falk's experimental data on a rectangular wing of aspect ratio $A\!\!R = 2$ with a centered jet in incompressible flow. It is seen that: 1) the entrainment-alone theory tends to underestimate the lift for $z_j/d_0 \leq 1.5$; 2) with the interaction effects added, the predicted results agree with experiment reasonably well; and 3) as the nacelle is raised upwards, the theoretical method overpredicts the lift, even with entrainment alone. One possible explanation is that the wing might have been affected by the low-dynamic-pressure viscous layer from the nacelle which is upstream of the leading edge. Comparison with Putnam's experiment[9] is shown in Fig. 2. Again, the entrainment-alone theory is inadequate to predict the lift and the present theory is reasonably accurate.

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