blade generates more circulation because the local sectional angle of attack is larger than that for the upward-moving blade. The pressure distribution on the wing at one spanwise location with and without the propeller (Fig. 5) clearly shows the interference effects on the pressure.

The pressure coefficient on a particular spanwise location on the propeller blades is shown in Fig. 6. This has been normalized with respect to the local relative velocity of that section. The angle of attack of this section with respect to the relative velocity is about 15 deg.

Conclusions

A piecewise constant singularity panel method has been extended to solve for a large class of unsteady, incompressible potential flows in three dimensions. The method was used to solve the unsteady interfering flowfield between a propeller and a wing. Due to the geometry and flowfield, a wake snipping procedure had to be introduced.

The present approach provides an efficient method for calculating the unsteady potential flow about quite complicated configurations. The efficient low-order method used makes an iterative solution practical.

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References

[1]Maskew, B., "Prediction of Subsonic Aerodynamic Characteristics: A Case for Low-Order Panel Methods," *Journal of Aircraft*, Vol. 19, Feb. 1982, pp. 157-163.

[2]Giesing, J.P., "Non-Linear Two Dimensional Unsteady Potential Flow with Lift," *Journal of Aircraft*, Vol. 5, March-April 1968, pp. 135-143.

[3]Djojodihardjo, R.H. and Widnall, S.E., "A Numerical Method for the Calculation of Nonlinear, Unsteady Lifting Potential Flow Problems," *AIAA Journal*, Vol. 7, Oct. 1969, pp. 2001-2009.

[4]Kalman, T.P., Rodden, W.P., and Giesing, J.P., "Application of the Doublet-Lattice Method to Nonplanar Configurations in Subsonic Flow," *Journal of Aircraft*, Vol. 8, June 1971, pp. 406-413.

[5]Morino, L. and Kuo, C.-C., "Subsonic Potential Aerodynamics for Complex Configurations: A General Theory," *AIAA Journal*, Vol. 12, Feb. 1974, pp. 191-197.

[6]Belotserkovski, S.M., "Study of the Unsteady Aerodynamics of Lifting Surfaces Using the Computer," *Annual Review of Fluid Mechanics*, Vol. 9, 1977, pp. 469-494.

[7]Basu, B.C. and Hancock, G.J., "The Unsteady Motion of a Two Dimensional Aerofoil in Incompressible Inviscid Flow," *Journal of Fluid Mechanics*, Vol. 87, July 1978, pp. 159-178.

[8]Katz, J., "A Discrete Vortex Method for the Nonsteady Separation Flow Over an Airfoil," *Journal of Fluid Mechanics*, Vol. 102, Jan. 1981, pp. 315-328.

[9]Morino, L., Kaprielian, Z. Jr., and Sipcic, S., "Free Wake Analysis of Helicopter Rotors," *Vertica*, Vol. 9, Feb. 1985, pp. 127-140.

[10]Kim, M.J. and Mook, D.T., "Application of Continuous Vorticity Panels to General Unsteady Two Dimensional Lifting Flows," AIAA Paper 85-0282, Jan. 1985.

[11]Rangwalla, A.A., "Application of a Potential Code to General Unsteady Problems in Three Dimensions," Ph.D. Thesis, Iowa State University, Ames, IA, 1986.

[12]Chorin, A.J. and Bernard, P.S., "Discretization of a Vortex Sheet, with an Example of Roll-up," *Journal of Computational Physics*, Vol. 13, Nov. 1973, pp. 423-429.

[13]Hess, J.L. and Valarezo, W.O., "Calculation of Steady Flow About Propellers by Means of a Surface Panel Method," AIAA Paper 85-0283, Jan. 1985.

[14]Nishida, M., "The Effect of Displacement Velocity on Propeller Performance," *Journal of Aircraft*, Vol. 20, Aug. 1983, pp. 734-736.

[15]Kobayakawa, M. and Onuma, H., "Propeller Aerodynamic Performance by Vortex-Lattice Method," *Journal of Aircraft*, Vol. 22, Aug. 1985, pp. 649-654.

[16]Kroo, I., "Propeller-Wing Intersection for Minimum Induced Loss," *Journal of Aircraft*, Vol. 23, July 1986, pp. 561-565.

Lift of an Airfoil with a Jet Issuing from Its Surface

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THE lift induced on a two-dimensional wing due to a thin jet emerging from the airfoil's lower surface is estimated by a simple inviscid model. When a thin jet sheet issues from the surface of a wing exposed to a freestream, the jet becomes part of the boundary of a separated flow region. In this analysis, such a separated flow domain is idealized as a deadwater region with constant pressure, bounded by the jet, part of the airfoil surface, and a separation streamline originating at the trailing edge of the wing, as illustrated in Fig. 1. In this model, the effect of the jet is to cause the appearance of a separation cavity under the wing. The cavity is assumed to have a constant pressure equal to the pressure of the freestream. In this case, the cavity must be open and semi-infinite.[1] A similar concept with ground plane interaction was studied by Agarwal and Deese[2] by numerical solution of the Euler equations. Measurements for weak blowing intensities were reported by Krothapali et al.[3] A three-dimensional version of this problem was studied experimentally by Tavella et al.[4]

The mathematical task is a boundary-value problem where the location of part of the boundary is not known a priori. It can be stated as

$$\nabla^2\Phi = 0 \text{ in } \Omega \tag{1}$$

$$\nabla\Phi\cdot n = -U_\infty \text{ on } c_1,\ c_2,\ c_3 \tag{2}$$

$$\nabla\Phi = 0 \text{ on } c_1 \tag{3}$$

$$\frac{(\Delta\Phi + U_\infty)^2}{U_\infty^2} = 1 - \kappa C_\mu \text{ on } c_2 \tag{4}$$

where Φ is the perturbation potential, U_∞ the freestream velocity, κ the jet curvature, and the jet momentum coefficient is defined as $C_\mu = m_j/q_\infty$, with m_j the jet momentum flux per unit length and q_∞ the freestream dynamic pressure. The problem is solved by approximating the wake shape through the vertical coordinates q: $y_1, y_2, y_3 \ldots$, of selected points on the free streamline and jet trajectories. The trajectories are defined by spline interpolation through those points. Equation (1) with the boundary conditions given by Eq. (2) is solved with a panel method. With Eq. (2) and (4), an objective function is

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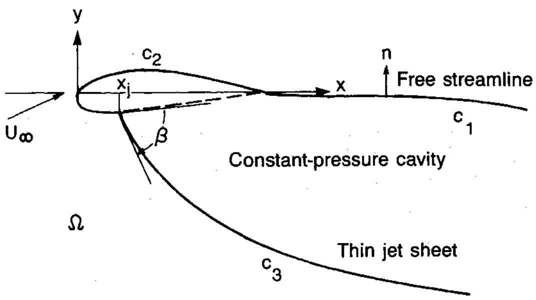

Fig. 1 Inviscid mathematical model.

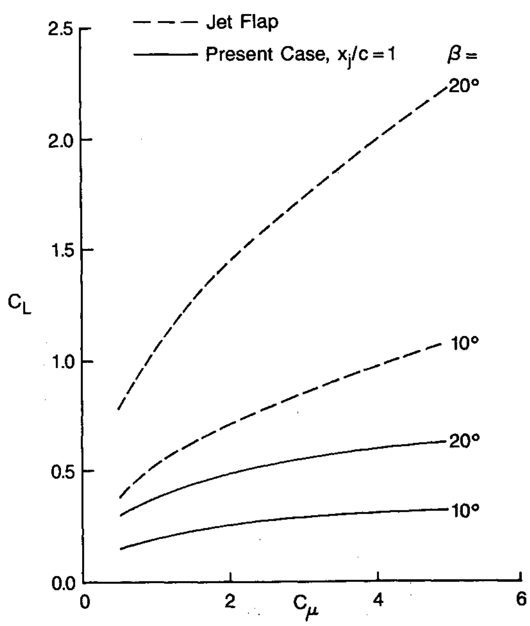

Fig. 2 Comparison with jet flap.

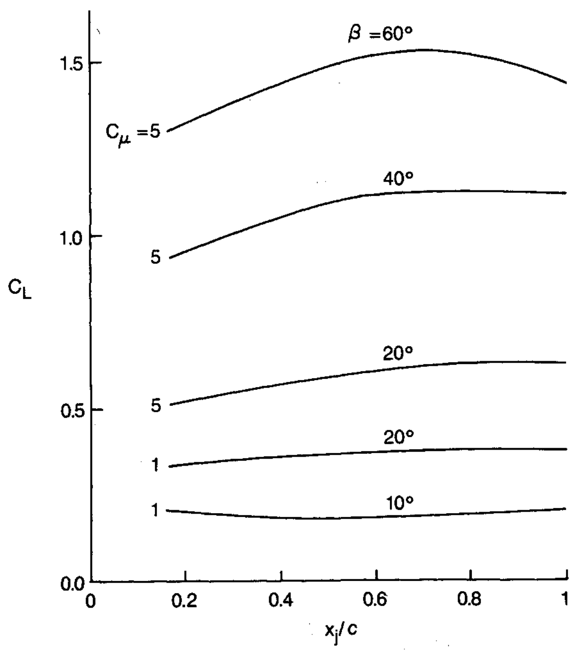

Fig. 3 Effect of jet location on induced lift.

defined as follows:

$$F(q) = |\text{abs}(\nabla\Phi + U_\infty) - \text{abs}(U_\infty)| + \left| \frac{(\nabla\Phi + U_\infty)^2}{U_\infty^2 + \kappa C_\mu - 1} \right| \tag{5}$$

where | | denotes the square norm integrated along c_1 and c_2. The function $F(q)$ is minimized through a nonlinear unconstrained optimization algorithm. The results that follow are for a symmetrical, 10% thick airfoil having an elliptical nose over 25% of the chord, and two parallel sides otherwise. Such an airfoil has a blunt trailing edge immersed in the deadwater domain. Figure 2 shows the lift produced by the present concept with the jet located at the trailing edge, as well as the lift produced by the classical trailing edge jet flap. β is the jet ejection angle, as shown in Fig. 1. The lift shown here is that induced by the aerodynamic forces alone and does not include the vertical component of the jet momentum flux. In this configuration, the present concept retains a semi-infinite wake starting at the trailing edge. Clearly, the jet flap is more efficient as a lift augmenting device. Figure 3 describes the evolution of lift for different jet locations along the lower surface, with location parameters defined in Fig. 1. For moderate jet deflection angles, the aerodynamic lift is almost independent of the jet location.

References

[1]Woods, L.C., *The Theory of Subsonic Plane Flow,* Cambridge University Press, Cambridge, England, 1961, pp. 430–431.

[2]Agarwal, R.K. and Deese, J.E., "Euler Solutions for Airfoil/Jet/Ground-Interaction Flowfields," *Journal of Aircraft,* Vol. 23, May 1986, pp. 376–381.

[3]Krothapali, A., Leopold, D., and Koenig, D., "An Experimental Investigation of Flow Surrounding an Airfoil with a Jet Exhausting from Lower Surface," NASA CR-166131, 1981.

[4]Tavella, D.A., Lee, C.S., Wood, N.J., and Roberts, L., "The Jet Spoiler as a Yaw Control Device," AIAA Paper 86-1806, June 1986.

Hypervelocity Gliding Maneuvers

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Nomenclature

A	= reference area of entry vehicle
C_D	= drag coefficient
C_L	= lift coefficient
D	= drag
g	= acceleration of gravity
L	= lift
ℓ	= lateral distance traversed during turn
m	= vehicle mass
R_0	= planetary radius (6367 km for Earth)
s	= longitudinal distance traversed following maneuver
t	= time

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