Unsteady Flow About a Joukowski Airfoil in the Presence of Moving Vortices

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Abstract

THE motion of discrete vortices in the vicinity of a Joukowski airfoil and the influence of these vortices on airfoil lift and drag are computed using a computer code that has been written based on conformal mapping and unsteady flow analyses. With this computer code, studies are made on the stability of a trapped vortex when perturbed away from its equilibrium position with a finite displacement, on the release of a free vortex at a location upstream from an airfoil, and on the behavior of a moving vortex of increasing strength. Numerical results indicate that under proper arrangements free vortices can be utilized to generate high lift or thrust on an airfoil.

Contents

In this work we study the motion of discrete vortices in the vicinity of an airfoil and compute the airfoil lift and drag as influenced by the moving vortices. The analysis is based on a formulation for the unsteady two-dimensional flow of an inviscid and incompressible fluid past a Joukowski airfoil.

The Joukowski transformation is used to map the symmetric airfoil into a circle, after which the complex potential of the physical flow is readily expressed in the transformed plane. At any instant, the velocities of vortex centers are computed and their displacements at a small time step later are determined using a predictor-corrector integration procedure. To satisfy the Kutta condition at the sharp trailing edge of the airfoil after the vortices have been displaced, a nascent vortex is shed in the wake, while the circulation around the airfoil is readjusted accordingly to keep the total circulation in the flow a constant. The instantaneous lift and drag are computed from the Blasius theorem for unsteady flows. Starting with a given initial condition, the evolution of the unsteady flow is thus computed by repeating this numerical procedure for every marched time step until a desired time level has been reached.

Three problems dealing with a 19.4% thick symmetric airfoil have been tackled using this technique. The results are summarized as follows.

Stability of a Trapped Free Vortex

In a previous work[1] it was found that a free vortex may be captured by an airfoil at certain neighboring positions at which the vortex becomes stationary. An equilibrium position of the captured vortex is considered to be stable if the vortex returns to that position after being displaced away from it. The linearized analysis of Ref. 1 revealed that all equilibrium positions are unstable, except those in a small region near the trailing edge of the airfoil.

We now study the behavior of a trapped vortex when it is displaced by a finite, instead of an infinitesimal, distance from an equilibrium position at which the vortex is stable according to the linear theory. The result of a numerical example is presented for a vortex perturbed from such a position above the trailing edge of the airfoil. The airfoil angle of attack is 5 deg, and the circulation of the trapped vortex is in the clockwise direction. A shown in Fig. 1, after being moved to three different locations marked by A, B, and C, respectively, the vortex always goes away from its equilibrium position. The same is true in every one of the cases that we have examined at different equilibrium positions. We can conclude that the stable equilibrium positions as predicted by the linear theory are all unstable if the perturbation amplitudes are not small. Thus, a discrete vortex cannot be stably trapped by an

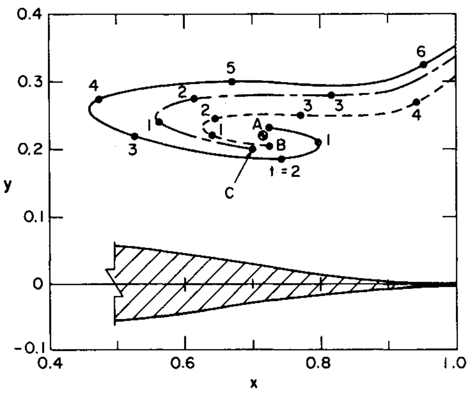

Fig. 1 Trajectories of a vortex when it is displaced from its equilibrium position (partially filled circle) to neighboring points A, B, and C (the angle of attack of the airfoil is 5 deg).

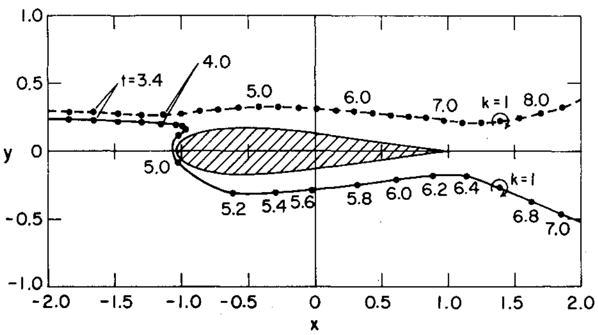

Fig. 2 Trajectories of a vortex of circulation $k=1$ after it is released upstream from a symmetric airfoil at $\alpha=0$. The initial vortex positions are $z=-5+i0.3$ (dashed line) and $z=-5+i0.25$ (solid line), respectively.

Presented as Paper 83-0129 at the AIAA 21st Aerospace Sciences Meeting, Reno, Nev., Jan. 10-13, 1983; received June 7, 1983; synoptic received April 2, 1984. Full paper available from AIAA Library, 555 W. 57th Street, New York, N.Y. 10019. Price: microfiche, $4.50; hard copy, $9.00.

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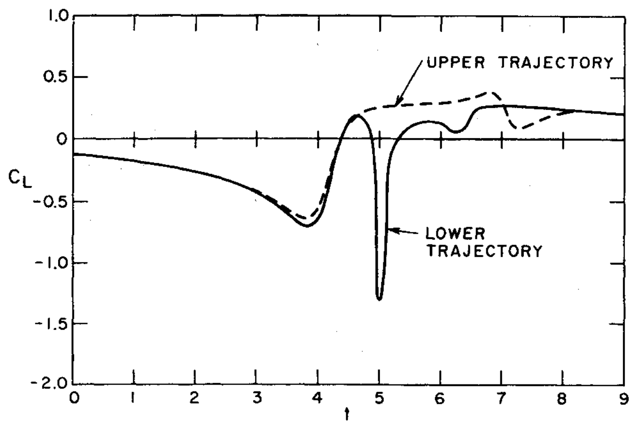

Fig. 3 Variation of lift coefficient with time when the vortex moves along the upper and lower trajectory shown in Fig. 2.

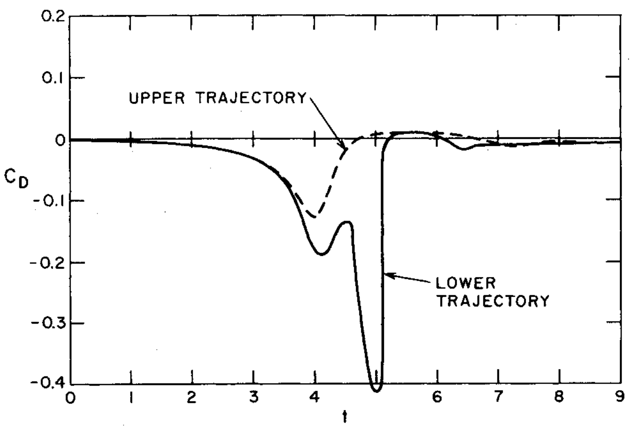

Fig. 4 Variation of drag coefficient with time when the vortex moves along the upper or lower trajectory shown in Fig. 2.

airfoil for lift augmentation without using external devices, such as a leading-edge flap or a spanwise blowing mechanism.

Release of a Free Vortex Upstream from an Airfoil

To study the influence of vortex motion on the aerodynamic performance of an airfoil, a free vortex of dimensionless strength $k=1$ is released at various locations upstream from an airfoil at zero angle of attack. This strength represents a clockwise circulation that would produce a lift coefficient of one if applied around the airfoil. Figure 2 shows two representative trajectories of the vortex, respectively above and below the airfoil. Time histories of lift and drag are plotted in Figs. 3 and 4, which indicate that the direction and magnitude of both the lift and drag are affected by the vortex motion. The result reveals that in a proper motion, a vortex can produce a thrust as well as an unsteady lift that is higher than the steady-state lift the vortex would produce when it were applied around the airfoil.

A Free Vortex of Increasing Strength

We use a crude discrete vortex model to simulate the flow around an airfoil after it becomes stalled at a 20 deg angle of attack. It is assumed that boundary-layer separation on the upper surface creates a weak vortex of clockwise circulation at a short distance upstream from the trailing edge. This vortex acquires such an induced velocity that it starts to move upstream along the upper surface of the airfoil. We assume that a part of the vorticities in the boundary layer swept by the vortex is carried with it, so that its circulation is increasing with time until it starts to move away from the airfoil.

The result obtained for a representative case shows that the lift increases as the vortex moves upstream, reaches a maximum when it is in the proximity of the midchord of the airfoil, and decreases afterward despite a continuing growth of the vortex strength. It is interesting to note that the incremental C_L of the airfoil caused by the moving vortex of variable strength is 2.28 at the peak, whereas if a vortex of the same instantaneous strength were captured by the airfoil the increased C_L would be only 0.7. The same phenomenon is observed in other cases with different initial conditions. It suggests that an efficient high-lift generation technique may be developed utilizing a moving vortex of increasing circulation.

Acknowledgment

The work of C.-Y. Chow was supported by the Air Force Office of Scientific Research under Grant AFOSR 82-0037, administered by Michael S. Francis.

References

[1]Huang, M.-K. and Chow, C.-Y., "Trapping of a Free Vortex by Joukowski Airfoils," *AIAA Journal*, Vol. 20, March 1982, pp. 292-298.