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Technical Notes

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High Aerodynamic Loads on an Airfoil Submerged in an Unsteady Stream

Ismet Gursul* and Chih-Ming Ho†
University of Southern California, Los Angeles, California 90089

Introduction

THE lift coefficients of stationary airfoils are about unity. For pitching and plunging airfoils, the lift coefficients are usually higher than the static ones, but they are still on the order of one. In the present experiment, a NACA 0012 airfoil placed in an unsteady stream is shown to have a phase-averaged lift coefficient of more than 10. This high lift coefficient is produced by a large coherent vortex that sheds from the leading edge and stays on the wing for an appreciable portion of the cycle.

Unsteady aerodynamics has applications in a wide variety of engineering devices: highly maneuverable aircraft, helicopter rotors, and turbomachines. Depending on the type of applications, achieving high lift coefficient or prevention of dynamic stall is desired. Unsteady airfoils in pitching,[1] plunging,[2] and translational[3] motion have been investigated in the past. Several detailed reviews on aerodynamics of two- and three-dimensional lifting surfaces are available.[4-6]

The idea of taking advantage of leading-edge vortices to increase the lift on a large-aspect-ratio airfoil was suggested by Kasper.[7] Two-dimensional inviscid potential flow over a wing with an attached free vortex was calculated by Saffman and Sheffield.[8] It was found that the convex streamlines provide large suction that creates a high lift coefficient for the wing. During maneuver, high lift is needed while the aircraft is decelerating. The leading-edge vortex usually cannot stay on the wing and will shed, leading to loss of high lift. Therefore, understanding the phase relation between the instantaneous lift and the evolution of the vortex is important for poststall operation.

This Note presents the experimental results for a NACA 0012 airfoil at an angle of attack of 20 deg, which is higher than the static stall angle. The freestream velocity was varied over a large range of amplitudes and frequencies. Velocity and lift measurements were carried out. The results show that, at an optimum reduced frequency, phase-averaged lift coefficient can be one order of magnitude higher than the conventional values.

Experimental Facility

Experiments were conducted in a vertical unsteady water channel with a cross-sectional area of 45.7 × 45.7 cm. The flow between the upper and lower reservoirs is gravity fed. The water surface in the upper reservoir is kept at a constant head so that the nonlinear characteristics of the pump is isolated. An essential part of this facility is the lower section, which consists of a rotating gate and a stationary gate each with the same opening pattern. The rotating gate is driven by a stepping motor controlled by a computer. The velocity in the test section is determined by the relative angular displacement between the two gates. This arrangement can provide a wide range of freestream velocity variations with many desired waveforms. For a sinusoidally varying freestream, the velocity can be represented in the form

$$U/U_\infty = 1 + R\cos\omega t = 1 + R\cos 2\pi t/T \tag{1}$$

where U_∞ is the average velocity, R the dimensionless amplitude, and $\omega = 2\pi/T$ the radial frequency. The freestream has been found to be uniform across the test section during the whole cycle as long as the frequency of fluctuations is not large ($\omega \leq 6\ s^{-1}$, so that no boundary-layer separation takes place in the contraction section). The freestream turbulence was about 0.5%. More details about the experimental facility, freestream control, and instrumentation can be found elsewhere.[9]

The chord length of the NACA 0012 airfoil was $c = 12.4$ cm, giving a Reynolds number on the order of 5×10^4 and blockage ratio 0.098. No blockage correction was made for the lift measurements. The freestream velocity was measured by a single component laser Doppler anemometer (DANTEC). A pair of waterproof load cells (Sensotec) was used to measure the lift force on the airfoil. Lift and velocity signals were digitized and processed by an UNIPAQ 386 personal computer. The phase-averaging technique was applied to the signals to extract the deterministic parts.

Flow visualization was carried out by illuminating air bubbles with a thin light sheet. A tungsten light source consisting of two 500-W lamps with a slit was used to illuminate the flowfield. A 35-mm camera was used to take the photographs.

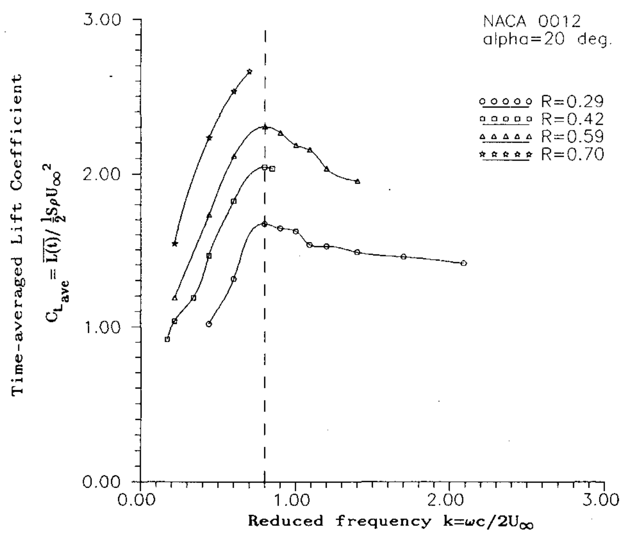

Fig. 1 Time-averaged lift coefficient as a function of reduced frequency and amplitude at an angle of attack of 20 deg.

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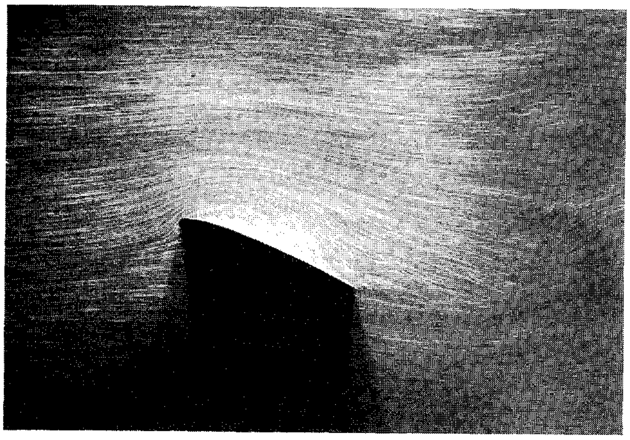
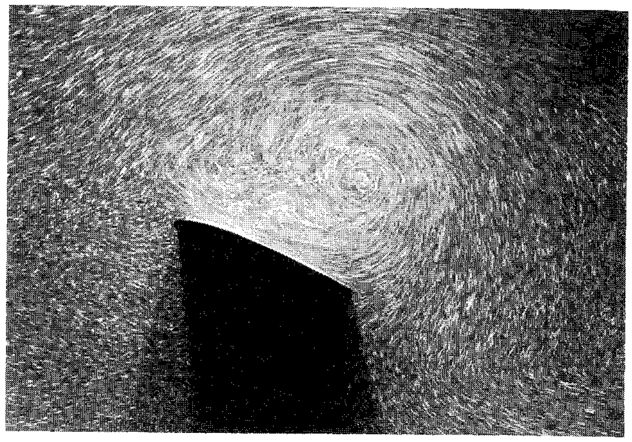
*Research Associate. Member AIAA.

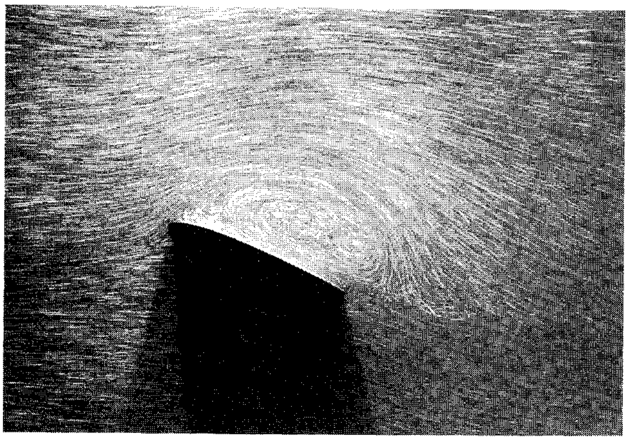
†Professor. Member AIAA.



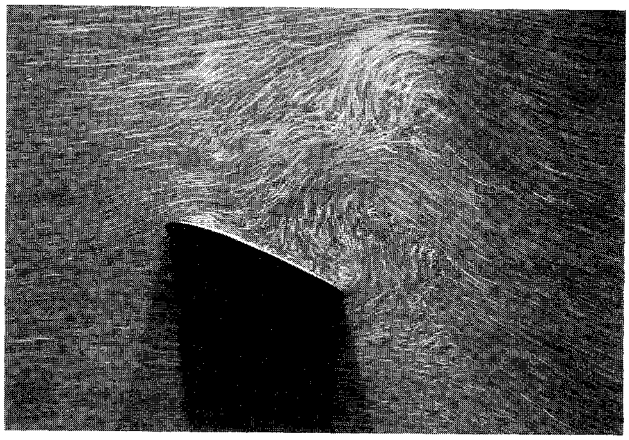
$t/T = 0$



$t/T = 0.50$



$t/T = 0.25$



$t/T = 0.75$

Fig. 2 Instantaneous streamline patterns at several phases during a cycle, $R = 0.70$, $k = 0.70$.

This camera could be triggered by a pulse at an instant that was phase referenced to the angular displacement of the rotating gate.

Experimental Results

It has been shown previously that, during deceleration, the downstream convection of vorticity decreases and the accumulated vorticity forms a separation vortex near the leading edge.[10] The lift increases as long as the convex streamlines reattach on the wing downstream of the vortex. After the vortex leaves the trailing edge, the streamlines do not reattach anymore and the lift drops. Hence, the lift coefficient changes during the cycle of freestream velocity variation. The reduced frequency, $k = \omega c / 2U_\infty$, is the ratio between the traveling time of the vortex along the chord and the period of freestream velocity variation. Therefore, the lift coefficient should be a function of the reduced frequency.

The lift coefficient of the steady NACA 0012 airfoil at this Reynolds number is about 0.8. The time-averaged lift coefficient, defined as

$$C_{L_{\text{ave}}} = \overline{L(t)} / \tfrac{1}{2} S \rho U_\infty^2$$

where $\overline{L(t)}$ is the time-averaged lift force, is shown as a function of the reduced frequency in Fig. 1 for different values of the amplitude R. The average lift coefficient increases with increasing R. At $R = 0.7$, the maximum average lift coefficient is roughly three times larger than the steady value. Note that there is an optimum reduced frequency at which the lift coefficient is maximum. The optimum reduced frequency does not depend on the velocity amplitude and has a value of around 0.8. The additional lift of the unsteady flow is contributed by the leading-edge separation vortex. To produce a high lift coefficient, the wavelength of the vortices should be about the same as the chord length ($\lambda \approx c$) so that highly curved attached streamlines can be achieved during most of the cycle. The wavelength of the vortices is given by

$$\lambda = U_c T = M U_\infty T \tag{2}$$

where $U_c = M U_\infty$ is the convection speed of the vortex and T is the period of the freestream velocity variation. For the case of optimum reduced frequency k_{opt}, $\lambda \approx c$ so that

$$\lambda / c = M \pi / k_{\text{opt}} \approx 1 \tag{3}$$

Measurements by Shih[10] show that $M = 0.35$–0.40. Then it follows that

$$k_{\text{opt}} \approx 1 \tag{4}$$

This simple approach provides a rational basis for estimating the optimum reduced frequency.

Flow visualization was carried out at $R = 0.70$ and at $k = 0.70$, which is close to the optimum value. Because of the limitation of the torque of the stepping motor, the optimum frequency at this amplitude could not be reached. In Figs. 2, instantaneous streamline patterns are shown for different phases during a cycle. At the beginning of the deceleration ($t/T = 0$), the shear layer is already separated from the leading edge and reattaches farther downstream. During the deceleration, this separation bubble grows to a coherent vortex

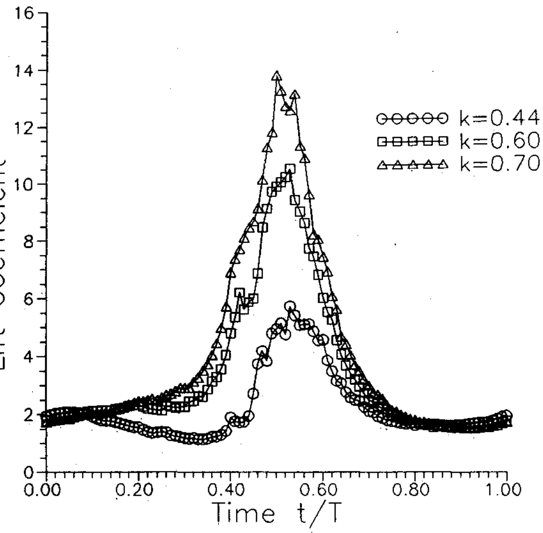


Fig. 3 Variation of phase-averaged lift coefficients for several values of reduced frequency for $R = 0.70$.

($t/T = 0.25$) and becomes very strong in the middle of the cycle when the freestream velocity is minimum ($t/T = 0.5$). With increasing freestream velocity, this vortex is washed away from the wing ($t/T = 0.75$).

In Fig. 3, the phase-averaged lift coefficient, defined as

$$C_L(t) = L(t)/\tfrac{1}{2}S\rho U(t)^2$$

is shown as a function of time over a cycle for several values of the reduced frequency at $R = 0.70$. Note that all phase-averaged lift curves collapse during the acceleration ($0.8 < t/T < 1.0$) due to attached flow. This phenomenon has been observed and studied by Shih.[10] For $k = 0.70$ (corresponding to the flow visualization photographs), the phase-averaged lift coefficient increases as the size of the separation vortex increases (see Figs. 2). At the middle of the cycle, $t/T = 0.5$, the leading-edge separation vortex reaches its climax and is located just above the wing. The size of the vortex is about one chord length. The phase-averaged lift coefficient can be as high as 14 at this moment.

High lift coefficients cannot be explained by acceleration dU/dt (or added mass effect) since the highest lift coefficient during a cycle occurs around $t/T = 0.5$, (when the acceleration of the freestream is zero). At this instant, the large separation vortex (Figs. 2) produces highly convex streamlines over the wing and causes a high pressure gradient in the normal direction to the wing surface. Consequently, this greatly increases the suction on the upper wing surface and explains the large lift coefficient at $t/T = 0.5$. The value of the lift coefficient at $t/T = 0.75$ (when the acceleration is maximum) suggests that the effect of acceleration is small. Moreover, it can be argued that there is no influence of acceleration on time-averaged force (see Fig. 1) since the average value of the acceleration terms is zero (assuming that the load due to acceleration can be written as $a\, dU/dt$, where a is a constant).

Acknowledgments

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Viscous Drag Reduction Using Streamwise-Aligned Riblets

P. Vukoslavčević,* J. M. Wallace,† and J.-L. Balint‡
University of Maryland, College Park, Maryland 20742

I. Introduction

FOR more than a decade, evidence has been accumulating that certain modifications of the geometry of the bounding surface of turbulent shear flows can passively reduce viscous drag. An effective and relatively easy to manufacture modification is a surface of grooves, known as riblets, aligned with the mean flow direction. Although such riblets considerably increase the wetted surface to planform area ratio, they have shown significant net reductions in viscous drag when compared to a similar flow over a flat plate. Their use in the most recent America's Cup regatta caught public attention, and they have been shown to be effective under commercial flight conditions.[1]

A number of investigators have made comparative measurements and computations of the total drag and of the mean and fluctuating velocity fields above riblet and smooth flat-plate surfaces in attempts to document and explain the drag reducing effect of riblets. Walsh and his co-workers,[2-6] using a drag force balance, reported up to 8% drag reduction for triangular riblets of height and span about twice the sublayer thickness, a result later confirmed by the drag balance measurements of Bechert et al.[7] and by pipe flow pressure measurements of Nitschke.[8]

Wallace and Balint[9] compared the streamwise turbulence intensity profiles from various experiments for smooth and riblet surfaces, accounting for the effect on the profiles of Reynolds number variation as documented for smooth surfaces by Purtell et al.[10] With the exception of data of Bacher and Smith,[11] riblets appear to significantly reduce the turbulence intensity over most of the boundary layer, a result that

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*Associate Professor; on leave from Veljko Vlahović University, Mašinski, Fakultet, 81000 Titograd, Yugoslavia.

†Professor, Department of Mechanical Engineering.

‡Assistant Research Scientist, Department of Mechanical Engineering.