High-Incidence Airfoil Aerodynamics Improvement by Leading-Edge Oscillating Flap

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Introduction

FLOW separation has been an important issue of study in fluid mechanics that often occurs in aircraft engineering applications. One of the classical topics involved is the stalled airfoil performance at high angle of attack (α). For an airfoil at a high α, the strong interaction between the separated flow and the freestream creates a complex flow phenomenon, and many techniques, such as acoustic excitation, boundary-layer blowing or suction, and oscillating-flap excitation, have been tested to control the separated flow for improving the airfoil's aerodynamic performance.

In the past few decades acoustic excitation in controlling flow separation has been broadly investigated. However, Chang et al.[1] found that the influence of the internal velocity perturbations on the flow structure is more important than that of the pressure fluctuations. As a result the effectiveness is limited in some cases. When the α of the airfoil greatly exceeds the stalled angle, no significant aerodynamic improvement is achieved by the acoustic excitation technique. For the oscillating-flap excitation technique, Francis et al.[2] mounted a vertical oscillating strip on the surface of the NACA 0012 airfoil and found that the vortex structure generated is very similar to that of dynamic stall over the airfoil. Their results show that the flow structure after the oscillating-strip excitation becomes an energetic rotating fluid. Miau and Chen[3] also studied a vertically oscillating-strip excitation on the turbulent boundary layer over a wall and found that the vortices shed from the oscillating strip enhance the momentum transfer between the freestream and the boundary layer, which makes the reattachment of vortices occur more upstream. Hsiao et al.[4] applied an oscillating flap on the leading edge of a NACA 63_3-018 airfoil and showed that the lift coefficient increases when the excitation frequency corresponds to the vortex-shedding frequency. However, the lift-to-drag coefficient does not always increase. When the leading-edge oscillating flap perturbs the shear layer in the leading-edge portion a better result can be obtained.

Although it has been proven that the sectional lift coefficient of a high-α airfoil is increased by flap excitation at certain excitation frequencies and positions of the flap, no conclusive result was obtained as regards the oscillating mode shapes of the flap motion. In this study, six different oscillating modes of the flap motion are employed to study the effectiveness of the aerodynamic improvement of a high-α airfoil. Phase averaging of pressure fluctuations on the airfoil's surface is calculated for investigating the dynamic leading-edge vortex evolution.

Experimental Setup

The present study was conducted in a low-speed, open-type wind tunnel with a test-section size of 120 × 90 mm, driven by a 200-hp ac motor. The freestream velocity ranges from 5 to 30 m/s. Figure 1a shows the schematic of the experimental apparatus. Thirty-eight pressure orifices on the upper surface and 19 on the lower surface were installed along the chord. An oscillating flap with a 12-mm chord length was mounted near the leading edge on the upper surface of the airfoil. The freestream velocity is 10 m/s, corresponding to a Reynolds number of 1.9×10^5 based on chord c.

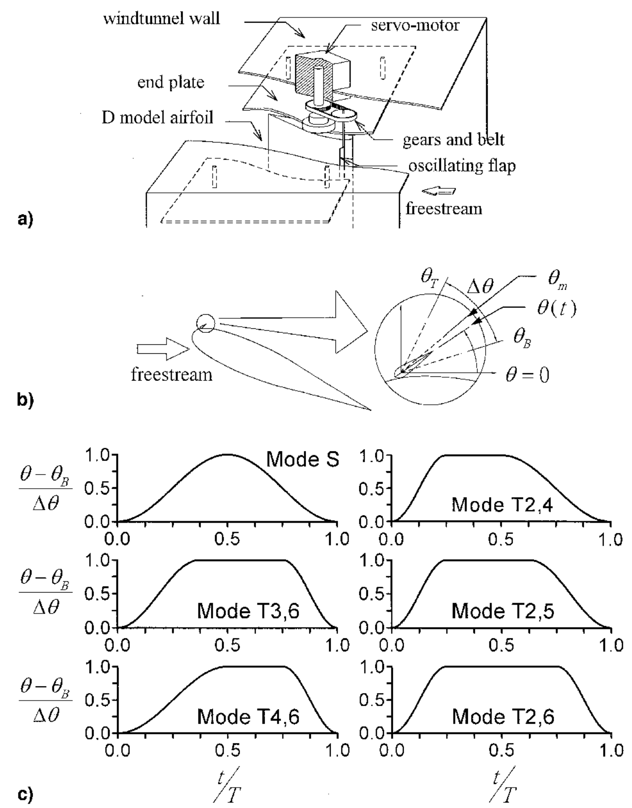

Fig. 1 a) Schematic of experimental arrangement, b) coordinate system of the flap motion, and c) oscillating mode shapes of the flap motion.

The flap motion is determined by the following four parameters as described in Fig. 1b: 1) excitation frequency f_e, its reciprocal is called excitation period T; 2) excitation amplitude $\Delta\theta$, the peak-to-peak value for the flap moving from angle θ_B to θ_T; 3) neutral angle θ_m, the mean position between θ_B and θ_T to determine the neutral position of the flap in motion; and 4) oscillating mode. Six different modes were tested including one sinusoidal wave, mode S, and five trapezoidal waves, mode $T_{i,j}$. All six modes are illustrated in Fig. 1c for comparison.

Experimental Results and Discussion

To understand the basic aerodynamic performance of the airfoil as well as for comparison with the flapping excitation, the two-dimensional airfoil model without the oscillating flap in place is first tested. The sectional lift coefficient is obtained through integration from the pressure distributions along the chord.

The basic excitation parameters of the flap motion, such as excitation frequency, excitation amplitude, and excitation's neutral angle are investigated using the sinusoidal mode, mode S, at a 24-deg α. The results show that the most effective excitation frequency corresponds to the vortex-shedding frequency. This has been confirmed with the hot-wire anemometer measurements. A gradually larger amplitude of excitation tends to increase the lift coefficient but becomes saturated at a certain value. A 50-deg neutral-angle θ_m enables the flap to

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effectively disturb the shear layer and, hence, obtains the maximum lift-coefficient improvement.

The lift coefficient vs α by six excitation modes are plotted in Fig. 2a. In all α tested, the excitation modes clearly form two groups with regard to the effectiveness of excitation: the first group, mode $T_{2,6}$, $T_{3,6}$, and $T_{4,6}$, produces higher lift coefficient than the second group, mode S and $T_{2,4}$; whereas mode $T_{2,5}$ falls between the two groups. At the 24-deg angle-of-attack (AOA) case in Fig. 2, the first group gives as much as a 70% lift-coefficient increase in contrast to a 40% increase in the second group. The aerodynamic improvement with the leading-edge oscillating-flap excitation is not only influenced by the excitation frequency, amplitude, and neutral angle, but is also very sensitive to the oscillating modes of the flap motion.

From the long-time-averaged pressure distributions on the airfoil's surface, the first group, mode $T_{2,6}$, $T_{3,6}$, and $T_{4,6}$, achieves a lower pressure on the upper surface than that of the other modes, and results in a higher lift coefficient. This is clearly shown in Fig. 2b. Furthermore, with the first-group excitation, the lowest pressure occurs around the midchord, indicating that the vortices shed from the leading edge entrain the momentum from the freestream energy to obtain a maximum strength of vorticity around the midchord region. On the contrary, the distributions with the other excitation modes rarely show a plateau. This indicates that the vortex-strengthening mechanism is related to the oscillating modes of the flap motion.

The phased-averaged pressure fluctuation, $-C_p'$, in time along the chord is also calculated from the instantaneous pressure data. The results indicate that the convection speed of the separated vortices and pressure fluctuation intensity also forms two groups, which are in agreement with those in the aerodynamic coefficient calculation. The pressure distributions at a 24-deg α, respectively excited with modes S and $T_{2,6}$, are depicted in Fig. 3. The vortex convection is shown by the lines through the dark region. With mode S excitation, the vortex rolls up and becomes well organized at $0.35c$ and then moves

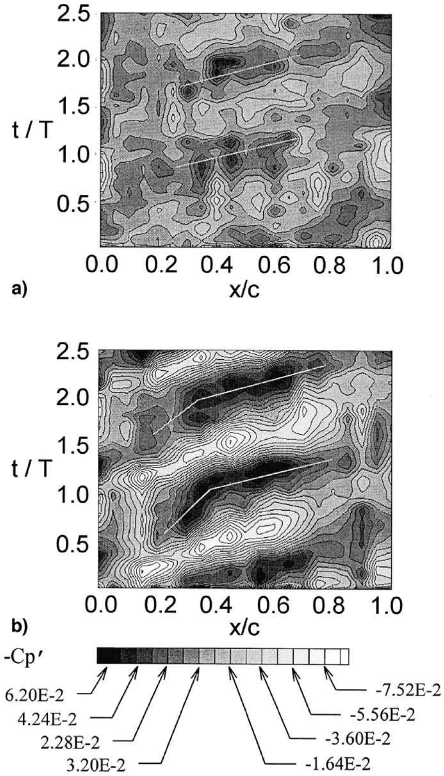

Fig. 3 Phase-averaged pressure distribution in time along chordwise direction, excited by a) mode S and b) mode $T_{2,6}$.

downstream at 65% of freestream velocity U, maintaining about the same strength before $0.65c$. On the contrary, with mode $T_{2,6}$ excitation, the vortex in the leading edge moves slowly but grows quickly to reach the same strength as in Fig. 3a. That is, before $0.35c$, the leading-edge vortex is enhanced quickly but moves slowly with a convection speed of $0.15U$. After $0.35c$, the vortex's convection speed increases to $0.55U$ and the vortex continues to be enhanced before reaching the maximum strength around $0.65c$. Figure 3 also shows that the pressure fluctuation in mode $T_{2,6}$ is much stronger than that in mode S, which means that either a more organized vortex is produced or the trajectory of vortex motion is pulled farther downward to the airfoil, resulting in a better aerodynamic performance because of the vortex lift.

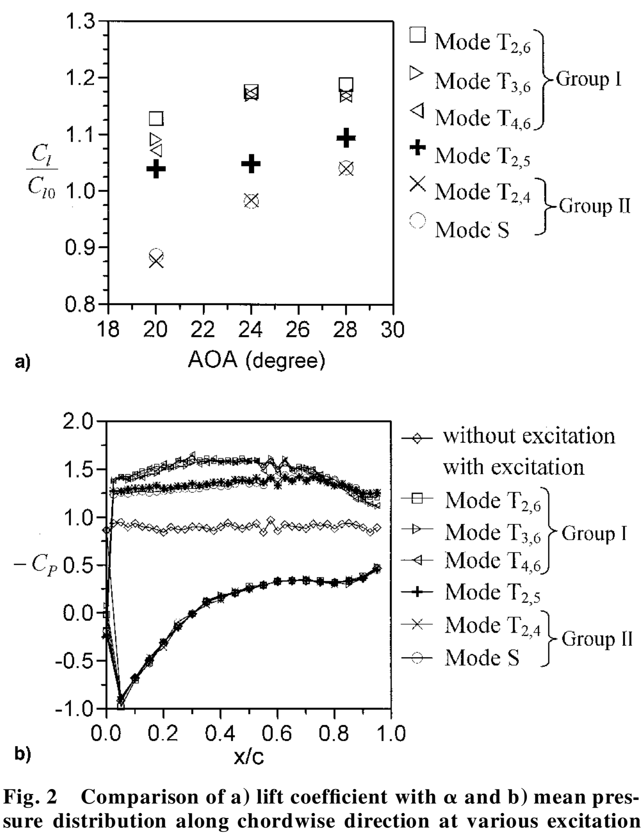

Fig. 2 Comparison of a) lift coefficient with α and b) mean pressure distribution along chordwise direction at various excitation modes.

Concluding Remarks

The effects of the leading-edge oscillating-flap excitation on a NACA63_3-018 airfoil with various oscillating modes were investigated in a low-speed wind tunnel. The long-time-averaging and phase-averaging calculations of pressure distribution over the airfoil surface are fulfilled. The results indicate that the unsteady flowfield above the stalled airfoil is strongly influenced by the oscillating-flap excitation. The parametric study confirms that the most effective excitation corresponds to a flap motion with the vortex-shedding frequency and a 50-deg neutral angle. A larger amplitude of excitation motion also produces a larger lift coefficient. Moreover, the oscillating mode of the flap motion is an important parameter that influences the aerodynamic performance. Excitation with mode $T_{2,6}$, $T_{3,6}$, or $T_{4,6}$ gives a much better lift-coefficient increase than mode S or $T_{2,4}$, whereas that of mode $T_{2,5}$ is in between them. At the stalled α, a 20–45% extra increase of lift coefficient is obtained by the most effective oscillating mode $T_{2,6}$ in comparison to mode S excitation. The excitation mode $T_{2,6}$ not only produces a stronger leading-edge vortex, but also causes an earlier vortex formation and a lower vortex convection speed on the vortex-enhancement process, indicating that the later the flap moves downward the more effective the excitation mode will be. However, the time for the flap to reach the top position shows only a slight influence.

Acknowledgment

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Sweep Effect on Parameters Governing Control of Separation by Periodic Excitation

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Nomenclature

C_l = airfoil lift coefficient
C_p = pressure coefficient
c = airfoil chord
c_{fl} = flap chord
c_μ = steady blowing momentum coefficient, $\equiv J/cq$
$\langle c_\mu \rangle$ = oscillatory blowing momentum coefficient, $\equiv \langle J \rangle /cq$
F^+ = reduced frequency, $\equiv fc/U_\infty$
f = oscillation frequency, Hz
h = slot height
J = average momentum at slot exit
q = freestream dynamic pressure, $\equiv \rho U_\infty^2/2$
Re = chord Reynolds number
U_∞ = freestream reference velocity
$\langle u' \rangle_f$ = phase locked rms level of velocity fluctuations
x/c = normalized streamwise location
α = angle of incidence
δ = flap deflection angle
Λ = sweep angle
ν = kinematic viscosity
ρ = density

Subscripts
2D = two-dimensional flow
3D = swept wing conditions

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Introduction

PERIODIC injection of momentum is a very promising tool in the control of separation. Its effectiveness was proven in two dimensions over a wide range of flow parameters such as Reynolds number, Mach number, and different geometries. Under favorable conditions the maximum lift generated on a flapped airfoil was doubled while its drag was reduced fourfold. However, the effect of sweep on this method of boundary-layer control was never investigated. Thus, to prove the efficacy of the method in applications involving swept-back wings, the effects of sweep have to be known. Furthermore, if the method is to be used as a design tool, a set of transformations is needed to convert data obtained in two dimensions to the cases involving sweep. The purpose of the present investigation is to provide these transformations and verify their validity experimentally.

Experiment

The wind-tunnel facility, oscillatory blowing apparatus, calibration procedure, and measuring techniques are described elsewhere.[1] The specific installation related to the present experiment will be described in this section. The experiment was carried out on a NACA 0018 airfoil (Fig. 1), having a chord of 180 mm. The small chord enabled mounting the airfoil across the larger span of the 0.6 by 1.2 m test section without causing prohibitive wind-tunnel interference. This arrangement provided a sufficiently large aspect ratio making the flow independent of the spanwise location at all yaw angles considered. The maximum aspect ratio was approximately 10.

The airfoil was made of composite materials and was hollow. Because the internal volume served as a settling chamber for the imposed oscillations the thicker airfoil section chosen improved the area ratio between the slot and the settling chamber. The airfoil was equipped with a flap whose total length was 30% of the chord. The blowing slot located above the flap shoulder was 0.9 mm high.

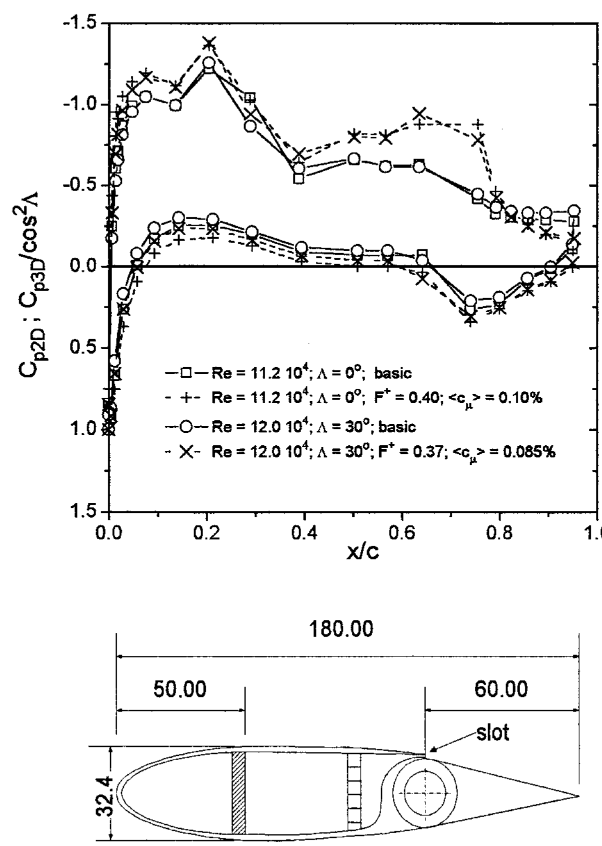

Fig. 1 Comparison of C_{p2D} (Λ = 0 deg) and $C_{p3D}/\cos^2\Lambda$.