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Technical Notes

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Control of Flow Around an Airfoil Using Piezoceramic Actuators

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Introduction

THERE have been many attempts to enhance aerodynamic efficiency through passive and active controls of separated flow over an airfoil.[1–3] Increase in lift by delaying separation has been one of the main subjects. Recently, active control methods have received more attention than passive ones because the former offer the potential for better aerodynamic efficiency than the latter. Among active control methods, steady or unsteady blowing[3–6] has been considered as an effective control method that directly interacts with the flow and delays separation on the airfoil. In this method, however, a certain amount of mass flux should be supplied to the flow.

Recently, the synthetic-jet actuator developed by Smith and Glezer[7] and Smith et al.[8] and the spring-board-type actuator developed by Jacobson and Reynolds[9] have received much attention because they operate at a low energy cost[8] and supply a sufficient amount of net momentum (but with zero-net mass flux) to the flow. These types of actuators have been applied to the flow over an airfoil to increase lift by two groups: Smith et al.[8] located a synthetic-jet actuator at the leading edge of a thick airfoil, whereas Seifert et al.[10] installed a spring-board-type actuator in the middle of an airfoil suction surface. In both papers, the main role of the actuators was to generate strong wall-normal velocity fluctuations (or near-wall vortices), which increased near-wall mixing through vortical interaction. The increased mixing subsequently increased the streamwise momentum near the wall and eventually produced lift enhancement by delaying separation.

Very recently, Jeon and Blackwelder[11] performed an experiment in which a flap-type actuator made of piezoceramic material was attached to the wall in a laminar boundary layer. They found from flow visualization that the net effect of the actuator motion was the increase in the streamwise momentum near the wall. The concept of applying the flap-type actuator to the flow over an airfoil has been considered before.[3] However, there seems to be no published work of investigating a possibility of increasing the near-wall streamwise momentum directly from an energy-efficient flap-type actuator. Therefore, the objective of the present study is to apply an energy-efficient flap-type actuator to the flow over an airfoil (NACA 0012), to increase lift, especially at high angle of attack.

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Experimental Setup

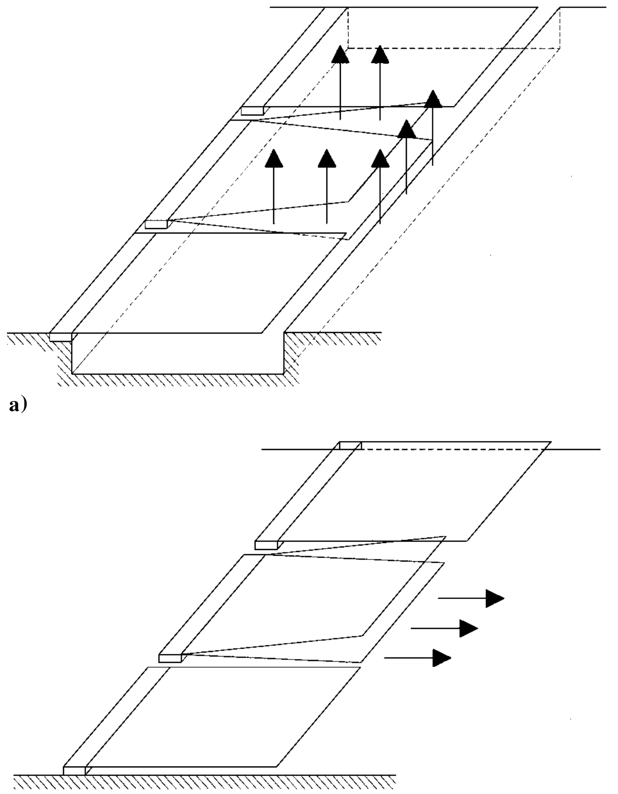
The experiment is conducted in an open-type, low-turbulence wind tunnel. The test section is 0.6 m wide, 0.3 m high, and 3 m long. The airfoil tested is a NACA 0012 airfoil, with a chord length C of 0.3 m and a span of 0.29 m. The Reynolds number based on the chord length and the incoming velocity U of 15 m/s is $Re = 3 \times 10^5$. The boundary-layer flow over the airfoil is tripped with a key chain of 2 mm thickness located at $x/C = 0.003$ on the pressure side of the airfoil, with which the leading-edge separation is avoided even at high angle of attack. An in-house two-component force balance is used to measure the lift and drag forces on the airfoil. The measurement uncertainty is about 1% in the lift coefficient C_L and 2% in the drag coefficient C_D.

The present actuator is made of a spring steel ($38 \times 38 \times 0.13$ mm) on which a unimorph piezoceramic material sheet (19×38 mm) is bonded. Seven actuators are mounted along the span of the suction surface with 2-mm gap between adjacent actuators. Their trailing tips are located at $x_t/C = 0.4$. The position of the actuators is determined to be an upstream location of the separation point at α (angle of attack) = 14 deg, for an effective control of separation at high angles of attack.[5] When the actuators are still, their trailing tips are located 1.2 mm away from the airfoil surface. Seven actuators are simultaneously driven in phase at the input voltage of 30 V and at the resonant frequency of about 170 Hz. The electrical current for their operation is 21.5 mA; thus, the power required is 0.645 W. The reduced frequency is $f^+ = f(C - x_t)/U \approx 2$, which is known to be an effective frequency for separation control.[5] At this condition, the peak-to-peak displacement at the trailing tip of each actuator is approximately 3 mm.

Figure 1 shows the schematic of the present actuator installation, compared with that of Seifert et al.[10] Seifert et al.[10] flush mounted piezoceramic actuators at the midchord along the span of an airfoil suction surface. The actuators were operated such that the fluid was ejected and sucked in the wall-normal direction (Fig. 1a), resulting in generation of strong streamwise vortices. In the present experiment, the piezoceramic actuators are attached to the suction surface of an airfoil, as shown in Fig. 1b. The actuators are operated such that the fluid underneath the actuators is ejected in the streamwise direction, adding net streamwise momentum to the boundary-layer flow.

Results

Figure 2 shows the lift coefficients and the quarter-chord pitching moment coefficients with and without control (cases of actuator on and off, respectively), together with those in the absence of the actuators (case of no actuator). Here the measurements are conducted up to near the stall angle. At low angle of attack, the lift coefficients for the cases of actuator on and off are smaller than that for the case of no actuator. On the other hand, at high angle of attack, the actuation increases C_L because the added momentum delays the trailing-edge separation. Specifically, the stall angle is increased by about 2 deg due to control, as compared to the case of no actuator. The maximum lift coefficient is also increased by 10 and 17%, respectively, as compared to the cases of actuator off and no actuator. The quarter-chord pitching moment coefficient becomes nearly zero with actuators at all of the angles of attack investigated, whereas it is negative at high angle of attack without actuators. As already mentioned, the seven actuators were simultaneously operated in phase.



a)

b)

Fig. 1 Schematic of the actuator installation: a) spring-board type[10] (generating the wall-normal velocity) and b) flap type (present study, generating the streamwise velocity).

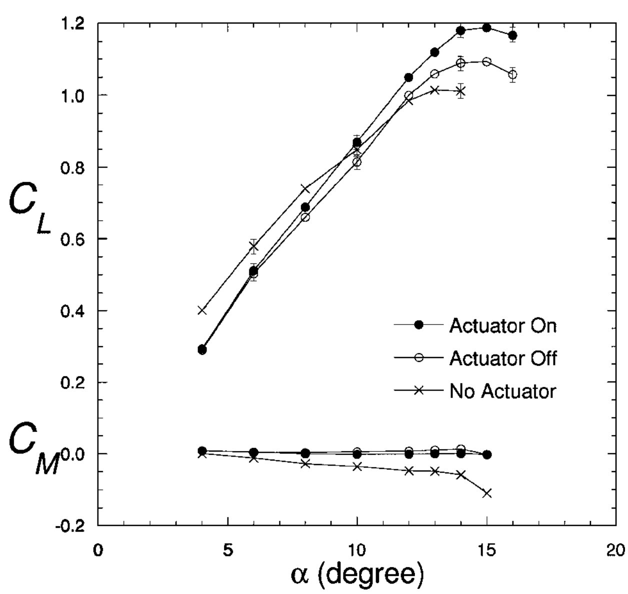


Fig. 2 Variations of the lift and moment coefficients with control; measurement uncertainty indicated with bars.

We have also operated them in different phases, but the result was nearly the same as that shown in Fig. 2.

Note that, at high angle of attack, the increase in lift in the case of actuator off is quite significant and is about half of that in the case of actuator on, presumably because disturbances shed by the still actuators in the flow energize the boundary layer. This suggests a possibility that a more optimal passive control produces the increase in lift as much as the present active control does. However, this is certainly beyond the scope of the present work and is left for future work.

The power efficiencies,[10] $C_L/(C_D + C_E)$, with and without control are shown in Fig. 3, where C_E (input power coefficient) =

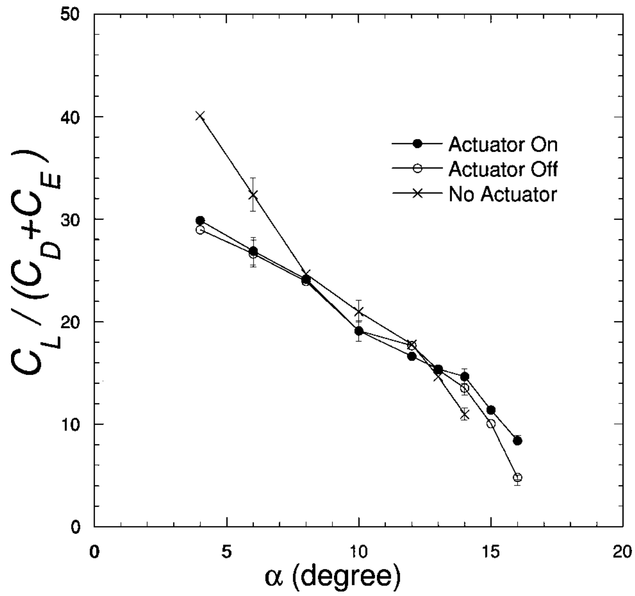
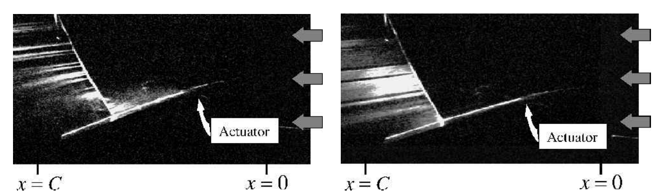


Fig. 3 Variation of the power efficiency with control; measurement uncertainty indicated with bars.



a) Actuator off b) Actuator on

Fig. 4 Flow visualization (fluid flows from right to left) using smoke generation at $\alpha = 15$ deg.

$W_i/(0.5\rho S U^3)$, where W_i is the electrical input power required to operate the seven actuators, ρ is the density, and S is the airfoil planform area. In the present study, $C_E = 0.0037$, which is much smaller than C_D at all of the attack angles considered. The power efficiency for the case of actuator off is worse at low angle of attack and better at high angle of attack than that for the case of no actuator. With actuator on, the power efficiency is not significantly changed at $\alpha \leq 13$ deg, but is improved at high attack angles ($\alpha \geq 14$ deg). For instance, the power efficiency increases by 75% at $\alpha = 16$ deg due to control.

The changes in the flowfield due to control are studied using flow visualization at $\alpha = 15$ deg. Figures 4a and 4b show the instantaneous streaklines, respectively, in the cases of actuator off and on, where the smoke is released at $x/C = 0.75$. With actuator off (Fig. 4a), the streaklines clearly show the separation downstream of the actuators (the separation occurs at $x/C \simeq 0.45$), whereas attached flow is observed with actuator on in Fig. 4b, indicating the delay of separation due to control.

Summary

The present study shows that the flap-type piezoceramic actuators attached to the airfoil suction surface can effectively increase the lift force and the power efficiency at high angle of attack by directly adding the streamwise momentum.

Acknowledgment

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Slug Frequency Measurement Techniques in Horizontal Gas–Liquid Flow

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Nomenclature

D = pipe diameter, m
d = bubble diameter, m
f = frequency, Hz
f_M = mean slug frequency, Hz
f_S = spectral component, Hz
J_g = gas superficial velocity, m/s
J_l = liquid superficial velocity, m/s
P_g = phase density function
P_g^* = filtered phase density function
s = sampling rate, Hz
T = time series duration, s
T_g = gas bubble duration, s
T_i = ith slug unit duration, s
t = time, s
y = vertical distance from pipe top wall, m
z = distance from pipe inlet, m

I. Introduction

THE cocurrent flow of gas and liquid has great importance in a huge variety of devices, including aerospace and microgravity systems. In many such applications, the so-called horizontal intermittent flow is encountered. This flow regime is characterized by an intrinsic unsteadiness, due to the alternating of liquid slugs filling the whole pipe cross section and of regions in which the flow consists of a liquid layer and a gas layer. The liquid slug together with one of the adjacent stratified regions is sometimes called a cell or slug unit. The intermittent behavior causes high pressure and flow rate fluctuations, so that an extremely careful design of the pipeline components (valves, orifices, etc.) is required. Moreover, the low-frequency values of the slugs (few hertz) may be in resonance with the characteristic frequency of the pipeline itself, causing serious damages if not taken into account. Thus, the correct prediction of slug frequencies is essential in all practical applications of gas–liquid horizontal flow. From another point of view, the slug frequency (or, alternatively, the slug length) is an input parameter of all of the slug flow models existing in the literature, such as those by Fabre and Linè[1] and De Henau and Raithby.[2]

During the past few decades much effort has been devoted to the investigation of slug frequency. Unfortunately, the results obtained were not in proportion, both because there is no theoretical description of this phenomenon and because the slug frequency shows no clear relationship with other quantities such as the void fraction or the pressure gradient. Most of the existing correlations are essentially empirical and express the average slug frequency as a function of the superficial velocities of the two phases, such as the correlation by Gregory and Scott.[3] Attempts to form theoretical predictions have been made, for example, by Taitel and Dukler[4] and Tronconi,[5] but their models are not applicable under several flow conditions.

In the absence of a complete mathematical description of slug flow, slug frequency must be estimated from statistical measurements. The methods commonly used consist in simply counting the number of slugs per unit time, as proposed by Hubbard,[6] or in taking the reciprocal of the mean time delay between two consecutive slugs, as proposed by Ferré.[7] The two definitions, which are perfectly equivalent to each other as one can easily verify, provide for a mean slug frequency value. A completely different approach to slug frequency measurements is represented by the Fourier analysis of the optical probe output. In fact, the power spectral density (PSD) maximum indicates the most important harmonic component, which is not necessarily the same as the mean frequency estimated with the earlier mentioned methods. Moreover, the PSD may exhibit additional peaks, corresponding to the frequencies of other meaningful harmonic components. A comparative analysis of the two different methods for measuring slug frequency is presented here.

II. Experiments

The experiments were carried out on air–water flow at atmospheric pressure and temperature, in a horizontal pipe of 0.08 m i.d.; the water mass flow rates were 3, 4.5, 7, and 10 kg/s, whereas the gas fraction of volume flow ranged from 0.2 to 0.8. Correspondingly, the superficial velocities were 0.6, 0.9, 1.4, and 2 m/s for the liquid and ranged from 0.3 to 8 m/s for the air. The experimental facility is schematically shown in Fig. 1.

Three single fiber optical probes were introduced into the test section at 96, 101, and 104 diameters from the pipe inlet, where the flow could be considered fully developed.[8] These probes have a conical tip, which is sensitive to the refractive index of the surrounding medium, so that the output is a binary signal, which is equal to 1 if the tip is surrounded by air and to 0 if it is surrounded by water (the so-called phase density function). This kind of instrumentation is well known,[9,10] and, although extremely delicate, it provides for highly accurate local measurements as compared with other instruments.[11]

The probes were moved along the vertical diameter of the pipe cross section by micrometric screws. The phase density function $P_g(t)$ was measured at five points uniformly distributed in the upper part of the pipe (0.05, 0.1, 0.15, 0.2, and 0.25 i.d. from the top). The time series duration and the sampling rate were set based on previous measurements.[8] In particular, the duration of each time series was 400 s to obtain steady local void fraction values; the sampling rate was adjusted to 2 kHz, so that the instrument could distinguish small bubbles or drops.

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