JOURNAL OF AIRCRAFT
Vol. 45, No. 6, November–December 2008

Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Leading-Edge Surface-Manipulated Flow Separation from an Airfoil

Hong J. Zhang*
China Jiliang University, Hangzhou, People's Republic of China
and
Yu Zhou†
The Hong Kong Polytechnic University, Hong Kong, People's Republic of China

DOI: 10.2514/1.36998

Nomenclature

A	=	perturbation amplitude
b	=	span of the wing
C_D	=	drag coefficient
C_L	=	lift coefficient
c	=	chord length of the wing
f_e	=	perturbation frequency
f_v	=	frequency of vortex shedding from the wing
Re	=	Reynolds number, $\equiv U_\infty c/\nu$
U_∞	=	freestream velocity
x, y, z	=	coordinates in the streamwise, lateral, and spanwise directions, respectively
α	=	angle of attack
ν	=	kinematic viscosity of the air

I. Introduction

FLOW separation is almost inevitable without applying any flow control, especially for the micro aerial vehicles (MAVs) and small-scale unmanned aerial vehicles (UAVs), which are characterized by relatively low Reynolds numbers [1]. Efforts have been made to suppress or delay flow separation in the last few decades. Other than extensive investigations into passive flow control, many active flow control schemes have been reported, for example, a pulsed momentum injection, a pulsed vortex generator, a microelectromechanical-system-controlled deployable micro vortex generator, and a high-frequency microvortex generator [2,3]. Zaman et al. [4] used acoustic excitation to delay flow separation from an airfoil. They achieved the most effective separation control at frequencies at which the acoustic standing waves forming in the test section induced transverse velocity fluctuations in the vicinity of the airfoil. Holman et al. [5] used two closely spaced piezoelectric-driven synthetic jets to control flow separation. This control appeared to be independent of relative phase and could be achieved without forming a mean jet. Zero-net mass-flux oscillatory jets, or synthetic jets, have been demonstrated to be feasible for industrial applications and effective in controlling flow separation [6,7]. Recently, Gilarranz et al. [8] performed an experimental study of flow separation from a NACA 0015 airfoil with synthetic jet control at the chord-length-based Reynolds number of 8.96×10^5. Their actuator was placed in a 2-mm-wide slot, across the entire length of the span, and at 12% of the chord measured from the leading edge on the suction side of the airfoil. They observed an 80% increase in the maximum lift coefficient and an increased stall angle from 12 to 18 deg. Huang et al. [9] demonstrated that flow separation could be effectively controlled by loudspeaker-produced acoustic excitation at the leading edge of an airfoil. An adaptive wing technique was developed for MAVs and UAVS [10]. Munday et al. [11], Pern et al. [12], and Santhakrishnan et al. [13] proposed a method using THUNDER actuators to realize adaptation and improve the aerodynamic performance of airfoils.

In this paper, a technique has been developed to control flow separation from an airfoil. Piezoelectric ceramic THUNDER actuators were installed on the suction side near the leading edge of the airfoil. Once excited, these actuators may create local surface perturbation and, hence, suppress or postpone flow separation.

II. Experimental Details

Experiments were carried out in a closed-circuit low-speed wind tunnel with a 2.4-m-long square working section (0.6 × 0.6 m). A wing of the NACA 0015 cross section was used, with a chord length of $c = 0.2$ m and a span of $b = 0.56$ m, resulting in an aspect ratio of 2.8. The airfoil was made with a slot of $0.07c$ in width on the upper surface and $0.08c$ downstream of the leading edge, in which two piezoelectric ceramic THUNDER actuators were installed. Without any loading, the actuator may vibrate at a maximum displacement of about 2 mm and a frequency of up to 2 kHz. The actuators were fixed at one end, whereas the other end was free, so that the actuators could create a perturbation displacement normal to the airfoil surface (Fig. 1). The actuators were connected to a 1.5-mm-thick plastic plate, flush with the surface of the airfoil. Driven by the actuators, this plate could oscillate in a direction normal to the airfoil surface to create a local perturbation. The actuating sinusoidal signals were generated by a signal generator and amplified by a piezodriver amplifier (Trek PZD 700). Refer to [14] for more details of the actuator and the amplifier.

The actuator and the thin plate, combined together, form a dynamically nonlinear system, the dynamic response of which may vary with the activating frequency. A test was conducted under a constant voltage of 110 V applied to the actuators. The amplitude of the perturbation displacement, A, of the thin plate was measured using a Polytec series 3000 Vibrometer. The excitation frequency, f_e, examined presently was 20–840 Hz. It is found that the amplitude, A, reaches the maximum, 0.6 mm, at $f_e \approx 80$ Hz and then decreases quickly for higher f_e. A is about 0.05 mm at $f_e \approx 200$ Hz and varies little with a further increase in f_e.

The wing was fixed on the bottom wall of the wind tunnel at one end through a cylinder rod. The other end was fixed on a three-component quartz piezoelectric load cell (Kistler model 9251A). Efforts have been made to ensure that the load cell measured only

Received 5 February 2008; revision received 12 August 2008; accepted for publication 24 August 2008.

*College of Metrology and Measurement Engineering; zhanghongjun@cjlu.edu.cn.
†Department of Mechanical Engineering; mmyzhou@polyu.edu.hk.

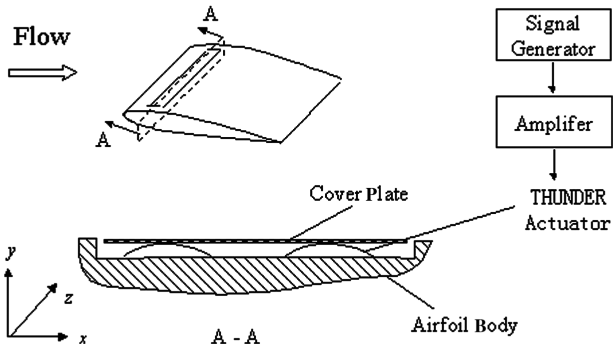

Fig. 1 Installation of actuators.

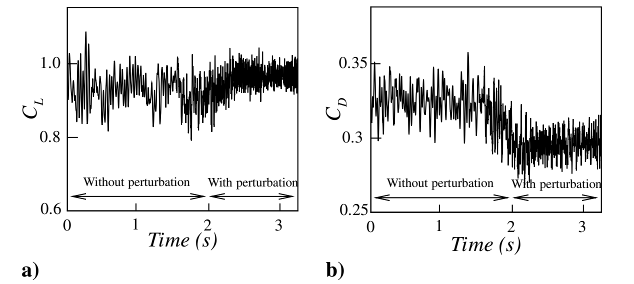

Fig. 2 Drag and lift signals measured from the load cell, with and without perturbation of 260 Hz.

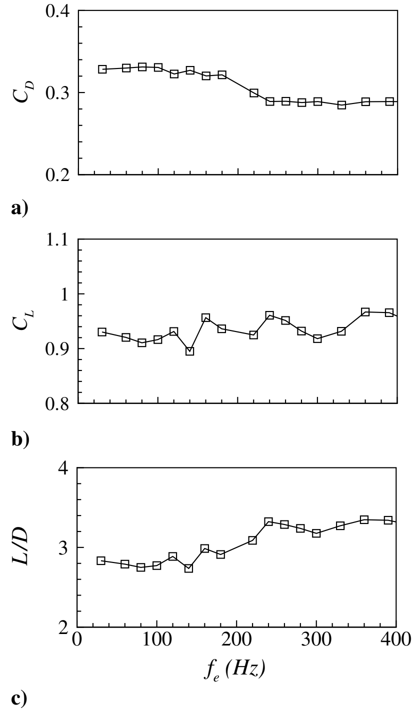

Fig. 3 Dependence of C_L, C_D, and L/D on the perturbation frequency ($\alpha = 11$ deg).

drag and lift forces and excluded the effects of bending and twisting moments. The electrostatic charge (pC) generated by the load cell is converted through a charge amplifier (Kistler model 5011) into a proportional voltage.

A single hot wire was placed at $0.1c$ upstream of the trailing edge and $0.2c$ away from the upper surface of the wing to monitor the dominant vortex frequencies and the flow characteristics, separated or attached. The load cell and hot-wire signals were recorded by a computer data acquisition system at a sampling frequency of 3500 Hz per channel. Measurements have been performed at the freestream velocity of $U_\infty = 9$ m/s or $Re = 1.2 \times 10^5$.

III. Results and Discussion

The hot-wire signal indicated that flow separation from the leading edge of the airfoil began at $\alpha \approx 11$ deg. At $\alpha = 11$ deg, stall occurred without surface perturbation. Then, the leading-edge surface perturbation was introduced with f_e increasing from 20 to 840 Hz. As evident in Table 1, when f_e was lower than 200 Hz, that is, $f_e C/U_\infty < 4.4$, the perturbation had little effect on the flow. However, once f_e exceeded 200 Hz, or $f_e C/U_\infty > 4.4$, the separated flow reattached, that is, the perturbation became effective.

As flow separation was suppressed, the aerodynamic performance of the airfoil was considerably improved. Figure 2 shows the drag and lift signals measured from the load cell without and with perturbation ($\alpha = 11$ deg, $f_e = 260$ Hz). As perturbation was introduced, there was a sharp drop in drag and a climb in lift. Meanwhile, the force fluctuations shrank, dropping by 37% in the rms value of the drag signal and 55% in the rms value of the lift signal when compared with the uncontrolled case. The variation in drag and lift is obviously due to a change from the separated to reattached flow.

The excitation frequency plays a crucial role in the present control of flow separation. Figure 3 presents the dependence on f_e of C_L, C_D, and their ratio. At $f_e < 220$ Hz, C_L, C_D, and their ratio change little. Once f_e is beyond 220 Hz, there is a decrease in C_D of 14% and an increase in C_L of about 7%, leading to an increase in L/D from 2.7 to 3.3, exceeding 20%.

Figure 4 displays the power spectral density functions, E_D and E_L, of the drag and lift signals. An arbitrary scale was used in the plot, as the frequency information is presently of main concern. The peak at $f \approx 40$ Hz is due to the oscillation at the natural frequency of the airfoil, which appears independent of flow velocity. In the absence of perturbation, the dominant vortex shedding frequency was $f_v = 18$ Hz, at which a pronounced peak occurs in E_D and E_L. The pronounced peak at f_v in E_D is also partially due to f_v approaching the half-natural frequency of the airfoil. With perturbation introduced, E_L is significantly reduced in the range of lower frequencies, say, less than 40 Hz, indicating a much lower fluctuation in the lift.

It is found that the perturbation frequency, f_e, must be much higher (about 10 times) than the vortex shedding frequency of the airfoil to enable flow control to be effective. The observation points to the excitation of the instabilities of the boundary layer, which are characterized by frequencies significantly higher than that of vortex shedding. Based on large eddy simulation, You and Moin [15] evaluated the effectiveness of synthetic jets as actuators for a NACA 0015 airfoil flow control. In their work, the actuating frequency $f_e C/U_\infty = 1.24$. Greenblatt and Wygnanski [16] proposed that the optimal reduced actuation frequency, $F^+ = f_e x_c/U_\infty$ (x_c was defined as the distance from the jet actuator to the tail of the airfoil), should be in the order of 1 for turbulent separation. F^+ is presently great than 4.1, much higher than the vortex shedding frequency. In their investigation to control vortex shedding from a circular cylinder based on internal acoustic excitation, Hsiao and Shyu [17] observed the most effective excitation frequency near the shear-layer instability frequency, which was 1 order of magnitude

Table 1 Perturbation frequencies and control performance ($\alpha = 11$ deg)

Perturbation freq., Hz	60	100	160	200	220	240	260	300	400	600	800
Effective control	N	N	N	N	Y	Y	Y	Y	Y	Y	Y

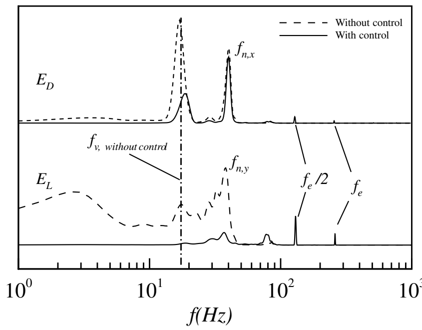

Fig. 4 Power spectral density functions of drag and lift signals ($\alpha = 11$ deg).

higher than the vortex shedding frequency. Similar to flow around a cylinder, the boundary-layer separation from an airfoil is closely linked to the shear-layer instability. In her manipulation of laminar boundary-layer separation based on a microsynthetic jet actuator, Hong [18] noted that the reduced frequency should be in the order of 1 of the Kelvin–Helmholtz instability or the Tollmien–Schlichting instability to enable effective flow control. One may surmise that the present perturbation at a frequency near that of the shear-layer instability transfers energy into the boundary layer and leads to early transition from the laminar to turbulent boundary layer; thus, the shear layer is prevented from rolling up into large-scale vortices, which is beneficial for the boundary-layer reattachment.

It is noted that the control does not work beyond 13 deg, that is, the α range at which the control is effective is only about 0–2 deg at present. This may be attributed to the low perturbation amplitude or very low power input. It is believed that the α range of effective control can be enlarged to some degree if the perturbation amplitude is increased.

IV. Conclusions

THUNDER piezoceramic actuators were used to control boundary-layer separation from a NACA 0015 airfoil at $Re = 1.2 \times 10^5$. The high-frequency perturbation can make the separated flow reattach on the airfoil and increase the static-stall angle of attack by about 2 deg, resulting in a decrease in the drag of about 14% and an increase in the lift of 7% and in the lift-to-drag ratio of 20%. It is found that the perturbation frequency needs to exceed 10 times of the dominant frequency of vortex shedding from the airfoil to achieve an effective control of the flow.

Acknowledgments

The authors are grateful for support given by the Research Grants Council of the Government of the Hong Kong Special Administrative Region through grant PolyU 5334/06E and by the Science and Technology Department of Zhejiang Province, People's Republic of China, through grant 2007C21G2080057.

References

[1] Katam, V., LeBeau, R. P., and Jacob, J. D., "Simulation of Separation Control on a Morphing Wing with Conformal Camber," AIAA Paper 05-4880, June 2005.

[2] Tilmann, C. P., Kimmel, R., Addington, G., and Myatt, J. H., "Flow Control Research and Applications at the AFRL's Air Vehicles Directorate," AIAA Paper 04-2622, June 2004.

[3] Amitay, M., Smith, D. R., Kibens, V., Parekh, D. E., and Glezer, A., "Aerodynamic Flow Control Over an Unconventional Airfoil Using Synthetic Jet Actuators," *AIAA Journal*, Vol. 39, No. 3, 2001, pp. 361–370.
doi:10.2514/2.1323

[4] Zaman, K. B. M. Q., Bar-Sever, A., and Mangalam, S. M., "Effect of Acoustic Excitation on the Flow over a Low *Re* Airfoil," *Journal of Fluid Mechanics*, Vol. 182, 1987, pp. 127–148.
doi:10.1017/S0022112087002271

[5] Holman, R., Gallas, Q., Carroll, B., and Cattafesta, L., "Interaction of Adjacent Synthetic Jets in an Airfoil Separation Control Application," AIAA Paper 03-3709, June 2003.

[6] Glezer, A., and Amitay, M., "Synthetic Jets," *Annual Review of Fluid Mechanics*, Vol. 34, Jan. 2002, pp. 503–529.
doi:10.1146/annurev.fluid.34.090501.094913

[7] Wygnanski, I., "The Variables Affecting the Control Separation by Periodic Excitation," AIAA Paper 04-2505, June 2004.

[8] Gilarranz, J. L., Traub, L. W., and Rediniotis, O. K., "A New Class of Synthetic Jet Actuators—Part II: Application to Flow Separation Control," *Journal of Fluids Engineering*, Vol. 127, No. 2, March 2005, pp. 377–387.
doi:10.1115/1.1882393

[9] Huang, L. S., Maestrello, L., and Bryant, T. D., "Separation Control over an Airfoil at High Angles of Attack by Sound Emanating from the Surface," AIAA Paper 87-1261, June 1987.

[10] Jacob, J. D., "On the Fluid Dynamics of Adaptive Airfoils," *Proceedings of the 1998 ASME International Mechanical Engineering Congress and Exposition*, American Society of Mechanical Engineers, Fairfield, NJ, 1998.

[11] Munday, D., Jacob, J. D., Hauser, T., and Huang, G., "Experimental and Numerical Investigation of Aerodynamic Flow Control Using Oscillating Adaptive Surfaces," AIAA Paper 02-2837, June 2002.

[12] Pern, N. J., Jacob, J. D. and LeBeau, R. P., "Characterization of Zero Mass Flux Flow Control for Separation Control of an Adaptive Airfoil," AIAA Paper 2006-3032, June 2006.

[13] Santhakrishnan, A., Pern, N. J., Ramakumar, K., Simpson, A., and Jacob, J. D., "Enabling Flow Control Technology for Low Speed UAVs," AIAA Paper 05-6960, Sept. 2005.

[14] Cheng, L., Zhou, Y., and Zhang, M. M., "A Perturbation on Interactions Between Vortex Shedding and Free Vibration," *Journal of Fluids and Structures*, Vol. 17, No. 7, June 2003, pp. 887–901.
doi:10.1016/S0889-9746(03)00042-2

[15] You, D., and Moin, P., "Large-Eddy Simulation of Flow Separation over an Airfoil with Synthetic Jet Control," *Annual Research Briefs*, Center for Turbulence Research, Stanford, California, 2006, pp. 337–346.

[16] Greenblatt, D., and Wygnanski, I. J., "The Control of Flow Separation by Periodic Excitation," *Progress in Aerospace Sciences*, Vol. 36, No. 7, Oct. 2000, pp. 487–545.
doi:10.1016/S0376-0421(00)00008-7

[17] Hsiao, F. B., and Shyu, J. Y., "Influence of Internal Acoustic Excitation Upon Flow Passing a Circular Cylinder," *Journal of Fluids and Structures*, Vol. 5, No. 4, July 1991, pp. 427–442.
doi:10.1016/0889-9746(91)90429-S

[18] Hong, G., "Effectiveness of Micro Synthetic Jet Actuator Enhanced by Flow Instability in Controlling Laminar Separation Caused by Adverse Pressure Gradient," *Sensors and Actuators A (Physical)*, Vol. 132, No. 2, Nov. 2006, pp. 607–615.
doi:10.1016/j.sna.2006.02.040