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Active Control of Vortex-Airfoil Interactions

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Abstract

It is well known that interactions between the leading edge of a blade and incoming vortical structures produce a sharp rise in pressure, contributing significantly to the noise production in fans, turbine machines, etc. Active control of interactions between an airfoil and incoming cylinder-generated vortices has been presently investigated. The essence of the control is to create a local perturbation, using piezo-ceramic actuators, on the surface near the leading edge of the airfoil, thus modifying the airfoil-vortex interactions. Both open- and closed-loop controls are used, where the surface perturbation was controlled by an external sinusoidal wave and a feedback pressure signal from a pressure transducer installed at the leading edge, respectively. Experiments were carried out in a wind tunnel. It was observed that the closed-loop control was superior to the open-loop one; the closed- and open-loop controls achieve a maximum reduction in the pressure fluctuation at the dominant vortex frequency by 73% and 44%, respectively.

Introduction

When a blade, foil, wedge or fin is subjected to an incoming vortical flow, the incident vortices may distort rapidly due to interactions with the solid surface, which is often accompanied by the generation of an intense impulsive sound at the leading edge of the body and subsequent radiation to the far field. This aerodynamic sound is often called blade-vortex interaction (BVI) noise and has become one of the important noise sources for many engineering products, for example, helicopter blades, tails of aircrafts and rotors of turbo-machines, fans, and so on. This noise may hurt human ears in a long term and even lead to the malfunction of machines. Naturally, the BVI noise and its control have attracted the interests of many researchers in the past [1-4].

The passive method is frequently used to control the BVI, which requires no external energy input to the blade-vortex system, and often relies on modifying the blade shape, introducing winglets to the blade, increasing the number or the length of blades, or adding curvature to the blade surface [5-7].

The active control requires external energies to bring about desired changes in the blade-vortex system, and can be open- or closed loop. Using an open-loop system, Kaykayoglu [8] changed interactions between upstream vortices and a downstream airfoil by oscillating the leading edge of the airfoil, which was controlled by an independent external disturbance signal. The vortex strength and the BVI noise were effectively suppressed when the excitation frequency of the external control signal coincided with the instability frequency of the vortex-airfoil system. Peter *et al*. [9] used actuators, which were made of piezo-ceramic or fibre composites and attached on the airfoil surface, to twist the airfoil. They managed to obtain a 10 dB reduction in the BVI noise level. In the so called closed-loop control, the actuators are activated by a feedback-signal. Ziada [10] introduced acoustic disturbances to vortices in order to effectively attenuate the global oscillations of incident jet vortices on a wedge and hence the BVI noise. This was realized by loudspeakers, located near vortex separation edge and activated by a feedback fluctuating pressure signal of flow measured with a microphone. The control action was based on an adaptive digital controller and a recursive root-mean-square algorithm. A reduction of 30 dB in the noise pressure was achieved.

The actuation mechanism is an important component in an active control system. Cheng *et al*. [11] proposed a novel perturbation technique to control the fluid-structure interaction. The essence of the technique was to create a perturbation on the structural surface using piezo-ceramic actuators, which altered interactions between vortex shedding from a square cylinder and structural vibration. Both open- and closed-loop systems were investigated [11,12]. Both were found to be effective in reducing the vortex strength and structural vibration. One naturally wonders whether this technique could be used for reducing the BVI noise since the noise generation was linked to interactions between vortices and airfoil.

This work aims to investigate the effective control of the BVI noise using the perturbation technique developed by Cheng *et al*. [11] This technique was used to control interactions between vortices generated from a cylinder and a downstream airfoil. The investigation was conducted in a wind tunnel. Both open- and closed-loop controls were used. The fluctuating flow velocity and pressure near the leading edge of the airfoil were monitored using the hotwire and pressure transducers, respectively. The flow structure alteration was also measured using a particle image velocimetry, which is not reported here due to the limitation in pages.

Experimental Setup

Experiments were carried out in a closed circuit wind tunnel with a square test section of 0.6 m × 0.6 m, and 2.4 m long. The free-stream turbulence intensity is less than 0.4%. Readers can refer to Zhou *et al*. [13] for more details of the tunnel. A circular cylinder with a diameter d = 10 mm made of stainless steel and an NACA0012 airfoil with a chord length c = 150 mm were horizontally mounted in tandem on the working section of the wind tunnel (Figure 1). The angle of attack of the airfoil was 0°. The distance between the cylinder and the leading edge of the airfoil was 10d. Measurements were conducted at a free-stream velocity $U_\infty = 11$ m/s. The corresponding Reynolds numbers, Re_d ($\equiv U_\infty d/\nu$, where ν is the kinematic viscosity) based on the cylinder diameter and Re_c ($\equiv U_\infty c/\nu$) based on the chord length of the airfoil were 7300 and 109000, respectively.

A curved piezo-ceramic actuator [11] was embedded in a slot of 200 mm length, 3 mm width and 3 mm depth on the upper surface and was less than 1 mm from the airfoil leading edge (Figure 1). The actuator (THin layer composite UNimorph piezoelectric Driver and sEnsoR) was developed by the NASA Langley Research Centre. The actuator, deforming out of plane under a voltage (Figure 2), is characterized by many advantages such as high displacement, high load capacity and small size [14,15]. Typically, without any loading, the actuator (THUNDER-11R) of 76.2 mm length, 2.54 mm width and 0.74 mm thickness may vibrate at a maximum displacement of about 2 mm and a frequency up to 2 kHz, which is due to a particular fabrication process [15]. One end of the actuator was glue-fixed on the bottom side of the slot, whilst the other end is free. The

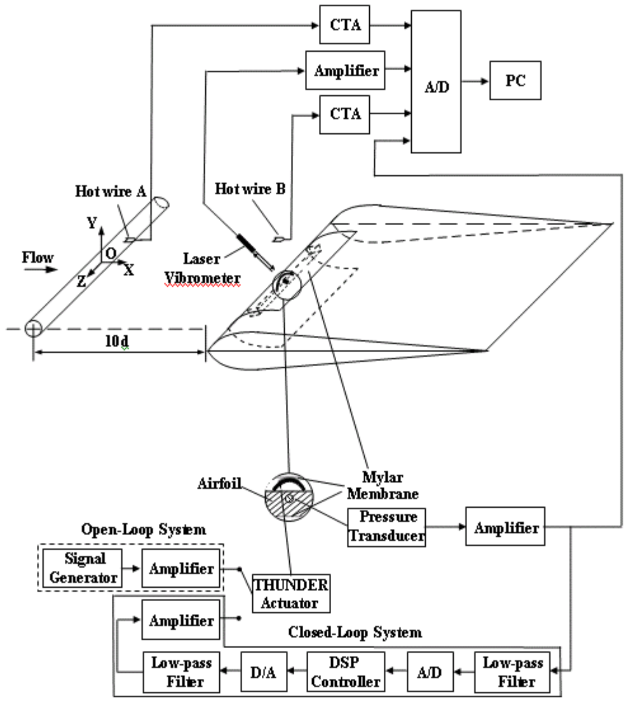

Figure 1. Experimental Setup.

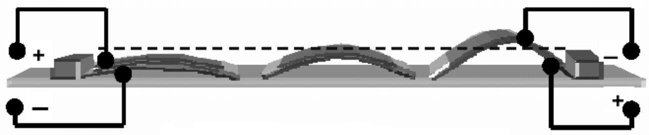

Figure 2. The relationship between typical deformation of THUNDER and applied voltage.

actuators and the walls of the slot around the actuators were well lubricated to reduce contact friction. A Mylar membrane, with superior strength, good heat resistance and insulation, was pasted on the top of actuator for smoothing the airfoil shape. Driven by the actuator, this membrane will oscillate to create the local perturbation on the airfoil surface.

In the open-loop control, the actuator is activated by a signal generated from a signal generator (HP-DS345) and amplified by a dual channel piezo-driver amplifier (Trek PZD 700-2); in a closed-loop control, a fluctuating flow pressure signal measured on the airfoil surface was used to drive the actuator. A pressure transducer (model 151-01), with a sensitivity of 1 volts/μBar and a frequency response of 1 kHz, was installed at the central part of the leading edge of the airfoil to measure the fluctuating flow pressure on the airfoil surface (Figure 1). After amplification, the feedback pressure signal was filtered at a cut-off frequency of 200 Hz and then sent to a Digital Signal Processor (DSP) controller fitted with 16-bit AD and DA converter. The sampling frequency of the AD converter is self-defined to be a few kHz, which satisfies the present experimental requirements. The converted analog signal was amplified by the dual channel piezo-driver amplifier to activate the actuators. The use of the two low-pass filters for both the feed-forward and feedback passages is to remove high frequency noises from turbulence and electronic components. The controller is developed and executed based on a real-time system, dSPACE, which has rapid control prototyping, production code generation, and hardware-in-the-loop tests. A digital signal processor (DSP) with SIMULINK function of MATLAB and software (ControlDesk 2.0) was applied to sample and process the feedback signal.

In order to evaluate the control effect, the steamwise fluctuating velocities along with the fluctuating flow pressure were measured using two tungsten hot wires, i.e. A and B (Figure 1), placed at x/d = 1.5, y/d = 1.5, z/d = 0 and x/d = 10, y/d = 1.5, z/d = 0, respectively. The coordinates x, y and z correspond to streamwise, transverse and spanwise directions, respectively (Figure 1). The perturbation displacement of membrane on the top of the actuator was recorded by a Polytec Series 3000 Dual Beam laser vibrometer. The four signals were simultaneously conditioned and digitized using a 12-bit A/D board at a sampling frequency of 3.5 kHz per channel. The duration of each record was 20 s.

Parameters Optimization and Control Performances

The parameters of the controller were first optimized in order to minimize the pressure fluctuation (p) at the leading edge of the airfoil. The optimization was achieved based on manually tuning. For the open-loop control, the tuning parameters include the frequency and voltage of the excitation signal (Y_p), perturbation frequency (f_p) and perturbation voltage (V_p); for the closed-loop control, the amplitude ratio ($A_{Y_p p}$) and phase shift ($\phi_{Y_p p}$) between Y_p and p were tuned. The general tuning procedure for closed-loop method is as follows: first vary $A_{Y_p p}$ by keeping $\phi_{Y_p p} = 0^\circ$ to find a $A_{Y_p p}$, i.e., $A_{Y_p p,opt}$, leading to the smallest p; then given $A_{Y_p p,opt}$ vary $\phi_{Y_p p}$ within a cycle to determine the $\phi_{Y_p,opt}$, under which p reaches the minimum. The $A_{Y_p p,opt}$ and $\phi_{Y_p,opt}$ were used as optimal parameters for closed-loop controller. These tuning processes led to an optimal configuration for each control method with the parameters: Y_p = 120 volts, f_p = 319 Hz for the open-loop control; $A_{Y_p p}$ = 1.4, $\phi_{Y_p p}$ = 143° for the closed-loop control.

Figure 3 shows typical time histories of p under control. Compared with the unperturbed case (Figure 3(a)), the amplitude of p deceases by up to 33% for the open-loop case (Figure 3(b) and 73% for the closed-loop case (Figure 3(c)). The p-spectrum, E_p (Figure 4), under the optimal condition displays in the absence of control a pronounced peak at the normalized vortex shedding frequency f_s^* (= $f_s d/U_\infty$ = 0.205), which is apparently due to the Kármán vortices generated by the cylinder. E_p has been normalized by the root mean square value (p_{rms}) of p so that $\int_0^\infty E_p(f)\mathrm{d}f = 1$. Once the open-loop control is imposed, the peak value of E_p at f_s^* is reduced by 30%. One additional peak at a magnitude of 0.021 occurs in E_p at f_p^* (= $f_p d/U_\infty$ = 0.29), apparently due to the perturbation. The closed-loop control leads to an even more impressive performance, resulting in a reduction by 76%. These results demonstrate not only the effectiveness of the present control technique on reducing the BVI noise but also the superiority of the closed-loop method to the open-loop one.

Note that since E_p is normalized by p_{rms}, the variation in the peak value may not accurately indicate the actual energy decrease caused by the active control because of the inclusion of external energy in p_{rms}. One way to estimate more accurately the energy ($E_{p,\Delta f}$) of p associated with f_s is to integrate E_p over a -3dB bandwidth about f_s, which is subsequently multiplied by p_{rms}. Use $E_{p,\Delta f}$ to represent the resulting quantity, calculated from Figure

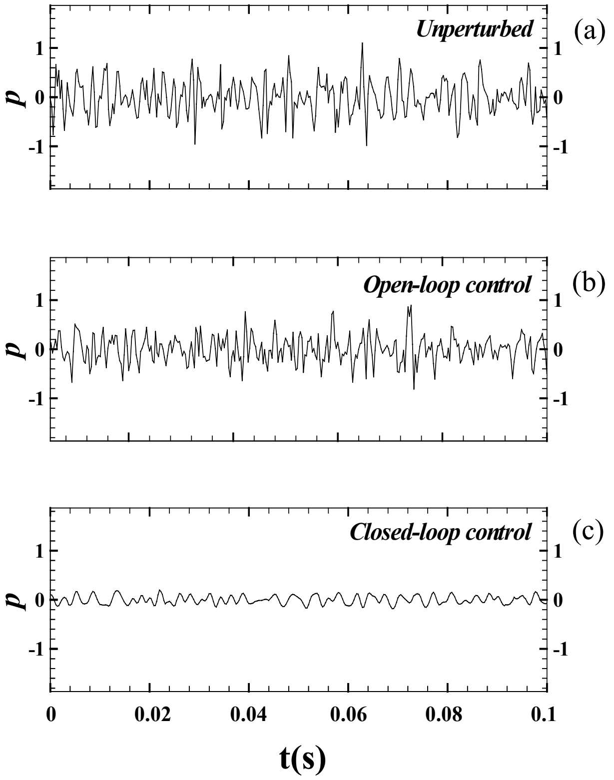

Figure 3. Typical time history of pressure signal (p) measured near the leading edge of the airfoil: (a) unperturbed; (b) open-loop control; (c) closed-loop control. The time origin is arbitrary.

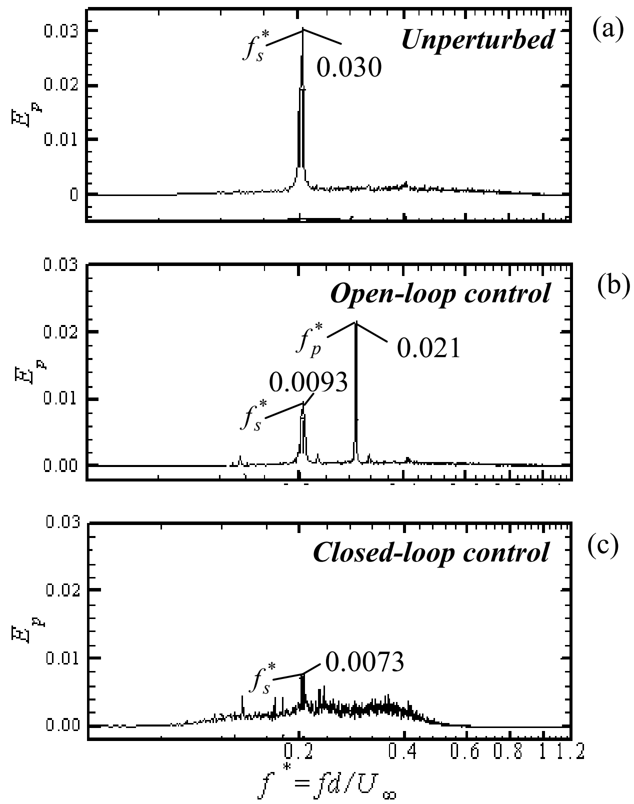

Figure 4. The p-spectrum E_p: (a) unperturbed; (b) open-loop control; (c) closed-loop control.

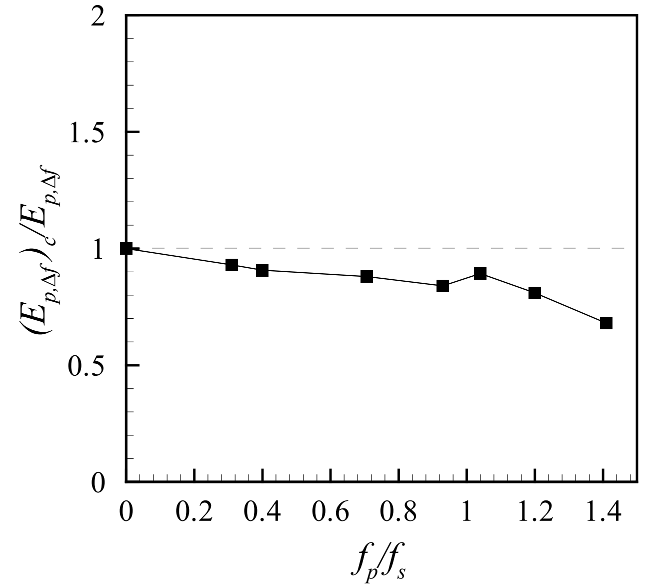

Figure 5. Dependence of the energy ratio, $(E_{p,\Delta f})_c / E_{p,\Delta f}$, on the perturbation frequency (f_p) in the open-loop control ($Re_d = 7300$).

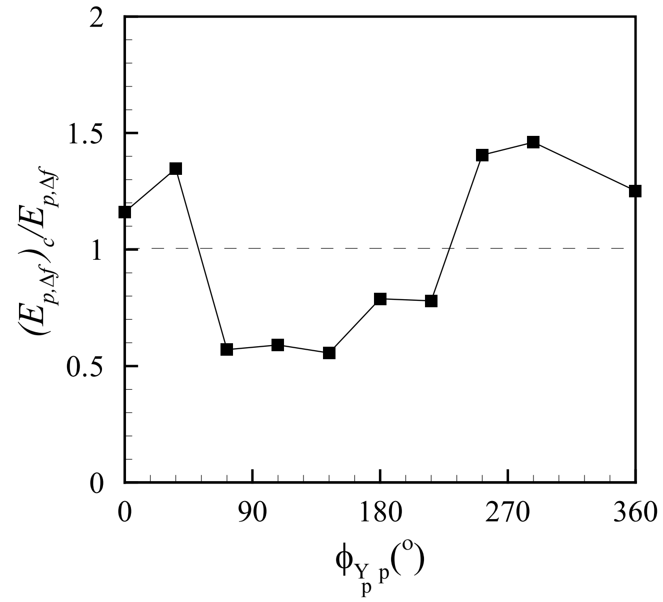

Figure 6. Dependence of the energy ratio, $(E_{p,\Delta f})_c / E_{p,\Delta f}$, on the phase shift ($\phi_{Y_p p}$) between the perturbation signal (Y_p) and the pressure signal (p) in the closed-loop control ($Re_d = 7300$).

4(a), in the absence of control and ($E_{p,\Delta f}$)$_c$ to denote that calculated from Figure 4(b) or 4(c), in the presence of control. Figure 5 shows the dependence of the energy ratio, $(E_{p,\Delta f})_c / E_{p,\Delta f}$, on f_p/f_s in the open-loop control. Here V_p was set at 120 volts. As f_p/f_s increases, $(E_{p,\Delta f})_c / E_{p,\Delta f}$ drops, indicating more reduction in the BVI noise. At f_p/f_s = 1.41, $(E_{p,\Delta f})_c / E_{p,\Delta f}$ is 67% of the unperturbed case ($(E_{p,\Delta f})_c / E_{p,\Delta f}$ = 1 at f_p/f_s = 0). In the closed-loop control case ($A_{Y_p p}$ is fixed at 1.4), $(E_{p,\Delta f})_c / E_{p,\Delta f}$ (Figure 6) exceeds 1 for $\phi_{Y_p p} < 51^\circ$ or $\phi_{Y_p p} > 229^\circ$; its maximum reaches 147% of the uncontrolled energy. On the other hand, for $51^\circ < \phi_{Y_p p} < 229^\circ$, $(E_{p,\Delta f})_c / E_{p,\Delta f}$ is significantly reduced, reaching a minimum of 0.44, i.e. 44% of the unperturbed energy, at $\phi_{Y_p p} \approx 143^\circ$. Apparently, the closed-loop control out-performs its open-loop counterpart.

Conclusions

The active control of vortex-airfoil interactions has been experimentally investigated. It can be concluded that the presently proposed control schemes can reduce markedly the fluctuating pressure associated with the vortex-airfoil interactions. The closed- and open-loop controls achieve a maximum reduction by 73% and 44%, respectively, indicating a superiority of the closed-loop scheme to the open-loop one.

The investigation points to a great potential of the present control technique for the BVI noise control. Further investigation is underway to understand the physics behind the control performances.

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