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Aerodynamic noise reduction by plasma actuators for a flat plate with blunt trailing edge

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ABSTRACT

An experimental study of active control of the vortex shedding narrowband tonal noise radiated near the blunt trailing edge of a flat plate with elliptical leading edge was performed using three different configurations of the single dielectric barrier discharge (DBD) plasma actuators. These devices can produce electric winds in the tangential, downward and spanwise directions, respectively, near the blunt trailing edge. Acoustics and flow measurements were carried out simultaneously at Reynolds numbers between 0.75×10^5 and 4×10^5, based on the flat plate chord length, inside an aeroacoustic facility. The range of alternating-current (AC) input voltages to these plasma actuators was relatively low at < 5 kV. The "tangential" plasma actuator is not very effective in the suppression of vortex shedding tonal noise (maximum 1−2 dB reduction), although the spatial distribution of the wake coherent modes calculated from the proper orthogonal decomposition becomes more compact than that produced by the baseline plasma off case, resulting in a shift of the tone frequency to a higher value. The "downward" plasma actuator can suppress the vortex shedding noise almost completely at the tone frequency (about 15 dB reduction at input voltage of 4.2 kV). The mechanism is related to the induced plasma jet acting as a virtual barrier to inhibit the interaction between the upper and lower separating shear layers, and to delay the formation of the vortex shedding. The "spanwise" plasma actuator, which can project array of streamwise vortices into the wake and compartmentalise the vortex shedding across the span, demonstrated a more superior tonal noise reduction capability at low input voltage (about 12 dB reduction at 3.0 kV). It is found that the plasma-induced jet magnitudes between 9 and 10% and 7% of the freestream velocity for the downward and spanwise plasma actuators, respectively, are already sufficient to achieve an effective reduction of the vortex shedding tonal noise.

1. Introduction

The unsteady flow structure behind a bluff body or blunt trailing edge has been studied extensively due to its importance in many engineering applications. The separation of the free shear layer from the sharp corners of the blunt trailing edge, for example, can lead to formation of vortices that shed alternately from each side of the body. These coherent vortices along with the unsteady velocity field will produce a force loading that increases the aerodynamic drag. If the frequency of the vortex

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Nomenclature

B	*width of the flat plate, m*
C	*chord length of the flat plate, m*
C_D	*drag coefficient that includes the mean $C_{D(\mathrm{mean})}$, and the fluctuating $C_{D(\mathrm{rms})}$ components*
f	*frequency, Hz*
$f_{(input)}$	*input frequency to the plasma actuators, kHz*
H	*flat plate thickness, also the bluntness, m*
l	*eigenvectors of the covariance matrix C_{ij}*
U	*mean flow velocity of the nozzle jet, ms^{-1}*
u,v,w	*velocity components in the streamwise, wall-normal and spanwise directions, respectively, ms^{-1}*
x,y,z	*streamwise direction measuring from the blunt trailing edge, wall-normal direction and spanwise direction, respectively, m*
$\hat{u}$, $\tilde{v}$	*plasma-induced jet velocity in the x-direction and y-direction, respectively, ms^{-1}*
u_{rms}, v_{rms}	*root-mean-square of the velocity fluctuation in the streamwise and vertical directions, respectively, ms^{-1}*
u_∞	*velocity at the potential flow region above the wake (used in Eqs. 3 and 4), ms^{-1}*
$V_{(input)}$	*input AC voltage to the plasma actuators, kV*
y^+	*normalized wall-normal distance (yu_τ/ν), where u_τ is the friction velocity and ν is the kinematic viscosity*
ΔSPL	*difference in sound pressure level between the baseline (plasma off), and control (plasma on) cases, dB*
λ_i	*eigenvalue of the covariance matrix C_{ij}*
θ	*momentum thickness of the wake flow, mm*
Ω_x, Ω_z	*Streamwise and spanwise vorticity, respectively, s^{-1}*
$\psi^{(i)}$	*POD-eigenmode*

shedding coincides with the natural frequency of the flow body, it could then induce structural instability and reduce the life-expectancy of many lift-generating bodies in the civil aviation and wind turbine industries.

The aeroacoustic problem of a bluff body or blunt trailing edge, i.e. the radiation of narrowband tone as a result of the bluntness-induced vortex shedding, represents a prominent issue that has hitherto received relatively less attention. More research efforts are therefore needed to mitigate this type of important noise source. Because the radiated aerodynamic noise is usually a by-product of the flow structure generated on the body, it is possible to apply control technique to stabilise the wake flow and, at the same time, reduce the level of noise radiation into the far field.

There are numerous studies that aim to control the unsteady flow behind blunt bodies by modifying or suppressing the coherent structures in the wake region, which could be achieved by either the passive or active flow control approaches. A general review of the passive flow control on the suppression of vortex shedding behind bluff body can be found in Choi et al. [1]. For example, one can use the splitter plate with different gap ratios behind the bluff body [2–6]. Roshko [6] demonstrated that vortex shedding can be completely suppressed behind a cylinder, thus resulting in a reduction of the base drag when splitter plate with length 5 times the cylinder diameter is attached at the aft region. Roshko also showed that varying the gap ratio of the splitter plate between 0 and 1.75 times the cylinder diameter will result in an extension of the shear layers to the downstream edge of the splitter plate. This modification of the wake structure is found to be able to prevent the entrainment of the outer flow to the base region. It is also shown by Liu et al. [7] that applying the porous coating on tandem cylinders can lead to stabilisation of the vortex shedding from the upstream cylinder. As a result, the impact of wake impingement with the downstream cylinder is reduced. They postulated that the modified flow field by the porous coating will eventually lead to reduction in the wake vortex shedding noise radiated from the upstream cylinder, as well as the interaction noise with the downstream cylinder. Using small element near the trailing edge of a rectangle cylinder at low Reynolds number, Chen et al. [8] found that these element successfully suppress vortex shedding and reduce the fluctuation in the lift and drag forces. Although many of these passive flow control methods are popular due to their simplicity and ease of implementation, they usually require geometrical modification or attachment of moving or fixed parts to the main body. As a result, they are not very versatile when the flow condition can change considerably over a short period of time.

The improvement in control and electrical technologies in the last few decades encourages the development of the active flow control. The miniaturisation of the actuators also means that very little parasite drag is produced when they are attached to the flow body. The active flow control both in the open-loop and closed-loop modes can adapt to various flow conditions effectively, thus allowing the user to switch them on and off easily. To attenuate the bluntness-induce vortex shedding, one could seek to prevent the cross-talk between the two separated shear layers, as well as to promote a faster break-up of the coherent structure in the near wake region. Using steady suction and blowing, Henning and King [9] showed that the spanwise coherence of the vortex sheet from a D-shaped elongated body could be modified. For the same set up, piezo-fluidic actuators were utilised to control the stability of the free shear layer. Stalnov et al. [10] studied a closed-loop feedback control of a D-shaped cylinder wake. Based on the proper orthogonal decomposition modeling, it was demonstrated that the body-