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Suppression of lift fluctuations on a circular cylinder by inducing the symmetric vortex shedding mode

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ABSTRACT

The flow around a stationary circular cylinder modified by two synthetic jets positioned at the mean separation points is numerically studied. The Reynolds number based on the free-stream velocity and the circular cylinder diameter is Re=500. The focus is to present a novel way to suppress the lift fluctuations by changing the vortex shedding mode, and thus particular attention is paid to the interactions between the synthetic jets and wake shear layers and the resulting vortex dynamics. The overall influences of both momentum coefficient and excitation frequency are discussed. In some simulated cases, the vortex lock-on phenomenon is discovered, which causes the typical Kàrmàn type vortex shedding to be converted into the symmetric shedding modes, leading to the complete suppression of lift fluctuations. In other cases, the asymmetric shedding mode still dominates the wake evolution. Detailed vortical evolution for each typical wake pattern is analyzed to reveal the control mechanism. Additionally, the control effectiveness is evaluated, indicating that the present control strategy contributes an effective way to suppress the lift fluctuations and reduce the mean drag.

1. Introduction

The flow around bluff bodies is characterized by the shedding of counter-rotating vortices, which is known as Kàrmàn vortex street. Practically, the alternate vortex shedding brings fluctuating loads on the structure, which is the main source of structural vibrations, acoustic noise and resonance (Williamson, 1996; Owen et al., 2001; Hwang et al., 2003). Hence a number of studies were conducted to suppress flow-induced forces by using different control techniques.

One effective way is weakening or suppressing the vortex shedding behind the bluff bodies (Owen et al., 2001). To achieve that, numerous researchers adopted the passive approaches, which are quite simple and easy to be implemented. One way is to affect the boundary layer development by surface roughness (Achenbach, 1971) and tripping wires (Hover et al., 2001; Alam et al., 2003, 2010). Some others, such as Roshko (1961) and Hwang et al. (2003), placed a splitter plate behind the bluff body to attenuate the interaction of the separating shear layers. Moreover, Baek and Karniadakis (2009) found that a slot parallel to the incoming flow was very effective in weakening or detuning vortex shedding since the slot actually created a jet to interact with the wake. For more information about the passive flow control techniques applied to bluff bodies, one can also read the reviews by Choi et al. (2008) and Kumar et al. (2008).

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On the other hand, active control strategies also play an important role in vortex shedding control. For instance, researches on flow over an oscillating cylinder or perturbed flow over a stationary cylinder were conducted. Griffin and Ramberg (1976) reported that when the cylinder was oscillating in line with the incoming flow, the vortex shedding could be synchronized with the body motion, which is usually named as "vortex-synchronization" or "vortex lock-on" phenomenon. Nishihara et al. (2005) and Xu et al. (2006) also investigated the flow features of a streamwise oscillating circular cylinder. Both of them confirmed the existence of the symmetric vortex shedding mode. The vortex lock-on phenomenon also occurred in the studies on streamwise perturbed flow over a circular cylinder (Konstantinidis et al., 2003, 2005; Kim et al., 2006, 2009; Konstantinidis and Balabani, 2007). Besides, there are also a number of investigations on the circular cylinder oscillation in cross-flow direction (Stansby, 1976; Williamson and Roshko, 1988; Blackburn and Henderson, 1999; Krishnamoorthy et al., 2001). Additionally, the rotational oscillation was also found to be an effective method to influence the behavior of the wake vortex (Tokumaru and Dimotakis, 1991; Lee and Lee, 2006).

In recent decades, the rapid development in new material and micro-electro-mechanical systems (MEMS) greatly improves the feasibility and efficiency of novel actuators for flow control. One of them, the synthetic jet, has been applied widely in various fields including the flow over a bluff body (Fujisawa and Takeda, 2003; Fujisawa et al., 2004; Zhang et al., 2008; Glezer, 2011). Crook et al. (1999) and Tensi et al. (2002) used the synthetic jet to control the flow around a circular cylinder. Crook et al. (1999) indicated that the synthetic jet could create strong entrainment surrounding the cylinder and thus the flow separation point could be delayed. Both drag reduction and separation delaying were found by Tensi et al. (2002) in their wind tunnel experiment.

The present authors also conducted a series of experimental studies on the control of flow around a circular cylinder by using synthetic jets and have achieved several preliminary results (Wang et al., 2007; Feng and Wang, 2010, 2012; Feng et al., 2010, 2011; Ma and Feng, 2013). When the synthetic jet was placed at the front stagnation point, the close or open envelopes could be formed upstream of the cylinder depending on the excitation strengths, leading to a shrink of the separated region behind the circular cylinder (Wang et al., 2007). When the synthetic jet was placed at the rear stagnation point, the wake vortex dynamics could be altered, where the symmetric vortex shedding mode occurred (Feng and Wang, 2010; Feng et al., 2010, 2011) and a reduction in drag was also found (Feng and Wang, 2012). Similar finding was also observed when the synthetic jets were placed at both the front and rear stagnation points (Ma and Feng, 2013). In particular, the occurrence of the symmetric shedding mode has many pragmatic benefits. The lift coefficient and its fluctuations induced by the symmetric mode are theoretically zero. It is suggested that the unsteady lateral loads, which sometime cause vibrations, acoustics or even structural breakdown, can be suppressed by introducing the symmetric mode (Alam et al., 2007; Marzouk and Nayfeh, 2009). This offers us a novel idea for flow control.

Based on the authors' previous works, at least two aspects should be further concerned. Firstly, restricted by the experimental conditions, the works mentioned above mainly focused on the change in flow patterns. However, the flow-induced forces, which are highly coupled with the vortex dynamics, were not remarked. This needs to be addressed to highlight the significance of the variations in vortex shedding mode. Secondly, the control efficiency of the synthetic jet in the previous configurations might not be the optimum one since many studies have concluded that the forcing near the separation point usually contributed to the best control efficiency. For instance, Jukes and Choi (2009a, 2009b, 2009c) conducted a series of works to modify the near wake of a circular cylinder by attaching dielectric barrier discharge (DBD) plasma actuators near the separation points. Jardin and Bury (2012) presented that the periodic tangential jet centered at the separation points could induce the 2P mode, where two pairs of vortices shed in one period. Based on the numerical simulations, recently, Munday and Taira (2013) found that the wake structure over a circular cylinder became more streamlined under the tangential-blowing control near the natural separation points, leading to a reduction of the drag coefficient.

Accordingly, in this study, two synthetic jet actuators are placed on a stationary circular cylinder at the mean separation points. The focus is to present a novel way to suppress the lift fluctuations by changing the vortex shedding mode. Thus, both flow-induced force and wake pattern of the cylinder with and without the synthetic jets are investigated numerically.

2. Computational model and methods

2.1. Simulation setup

The Reynolds number Re based on the cylinder diameter D and the free-stream velocity U_∞ is 500. As depicted in Fig. 1, two synthetic jet actuators are symmetrically placed on both sides of a stationary cylinder. The actuator consists of a jet slot with a width of $b = D/60$ and a cavity with a bottom width of $B = 10\sqrt{2}b$. The jet slots are centered at the mean separation points, where the time-averaged shear stress on the cylinder wall is zero (Wu et al., 2004). In this study, the azimuthal angle measured from the front stagnation point to the time-averaged separation point is $\varphi_s = 96^\circ$. The angle between the slot centerline and the tangential direction of the local cylinder surface is $\theta_j = 45^\circ$. The original point of the coordinate system is located at the cylinder center, with x- and y-axis being parallel and perpendicular to the free stream, respectively.

In our previous experimental studies, such as Feng and Wang (2010), the generation of the synthetic jet was realized by a piston-driven system, which transformed the circular motion of a servo electromotor into the reciprocating motion of a piston. To simplify the simulation of the piston motion in a real synthetic jet actuator, the method used by Zhang et al. (2012) and Esmaeili Monir et al. (2014) is adopted here, which defines the bottom of the cavity as a periodic velocity inlet.

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