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Control of wakes and vortex-induced vibrations of a single circular cylinder using synthetic jets

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ABSTRACT

This paper presents a study on active control of the wakes and one-dimensional vortex-induced vibrations (VIVs) of a single circular cylinder using a pair of synthetic jets (SJs) at a low Reynolds number Re = 100. To facilitate this study, a lattice Boltzmann method based numerical framework is established, in which the multi-block scheme and the overlap-mesh approach with improved information exchange mechanisms are used to balance the computational accuracy and efficiency, and the interpolated bounce-back scheme and a corrected momentum exchange scheme are adopted for accurate force evaluation. Two configurations are considered. In the first configuration, the cylinder is fixed, on which a pair of SJs is implemented and operates in phase. Effects of the SJ pair on the cylinder wake are investigated in a systematical way, with the focus placed on the SJ's momentum coefficient, frequency and position. Simulation results indicate that the Kármán vortex street formed behind the cylinder can be effectively suppressed when the SJ pair operates with sufficiently high momentum coefficient, at a frequency close to the cylinder's natural vortex shedding frequency, and is placed in the quarter arc edge of the cylinder's leeward side. In the second configuration, the same cylinder is allowed to oscillate in the cross-flow direction under the excitation of asymmetrically shedding vortices as well as the constraint of a spring. It is well demonstrated that this one-dimensional VIV of the cylinder can be successfully suppressed by the use of SJ control. Due to stronger vortex shedding induced by increased relative motion between the cylinder and its surrounding flow, however, not all the cases that perform complete wake suppression on the fixed cylinder are able to completely suppress the VIVs of the oscillating cylinder. Through the present study, details about SJ-controlled flow around the cylinder and in the wake are also revealed.

1. Introduction

Asymmetric vortices shed from bluff structures in flows cause dynamic loading on the structures. When the shedding frequency matches the structure's natural frequency, large-amplitude vibrations may occur, and, if that happens, the structure is prone to damage due to extreme stress or fatigue. Therefore, it is desirable to control the asymmetric vortex

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shedding and suppress the vortex-induced vibrations (VIVs). For years, numerous flow control methods have been used to suppress the asymmetric vortex shedding and VIVs, including passive (no power required), active open-loop (no sensor required) and active closed-loop (sensor required) schemes, on which Choi et al. (2008) has given a comprehensive review.

As a promising active flow control method, synthetic jets (SJs) have been used in various applications, including flow separation control (Wang et al. 2007; Tang et al. 2014), mixing control (Pavlova et al. 2008), and turbulence control (Rathnasingham and Breuer, 2003). A SJ is a chain of vortex rings/pairs produced through a small orifice/slot by oscillation of single or multiple diaphragms attached to a cavity. An attractive feature of the SJ is that it can produce non-zero momentum flux to control ambient flows with zero net mass flux. Since its emergence, the SJ technology has been applied on bluff bodies to modify wakes and control VIVs. Using a single SJ, Feng et al. (2010) and Feng and Wang (2012, 2014b) experimentally investigated its effects on wake modification and drag reduction of a cylinder. The same group (Feng and Wang, 2010, 2014a) also investigated the effects of a single SJ on modifying wakes when the SJ is located at the rear or front stagnation point of a cylinder. For control using multiple SJs, Williams et al. (1992) utilized a pair of in-phase and out-of-phase SJs operating at low frequencies to alter vortex shedding frequencies and wake patterns behind a cylinder at a cylinder diameter based Reynolds number Re=470. Munday and Taira (2013) investigated the effects of excitation frequency and velocity amplitude of a pair of out-of-phase SJs on the lock-on characteristics and drag reduction of a cylinder at Re=100. And Ma et al. (2014) found several new wake patterns behind a circular cylinder, such as the symmetric 2P mode and asymmetric 2P+2S mode, when a pair of in-phase SJs is implemented. In addition to on circular cylinders, SJs were also applied on bluff bodies of other shapes. Pastoor et al. (2008) employed a pair of SJs on a D-shape cylinder for the purpose of drag reduction. By applying a feedback controller, they experimentally achieved a 15% drag reduction at the body height based Reynolds number ranging from 23 000 to 70 000. They attributed the drag reduction to the mechanism that the use of in-phase SJs enhances the initial symmetry of the wake by forcing synchronous vortex shedding. Parkin et al. (2014) did a numerical study on a similar D-shape cylinder. At the Reynolds number of 23 000, they found the optimal drag reduction occurred at the SJ forcing frequency approximately half of the natural vortex shedding frequency.

Although in some of the above-mentioned investigations SJs have been applied to modify wakes of single circular cylinders, their effects at very low Reynolds numbers such as Re=O(100) have not been fully understood, and the control was mainly focused on drag reduction instead of VIV mitigation. The VIV control at such low Reynolds numbers is still meaningful and worth investigating. For instance, the VIVs of a hot-wire or hot-film probe may cause significant errors in the velocity or temperature measurements (Perry and Morrison 1971; Atta and Gharib 1987; Anderson et al. 2005). Although its practical implementation is very challenging, the SJ control can be a new way of handling similar low-Reynolds-number VIV problems. Therefore, the present study aims to investigate the effects of three key parameters of a pair of SJs, i.e., the momentum coefficient, frequency, and location, on suppressing the asymmetric vortex shedding and one-dimensional VIVs of a circular cylinder at a Reynolds number Re=100. To focus the present investigation, this pair of SJs is placed symmetrically about the cylinder's centerline, issues along the incoming flow direction, and operates in phase.

This paper is organized as follows. In Section 2 two SJ-based flow control problems are described. In Section 3 a lattice Boltzmann method based numerical framework is introduced and validated. Section 4 presents the results and discussions associated with the two simulation scenarios. In the end conclusions from the present study are drawn.

2. Problem description

In the present study, two SJ-based flow control problems are considered: control of asymmetric wakes behind a fixed circular cylinder and the resulting lift oscillation experienced by the cylinder, and control of one-dimensional VIVs of the same cylinder that is allowed to move in the cross-flow direction. In both problems, the diameter-based Reynolds number is fixed at Re=100, at which the flow is unsteady, laminar and two dimensional as reported by Williamson (1996).

2.1. Fixed cylinder in uniform flows

In this problem, a circular cylinder is horizontally immersed in a uniform flow. At the Reynolds number of interest, i.e., Re=100, the flow around the cylinder will be governed by absolute wake instability. The upper and lower shear layers will strongly interact, as depicted in Fig. 5a. The vortex A that is produced by the roll-up of the upper shear layer pulls the lower shear layer up and hence induces the creation of the new vortex B. Once growing and convecting downstream, vortex B will trigger the creation of a new vortex from the upper shear layer. In this way, strong vortices of opposite signs shed and convect alternatively in the wake, forming a von Kármán vortex street. To control this asymmetric wake and the resulting lift oscillation experienced by the cylinder, a pair of SJs is implemented on the leeward portion of the cylinder, symmetrical about the cylinder's horizontal centerline, as shown in Fig. 1.

The SJs are activated after the flow achieves its steady state. Their velocity is given as

$$\boldsymbol{u}_{sj}^{u} = U_{\max}\ \sin\left(2\pi f_e t + \phi_u\right)(\cos(\beta),\ \sin(\beta)) \tag{1}$$

$$\boldsymbol{u}_{sj}^{l} = U_{\max}\ \sin\left(2\pi f_e t + \phi_l\right)(\cos(-\beta),\ \sin(-\beta)) \tag{2}$$

where the superscripts "u" and "l" indicate the upper and lower SJs, respectively. $U_{\max}$ is the amplitude of jet velocity, f_e the