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Numerical study of flow patterns and force characteristics for square and rectangular cylinders with wavy surfaces

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ABSTRACT

This paper presents a numerical study of three-dimensional flow around wavy rectangular cylinders with sinusoidal variations in cross-section area along the spanwise direction over wide Reynolds number regimes. The detailed near wake vortex structures and force characteristics of the wavy rectangular cylinder are captured and the influence of length-to-thickness ratio ($L/D_m=1$ to 8) of the wavy rectangular cylinder is discussed and compared with a plain straight rectangular cylinder with the same size and flow conditions. Experimental measurements were also performed for the validation of the present numerical results using the PIV technique. For a square cylinder ($L/D_m=1$), significant force reduction occurs for a wavy square cylinder compared with a straight square cylinder. The three-dimensional free shear layers behind the wavy square cylinder are more stable than those of the straight square cylinder. For a rectangular cylinder ($L/D_m \geq 2$), several vortex shedding patterns can be observed. The free shear layers exhibit a steady flow feature with symmetrical flow patterns behind the wavy cylinder for Re=100. At Re=500, the mean drag coefficient and the fluctuating lift coefficient of the wavy rectangular cylinders are greatly suppressed compared to a plain straight cylinder, while such advantageous features gradually disappear with the increase of the aspect ratio and Reynolds number. At Re=5000, the advantageous characteristics on flow control disappear for wavy cylinders with $L/D_m > 2$ due to breaking down of the periodic repeated additional transverse vortices. Finally, a wavy cylinder $L/D_m=8$, with an angle of incidence $\alpha=15^\circ$ is studied. Results show that such wavy surface does not possess a significant advantage in flow separation control.

1. Introduction

Unsteady flow around square and rectangular bluff bodies is a topic with practical importance in engineering applications, such as tall buildings, marine structures and bridges cross-sections design. It involves complex phenomena like flow separation and reattachment, unsteady vortex shedding formation, etc. The fluid dynamic vibrations acting on a square and rectangular cylinders have been the subject of extensive numerical and experimental investigations (e.g. Davis and Moore, 1982; Deniz and Staubli, 1997; Lubcke et al., 2001; Mills et al., 2003; Norberg, 1993; Ohya et al., 1992; Okajima, 1982, 1990; Okajima et al., 1990; Oka and Ishihara, 2009; Sen and Mittal, 2011; Sheard, 2011; Shimada and Ishihara, 2002; Yakhot et al., 2004). Many important physical phenomena were observed. In particular, Knisely (1990) reviewed and summarized the characteristics of Strouhal numbers of rectangular cylinders at different angles of incidence. Nakamura et al. (1991) concluded that vortex shedding from

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elongated flat plates with square leading and trailing edges is dominated by the impinging shear layer instability, when a single separated shear layer can be unstable in the presence of a sharp downstream corner. Naudascher and Wang (1993) investigated the flow-induced vibrations of prismatic bodies and grids of prisms. The wake structure on the rectangular cylinder was classified into several types: leading-edge vortex shedding (LEVS), impinging leading-edge vortices (ILEV), trailing-edge vortex shedding (TEVS) and alternate-edge vortex shedding (AEVS). The wake structure and the fluid-dynamic loading on the rectangular cylinder are mainly affected by the aspect ratio of the cylinder, the Reynolds number and the incidence angle. Kondo and Yamada (1995a, b) investigated computationally the aerodynamic characteristics of a rectangular cylinder with or without an angle of attack. Using the three and two-dimensional simulations, Hirano et al. (1999) successfully captured the detailed behavior of the shear layer and the vortex motions around a rectangular sectioned object. The relationship between the structure and aerodynamics of rectangular sectioned objects is also investigated. Moreover, the effects of an asymmetric confined flow on a cylinder of rectangular cross-section were also investigated and discussed by Cigada et al. (2006).

How to control the vortex shedding from the rectangular cylinder and hence to reduce the drag forces and minimize the effects of vortex-induced vibration is a great challenge in flow control. Over the past years, many experimental and numerical investigations had been carried out on the control of vortex-induced vibration of rectangular or square cylindrical structures (Choi et al., 2008; Sanchez-Sanz and Velazquez, 2011). For example, Tombazis and Bearman (1997) introduced a spanwise wavy surface to the trailing face of the cylindrical bodies, while Bearman and Owen (1998) experimentally investigated the three-dimensional features of the wake behind a rectangular cross-section body with a wavy leading edge. Results revealed that such a rectangular body can completely suppress the vortex shedding and substantially reduce the drag up to 30% at a Reynolds number of 40 000. Darekar and Sherwin (2001a,b) numerically investigated the flow past a square cylinder with a wavy front face at low Reynolds numbers. They showed that the unsteady and staggered Kármán vortex wake could be suppressed to a steady and symmetric wake structure due to the waviness of the cylinder. The maximum drag reduction of about 16% was obtained at a Reynolds number of 100 compared with a straight square cylinder. At higher Reynolds numbers, the drag reduction increases substantially. Dobre et al. (2006) applied spanwise sinusoidal perturbations on the upstream faces of square cylinders to control the wake structures. Kurata et al. (2009) experimentally investigated flow past a rectangular cylinder with small cut-corners at the front-edge. The relation between drag reduction and the cutout dimension was discussed.

Similar to the investigations above, a wavy circular cylinder whose diameter varied sinusoidally along its spanwise direction was introduced and studied in detail by the authors (Lam and Lin, 2008, 2009, etc.). The detailed three-dimensional wake structures behind the wavy circular cylinders were captured and the optimal values of spanwise wavelength λ/D_m based on drag control and fluctuating lift suppression were obtained. At high Reynolds number of 3000, the wavy circular cylinder with spanwise wavelength $\lambda/D_m=1.9$ can lead to significant drag reduction and suppression of fluctuating lift of the bodies. While, in laminar flow condition, two optimal spanwise wavelengths with $\lambda/D_m=2$ and 6 at $\mathrm{Re}=100$ were obtained for the control of wake pattern and force reductions. With a larger value of spanwise wavelength $\lambda/D_m=6$, the vortex shedding behind the wavy circular cylinder was greatly suppressed and the drag force was significantly reduced. Furthermore, Lam et al. (2010a) carried out force measurements on a single wavy circular cylinder with wavelength ratio of $\lambda/D_m=6$ and wave amplitude ratio of $a/D_m=0.15$ at Reynolds number from 6800 to 13 400, and performed the large eddy simulation for the same wavy cylinder at $\mathrm{Re}=7500$. The results showed that both the mean drag coefficients and the fluctuating lift coefficients of such wavy circular cylinder were evidently smaller than those of a purely circular cylinder within the same Reynolds number range. It was concluded experimentally and numerically that the wavy cylinder of $\lambda/D_m=6$ is the best choice for the control of cylinder fluctuating lift and drag reduction.

Therefore, it is anticipated that a wavy rectangular cylinder with similar wavelength ratio $\lambda/D_m=6$ would also give the best effect in fluctuating lift suppression and drag reduction both in laminar flow and turbulent flow conditions. The aim of the current work is to carry out numerical studies on three-dimensional flow around wavy square and rectangular cylinders over a wide Reynolds number range so as to investigate their advantages in flow control. The detailed near wake vortex structures around the wavy rectangular cylinder are captured and the influence of the wavy rectangular cylinder length to thickness ratio ($L/D_m=1$ to 8, where L and D_m are the length and thickness of the rectangular cylinder, respectively) is studied and compared with a plain straight rectangular cylinder with the same L/D_m ratio and flow condition. The pressure fields, vortex shedding frequencies and force coefficients of the wavy rectangular surfaces are calculated and analyzed. Finally, a long wavy rectangular cylinder, $L/D_m=8$, with an incidence angle $\alpha=15^\circ$ is also simulated to assess the advantage of wavy cylinders on the control of flow separation. It is hoped that the introduction of wavy surfaces with certain optimal geometry of wavelength and wave amplitude ($\lambda/D_m=6$, $a/D_m=0.15$) to rectangular bodies can provide good aerodynamic effects, such as drag reduction, better lift to drag ratio, suppression of fluctuating lift, control of aerodynamic stalls, etc.

2. Geometry of models

Fig. 1(a) shows the schematic diagram of a wavy rectangular cylinder. The geometry of it can be described by Eq. (2.1) and the mean thickness D_m is defined by Eq. (2.2):

$$D_z = D_m + 2a\cos(2\pi z/\lambda), \tag{2.1}$$

$$D_m = (D_{min} + D_{max})/2, \tag{2.2}$$