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Numerical study of flow control via the interaction between a circular cylinder and a flexible plate

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Flow control through the interaction between a fixed circular cylinder and a detached flexible plate is numerically investigated in this study. Based on the diameter of the cylinder (d), the laminar flow with a Reynolds number of 100 is considered in this work. A flexible plate undergoing fish-like motion is placed in either the downstream or upstream of the cylinder. The gap between the cylinder and the plate (S), the oscillation frequency (St_f) and the oscillation amplitude (A) are crucial parameters. When the flexible plate is in the downstream of the cylinder, a stable flow pattern is generated under some conditions (for example, $St_f=0.4$ together with $A/d=0.1$ at $S/d=0.1$–2.5 and $St_f=0.2$ with $A/d=0.2$–0.4 at $S/d=1$). Meanwhile, compared to the case of the rigid plate, a further drag reduction is obtained due to the motion of the flexible plate (the maximum drag reduction is 2.9% at $A/d=0.2$, $St_f=0.2$ and $S/d=1$). In addition, the net saving can also be found, which means that both drag reduction and energy saving can be achieved (the maximum net saving is 98.54% at $A/d=0.5$, $St_f=0.1$ and $S/d=2.5$). In contrast, when the flexible plate is in the upstream of the cylinder, a much smaller drag can be achieved compared to the case of the flexible plate in the downstream. Moreover, a significant drag reduction can be attained compared to the rigid plate case (the maximum drag reduction is approximately 28% at $A/d=0.5$, $St_f=0.5$ and $S/d=2$). The established results in this study imply that the flexibility of the plate is of importance in controlling the flow over a bluff body.

1. Introduction

As the most representative example in the family of bluff bodies, the viscous flow over a circular cylinder has been extensively studied (Williamson, 1996; Williamson and Govardhan, 2004). Among various studies, flow control is always an attractive topic due to its importance in engineering applications, which is related the drag reduction, lift enhancement, vibration suppression, and so on (Choi et al., 2008; Dong et al., 2008).

There are a large number of strategies in regard to flow control over a circular cylinder. Based on the requirements of energy input, these strategies can be roughly classified into two types: passive control and active control. For passive control, no external energy is consumed. Techniques in this category include changing the surface shape (surface with dimples or grooves) (Bearmann and Harvey, 1993; Lim and Lee, 2002), altering the surface properties (hydrophobic or

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slipping surface) (You and Moin, 2007; Legendre et al., 2009), and utilizing ground effects (Nishino et al., 2008; Wang and Tan, 2008). In addition, placing another object in the wake, such as a much smaller cylinder or rod (Strykowski and Sreenivasan, 1990; Wang et al., 2006), is also a feasible choice. For this type of approach, a widely used object is the splitter plate, as its geometry is the simplest. Experimental study has determined that putting a splitter plate in the wake of the cylinder can suppress vortex shedding (Roshko, 1955; Unal and Rockwell, 1987) and decrease the Strouhal number (Gerrard, 1966; Apelt et al., 1973). Such findings have been confirmed by numerical simulations (Kwon and Choi, 1996; Hwang et al., 2003). For active control, it is associated with energy consumption. Some typical means in this category consist of cylinder oscillation (Dennis et al., 2000; Cetiner and Rockwell, 2001), blowing/suction (Lin et al., 1995; Fujisawa et al., 2004), and electromagnetic forcing (Kim and Lee, 2000; Artana et al., 2003).

The flow over multi-objects is ubiquitous. The ensuing interactions between objects may change the hydrodynamic behavior of an individual object. A well-known example is the flow over two cylinders in tandem arrangement (Zdravkovich, 1977; Slaouti and Stansby, 1992). Compared to the case of a single cylinder, the trailing cylinder can achieve a reduction in drag, which is attributed to the suppression of vortex shedding from the leading cylinder. Actually, such hydrodynamic interactions have been applied in passive flow controls, an example being the use of a splitter plate in the wake of a cylinder (Roshko, 1955; Unal and Rockwell, 1987; Gerrard, 1966; Apelt et al., 1973; Kwon and Choi, 1996; Hwang et al., 2003). In contrast, due to the excellent propulsive features caused by their deformable body, swimming fish have become an attractive research topic. Lighthill (1969) first introduced the hydrodynamics of fish propulsion. After that, ever-increasing interest has been drawn to investigating the various mechanisms of fish locomotion. One focus is hydrodynamic interactions in fish schools. Weihs and Webb (1983) reported that fish schools would consume the least overall energy when two successive swimming fish maintain a staggered configuration. Fish (1999) indicated that the fish in the second rank would experience a lower incoming velocity, which is beneficial to their locomotion. Using a traveling wavy foil to represent the fish body, the characteristics of fish interactions, including the side-by-side arrangement (Dong and Lu, 2007) and tandem arrangement (Deng et al., 2007), have recently been studied via numerical simulations. Dong and Lu (2007) revealed that the in-phase motion mode could reduce swimming power and that the anti-phase mode could enhance the forces exerted on the body. Deng et al. (2007) reported that the thrust performance of downstream fish depends on the Strouhal number. A relatively low Strouhal number would result in a thrust enhancement and vice versa. Similar to the deformable bodies of fish schooling, the interactions between two tandem flapping flags have been measured in the laboratory by Ristroph and Zhang (2008) and have been numerically simulated by Zhu (2009). In contrast to the situation of rigid bodies (Zdravkovich, 1977; Slaouti and Stansby, 1992), the leading flag always benefits from drag reduction.

Due to the flexibility of the deformable body, the resultant flow interaction dramatically differs from that of the rigid one. It is natural to pose the following two questions. Is it possible to utilize a flexible body to control the flow over a circular cylinder? Can the performance of a flexible body be enhanced compared to the use of rigid body (Strykowski and Sreenivasan, 1990; Wang et al., 2006; Roshko, 1955; Unal and Rockwell, 1987; Gerrard, 1966; Apelt et al., 1973; Kwon and Choi, 1996; Hwang et al., 2003)? These problems are the primary motivators of the current investigation. Although there are a few works concerned with the interactions between rigid-flexible bodies (Liao et al., 2003; Beal et al., 2006; Jia and Yin, 2009; Tian et al., 2010), they have mainly focused on the hydrodynamic behaviors of the flexible body. In contrast, our task is to explore the feasibility of flow control via the combination of a rigid body and a flexible body. It is noted that Xiao et al. (2011, 2012) recently studied the near-wake interaction between an undulation foil and a D-section cylinder at a high Reynolds number in which the foil is inserted in the wake of the cylinder. In the current study, a traveling wavy plate is selected to represent fish-like motion (Dong and Lu, 2005). This flexible plate is used to construct a united system together with a circular cylinder. They are placed in a line. The plate is located either in front of the cylinder or in its wake. In the current plate-cylinder system, their interaction is mainly governed by the Strouhal number of the plate motion (St_f) (the definition of St_f is given in Section 3), the maximum amplitude of the motion (A), and the gap between the cylinder and the plate (S). When the plate is in front of the cylinder, the gap is defined as the distance between the trailing point of the plate and the leading point of the cylinder, and when the plate is in the wake of the cylinder, the gap is defined as the distance between the trailing point of the cylinder and the leading point of the plate. Although the flow behaviors may show some differences if the plate's length is varied, we simply concentrate on the effects of other parameters in this study. Therefore, the length of the plate (l) is fixed. It is equal to the diameter of the cylinder (d). Based on d, the Reynolds number is chosen as $Re = 100$. To investigate the performance of the plate-cylinder interaction on the flow control, we conduct extensive numerical simulations by varying St_f, A and S. To do so, the boundary-condition-enforced immersed boundary-lattice Boltzmann method (IB-LBM) (Wu and Shu, 2009) is adopted. This method has been well verified and can accurately and efficiently simulate the flows over both stationary and moving objects (Wu et al., 2010; Wu and Shu, 2010).

The paper is organized as follows. The boundary condition-enforced IB-LBM is briefly described in Section 2. It is followed by the definition of the plate-cylinder system and the numerical verification. Section 4 presents the detailed numerical study of the interaction between the cylinder and the flexible plate. Finally, concluding remarks are provided in Section 5.

2. Description of methodology

In this section, the adopted numerical method, i.e., the boundary condition-enforced IB-LBM (Wu and Shu, 2009, 2010; Wu et al., 2010), will be briefly described.