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Simulations of passive oscillation of a flexible plate in the wake of a cylinder by immersed boundary method

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ABSTRACT

The behavior of a passive plate placed behind a D-cylinder is numerically studied by using the modified immersed boundary methods. The linear Euler–Bernoulli Beam theory is employed as the structure model for the flexible plate. The effects of the Reynolds number, the mass ratio and rigidity of the material and the distance between the D-cylinder and the plate are investigated. Results show that, the initial perturbation is inhibited when the Reynolds number is small. By increasing the Reynolds number, the larger the Reynolds number the larger amplitude of the plate's oscillation. When the plate is placed close to the D-cylinder, its surface is surrounded by the vortical layer and there is no vortex shed from the D-cylinder, the 'attached vortex mode'. The 'Kármán vortex street' is formed at the front of the plate when it is placed further behind the D-cylinder, the 'vortex street mode'. Compared with the effects of Reynolds number, the material parameters do not play a crucial role on the plate's oscillation behavior. The drag forces which act on the plate are related to the flow structures. When the distance is smaller with $S/L = 1.5$, the plate is located in the suction domain and negative drag acts on the plate initially. For the large distance case, when the incoming shed vortex contacts the plate's head, a low pressure domain is generated and this results in lower drag. The 'vortex street mode' can get more kinetic and strain energy by the plate, since the shed vortices make the plate's deformation mode more complex and the oscillation frequency is also larger than the one of the 'attached vortex mode'.

1. Introduction

Interactions between flexible structure and surrounding fluid flow are common in nature and industry. Some are profitable, nevertheless, some are not. For example, in paper printing procedure, paper flutter may cause wrinkles and folds of the paper [1]. In human upper-airway where the soft palate (a flexible flap of tissue) is located, when the soft palate is impaired, it may induce conditions of snoring and Obstructive Sleep Apnea/Hypopnea (OSAH) [2]. The heart valves between atrium and ventricle play important roles in blood transport of human heart [3]. Moreover, in the animal world, scientists found that when fish lead a school swimming, the downstream fish in the wake of upstream fish may save energy compared with single cruising [4].

The objects mentioned above, *e.g.*, soft palate, heart valves and swimming fish, can be treated as a flexible body or plate for academic studies. Many studies (including experimental, numerical and theoretical studies) have been done in the past. Concerning the physical basis, different models have been developed. Farnell et al. [5] assumed a filament which was composed of several elements, and each element was fixed to one another at the hinge point with a spring. It was shown in their work that the filament oscillation would be suppressed when reducing its length. Later on, the coupled states of two flapping filaments were also studied [6]. With an analogous model of Farnell et al. [5], Eldredge [7] employed the articulated rigid bodies model to represent a flexible body, and an articulated system with three linked rigid bodies in a free stream was studied at $Re = 200$. Argentina and Mahadevan [8] proposed a linearized flag theory involving a simplified model of the pressure loading based on thin airfoil theory. They concluded that the instability occurs when the frequency of the lowest mode of elastic bending vibrations coincides with the frequency of aerodynamic oscillation of the hinged rigid plate. Based on the model for an inextensible flexible sheet, Alben and Shelley [9] solved the

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fully nonlinear dynamics numerically in an inviscid 2D flow with a free vortex sheet. The transition from stable periodic flapping to chaotic flapping with decreasing bending rigidity was reported and both bi-stability and hysteresis were found with this nonlinear dynamical model, which is consistent with previous experiments of Shelley et al. [10]. Following this model, Michelin and Smith [11] added a prescribed heave motion at the head of the flexible sheet (wing), and the dynamical equations were solved with Chebyshev spectral methods. The influence of the wing's rigidity on its propulsive performance was investigated. The peaks in mean thrust were found to correspond to maximum values in the trailing-edge amplitude, which were the results of the resonance between the frequency of the prescribed heaving motion and the natural frequencies of the system. Considering the fluid viscous effect, Connell and Yue [12] adopted the aforementioned full nonlinear model and developed a fluid–structure direct simulation solver coupling a direct numerical simulation of the Navier–Stokes equations. Besides these beam models, the neo-Hookean solid model was also used, especially in the simulation of heart valve [3,13]. Compared with the beam models, the neo-Hookean solid model is more precise and its applications could be more extensible.

The physical model of the work mentioned above can be briefed as a flexible body placed in a uniform incoming flow. However, the real flow environment in industry or nature, is more complex than the uniform incoming flow, including various vortices. Interactions between flexible structure and its surrounding vortices may play a crucial role. Therefore, to give an explanation of the interactions between the structure and the vortices from the hydrodynamic point of view becomes an important issue. In the animal world, some studies on the fish swimming in the vortex wakes were carried out in laboratories [14–17]. Liao et al. [15] first compared the behavior of fish swimming in the wake of a D-section cylinder with that in a free stream. It was shown that fish swim between vortices generated behind the cylinder rather than through them. The beating frequency of fish tail is close to the shedding frequency of the vortices from the D-section cylinder. As a result of this, the energy consumption of the fish decreased. Beal et al. [16] put a 'dead' fish in the wake of a D-section cylinder. It was observed that the fish is propelled upstream when its flexible body resonates with incoming vortices. Accordingly, relevant numerical investigations were made by the authors [18,19] with the immersed boundary (IB) method, and it is believed that the bypassing vortices play a positive role in enhancing thrust and saving energy. In the field of oceanic engineering, the so-called 'Energy Harvesting Eel' device is used [20,21]. A piezoelectric membrane (similar to an eel) is placed in the wake of a bluff body, the 'Kármán vortex street' forming behind the bluff body can induce oscillations of the membrane, and the piezoelectric material can convert the mechanical energy to electrical power. The internal batteries are used to store the surplus energy for later use. Both of the nature discovery (fish gait in vortices) and the industry application (energy harvesting eel) need a careful inspection to understand the hydrodynamic mechanism as well as structure response of the flexible body. Unfortunately, there are only few numerical work on this to give a reliable physical explanation, *e.g.*, Manela and Howe [22] put a cylindrical pole attached with the flag in order to make periodical shedding vortices. In their study, the motion of the flag was decomposed to the vortex-induced part and the corresponding flag 'reaction' part. However, for simplification, their model neglected the interaction of the flag motion on the motion of fluid.

In the present study, we investigate the oscillation behavior of a flexible thin-plate in the wake of a D-section cylinder which is a simple model of the flexible body and vortices interactions. Meanwhile, for simplification, the Euler–Bernoulli beam model is used to represent the flexible plate. The immersed boundary method is employed to simulate the flow motion with an embedded body (flexible plate). First proposed by Peskin [23] to study the blood flow with the heart valve in 1970s, the immersed boundary method has been developed into a reliable technique to simulate fluid structure interaction problems. Due to its high efficiency and simplification, the immersed boundary method has been applied widely in various fields, including complex biological flow [24,25], particle laden and bubbly flow [26–29], compressible flow [30], etc.

The motivation of this paper comes from the fish swimming studies [15,16] and the design of 'Energy Harvesting Eel' device [20,21]. Interactions between the flexible structure and incoming vortices may dominate the oscillation behavior of the structure, however, the aforementioned studies are more concerned about the structure oscillation in uniform flow. Furthermore, studies on the interaction of flexible structure and incoming vortices also have applications in other fields, *e.g.*, active vorticity control [14,31], etc. In our study, a flexible thin-plate is employed, and a linearized Euler–Bernoulli beam model is used. The Reynolds number set in the computation of this paper is lower than that in the experiments. Nevertheless, we believe that some qualitative results can be obtained and these may provide new insights into the mechanism of the plate oscillating in a vortex wake, which may be useful for the applications of underwater biomimetic vehicle, ocean energy extraction device and active vorticity control. The rest of the paper is organized as follows. In the next section, the problem is illustrated. Then both the fluid solver and the solid structure solver are introduced. As will follow, the numerical results of the plate's oscillation behavior and the flow field structures are demonstrated and discussed. The concluding remarks are given in the final section.

2. Problem statement

A two dimensional D-section cylinder (D-cylinder) with diameter d and a flexible thin-plate with length L are placed sequently at the center of the computation domain (as shown in Fig. 1). The distance between them (from the cylinder center to the plate head) is represented by S. The head of the plate is fixed while the rest of the body can oscillate passively. The thickness of the plate is denoted by h fixed as $h = 0.03L$, therefore, the linear beam theory model can be accurate in this situation. A uniform constant velocity, U_0, is specified at the domain entrance, as well as at the top and the bottom boundaries of the computational domain. A no-reflect boundary condition is used on the outlet boundary. The constant velocity is imposed all through the computational domain as an initial condition. The dimensionless parameter, Reynolds number $Re = U_0L/\nu$ (U_0 and ν are the constant incoming flow velocity and kinematic viscosity of the fluid respectively), is employed. The diameter of the cylinder is chosen as $d = 0.5L$. For the structure model, two parameters are also introduced, the mass ratio μ and the non-dimensional rigidity η (to be mentioned later). The ranges of the parameters chosen in this paper ensure the plate can oscillate periodically with proper amplitude in the wake of the D-cylinder.

3. Methodology

3.1. The solid structure model

The linear Euler–Bernoulli Beam theory is employed here to govern the motion of the thin plate and it has been used to study the vortex-induced vibration of a circular cylinder [32]. The Euler–Bernoulli Beam theory describes the relationship between beam's deflection and the applied load. It covers the case for small deflections and it is a special case of Timoshenko Beam Theory which accounts for shear deformation and is applicable for thick beams [33]. Therefore, the effect of fluid shear stress (viscous effect) on Euler–Bernoulli Beam is ignored and only the fluid