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Numerical Investigation of the Dynamics of a Flexible Filament in the Wake of Cylinder

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Abstract. Fluid-structure-interaction problems are ubiquitous, complicated, and not yet well understood. In this paper we investigate the interaction of a leading rigid circular cylinder and a trailing compliant filament and analyze the dynamic responses of the filament in the wake of the cylinder. It is revealed that there exist two flapping states of the filament depending on the cylinder-filament separation distance and the relevant critical distance distinguishing the two states is associated with the Reynolds number and the filament length. It is also found that the drag coefficient of the cylinder is reduced but that of the filament may be increased or decreased depending on its length. Compared with a single filament in a uniform flow, the filament of the same mechanical properties flapping in the wake of the cylinder has a lower frequency and a greater amplitude.

AMS subject classifications: 74K20, 76D05, 76Z10

Key words: Fluid-structure interaction, immersed boundary-lattice Boltzmann method.

1 Introduction

Fluid-structure-interaction (FSI) problems are everywhere in our daily life. Arguably the FSI problems may be further categorized into two subsets: fluid-*rigid*-structure-interaction such as a flying aircraft interacting with the air and fluid-*flexible*-structure-interaction such as red blood cells moving in the flowing blood in human arteries. These two types of the FSI problems have already been extensively studied theoretically, experimentally and computationally. The readers are referred to the following papers and

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references therein: sedimentation of an elliptical particle [1], numerical simulations on the dynamics of plates falling freely in a fluid under the influence of gravity [2]; experimental and computational studies on the dynamics of flexible filaments in a flowing soap film [3,4], a flapping flexible plate in quiescent fluid [5], resonance and propulsion performance of a heaving flexible wing [6], capsule deformation [7,8], and effects of flexibility on the aerodynamic performance of flapping wings [9].

However, many FSI problems encountered are even more complicated. They may involve the interaction of a viscous fluid and both rigid and flexible structures. To name a few such examples: flag flapping in a wind (involving the rigid pole, the flexible flag and the flowing air) and fish swimming in the wake of a bridge pillar or a navigating ship. The FSI problems involving both rigid and compliant structures in a viscous flow are less investigated and yet not well understood because of the intrinsic mathematical and physical complexity of this type of fluid-structure-interaction. Liao et al. [10] demonstrated how a trout might exploit the vortices to reduce the cost of locomotion in the wake of a stationary object in a water flow. Beal et al. [11] showed that a streamlined body passively oscillating within a vortical wake could extract sufficient energy from the eddies to propel itself upstream. Eldredge and Pisani [12] investigated the passive locomotion of a simple articulated fish-like system in the wake of an obstacle. Sui et al. [13] first simulated the interaction of a leading rigid cylinder and a trailing *massless* flexible filament in a two-dimensional flow as application of a newly developed numerical method for the FSI problems. Jia and Yin [14] identified by laboratory experiments three response modes of a flexible filament in the wake of a rigid cylinder in a flowing soap film. Wang et al. [15] found the filament in the wake of a upperstream cylinder gained a thrust rather than drag in two dimensions. Tian et al. [16] performed simulations on the interaction of a leading flexible filament and a trailing rigid cylinder.

Because of the presence of both rigid and deformable bodies in a viscous flow, the interaction among the bodies and the flow may become different and more complex, and new phenomena may emerge. Previous experiments with tandem rigid cylinders [17] found that the drag of a trailing object was less than that of a leading one. A recent experiment on two tandem flapping rubber threads in a two-dimensional viscous flow reported by Ristroph and Zhang [18] revealed just the opposite: the drag of the downstream flag was greater than that of the upstream flag. A computational study [19] on the similar problem showed that even more complicated scenarios happened as the Reynolds number was varied. What would happen if a rigid body and a deformable body are placed in tandem in a viscous flow? Here we consider a flexible filament interacting with the wake of a upstream rigid cylinder in a viscous incompressible flow in two dimensions. Numerous simulations are performed with various dimensionless parameters and our numerical results indicate the existence of two flapping modes of the filaments associated with the suction zone behind the cylinder [12] and the drag of the leading cylinder is always reduced but the drag of the trailing filament may be decreased or increased depending on the dimensionless filament length.

The remainder of the paper is organized as follows. Section 2 presents the physical