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Particle-Based Modeling of Asymmetric Flexible Fibers in Viscous Flows

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Abstract. The present paper follows our previous work [Yang et al., Phys. Rev. E, 90 (2014), 063011] in which the bending modes of a symmetric flexible fiber in viscous flows were studied by using a coupling approach of smoothed particle hydrodynamics (SPH) and element bending group (EBG). It was shown that a symmetric flexible fiber can undergo four different bending modes including stable U-shape, slight swing, violent flapping and stable closure modes. For an asymmetric flexible fiber, the bending modes can be different. This paper numerically studies the fiber shape, flow field and fluid drag of an asymmetric flexible fiber immersed in a viscous fluid flow by using the SPH-EBG coupling method. An asymmetric number is defined to describe the asymmetry of a flexible fiber. The effects of the asymmetric number on the fiber shape, flow field and fluid drag are investigated.

AMS subject classifications: 76M28, 76D99, 74S99

Key words: Fluid-structure interaction, asymmetric flexible fiber, drag force, smoothed particle hydrodynamics (SPH), element bending group (EBG).

1 Introduction

Trees, grasses and some animals have to withstand fluid forces such as aerodynamic forces in air or hydrodynamic forces in water. They can change their shapes or postures to adapt the fluid forces. This strategy can change the fluid forces imposed on them. For example, a fish can get forward thrust and use environmental vortices by waving

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motion [1,2] and a plant can reduce fluid drag by reconfiguration [3,4]. For flexible structures such as most plants, some animals and flags, their shapes become a function of the relative speed between the corresponding object and the ambient fluid. Thus dynamics and flow patterns of the interactions of flexible structures and fluids are much more complex than that of rigid structures and fluids [5,6].

There have been a number of experimental, theoretical and numerical studies on the dynamics of flexible structures interacting with fluid flows over the past decades. Vogel [3,7] experimentally studied the fluid drag and reconfiguration of broad leaves in high winds. The experiments showed that some broad leaves rolled up into cone shapes in strong winds and the drag on the leaves increases slower than the square of the wind speed. Laura et al. [8] also studied the reconfiguration of broad leaves experimentally and numerically. Gossellin et al. [9] investigated experimentally the drag reduction of two flexible plates of different shapes in air. Alben et al. [10,11] experimentally and numerically studied the drag reduction of a flexible fiber immersed in a soap film. Yang et al. [12,13] numerically investigated the bending modes and drag reduction of a flexible fiber immersed in a viscous flow using a coupling method of smoothed particle hydrodynamics (SPH) and element bending group (EBG).

Although a flexible fiber is a very simple structure, the dynamics of a flexible fiber interacting with a viscous flow have not yet been thoroughly explored. Most previous studies on drag reduction of flexible fibers in flows were focused on cases in which a symmetric flexible fiber (fixed on its midpoint) is immersed in a viscous flow. However, there are more frequent cases with asymmetric flexible fibers (fixed on points different from its midpoint) interacting with viscous fluids and these can produce quite different behaviors from symmetric fibers.

Due to the existence of moving interfaces and deformable boundaries, it is usually a big challenge to model fluid-flexible fiber interaction, especially for cases with high Reynolds numbers. As such, a numerical approach which can well treat moving interfaces and deformable boundaries would be appealing in modeling fluid-flexible fiber interaction. Yang et al. [12,14] developed a SPH-EBG coupling method to model the interaction of a flexible fiber interacting with viscous fluids. The SPH method is used to model fluid motion, while the EBG method is used to model fiber motion. Since both SPH [15] and EBG [16] are Lagrangian particle methods, the coupling of these two methods does not lead to significant difficulties. The SPH-EBG coupling method was first used to model red blood cell (RBC) deformation in a shear flow [17]. Later it was extended to model a flexible fiber in a viscous flow [12,13] and dam-break flows impacting on flexible structures [14].

In this paper, the SPH-EBG coupling method is further used to study the dynamics of an asymmetric flexible fiber interacting with a viscous flow including the fiber shape (bending modes), flow field, and drag force. Comparing to the simulation of symmetric cases, there is no more numerical difficulty in simulating asymmetric cases. The numerical method used for this work is nearly the same as the method used in [12]. In order to make the flow field smoother and the method more stable, the artificial viscosity pro-