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A momentum exchange-based immersed boundary-lattice Boltzmann method for simulating a flexible filament in an incompressible flow

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ABSTRACT

A momentum exchange-based immersed boundary-lattice Boltzmann method, which is used to solve the fluid–flexible-structure-interaction problem, is introduced in this paper. The present method, overcoming the drawback of the conventional penalty method employing a user-defined spring parameter for calculating the interaction force induced by the immersed boundary, uses a concept of momentum exchange on the boundary to calculate the interaction force. Numerical examples, including a laminar flow past a circular cylinder, a filament flapping in the wake of the cylinder, a single filament with the upstream end fixed flapping in a uniform flow field and the interaction of two filaments flapping in the flow, are provided to validate the present method and to illustrate its capability of dealing with the fluid–flexible-structure-interaction problem. Particularly, with considering the filament mass effects, a single filament with a fixed centre point undergoing a bending transition in the flow is firstly studied in the present paper. Our numerical results compare qualitatively well to experimental results. For a single filament with a fixed centre point, it is found that the flexure modulus has a significant effect on the final state of the filament: for a larger flexure modulus, the filament reaches the 'quasi-steady' state finally; for a small flexure modulus, the filaments will be flapping like two filaments.

1. Introduction

Fluid–structure-interaction (FSI) problems are found in many engineering applications and biology kinematics. In mechanical engineering, e.g. the design of pumps, aircraft, artificial heart valves and many other devices require the consideration of fluid–structure-interaction phenomena that play a key role in the dynamic stability of the structure. In civil engineering, to build bridges, dams, Marine platform, water supply and drainage, protective engineering, etc., the FSI investigations should be done as well. In biology kinematics, many motions involve complicated interactions between deformable bodies and their surrounding viscous incompressible fluids. On a macroscopic scale, some examples include a fish swimming in the water, a flag flapping in the air, and a leaf falling in the sky. On a mesoscopic scale, there are such as swimming sperms inside the body liquid and red cells in blood. These motions in physics can be considered as a

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fluid–flexible-structure-interaction problem, in which the geometry of the deformable body can change with time due to the hydrodynamic forces acting on the body, and the geometry changing of the deformable body gives a time-dependent effect on the local flows on the other hand. As this fluid–flexible-structure-interaction problem has many implicit applications in aeronautical engineering and bioengineering, it has attracted intensive research interests among the fluid scientists in recent years, and extensively studies have been carried out to investigate its mechanisms.

Laboratory experiments have been carried out to study the dynamics of flexible filaments in a flowing soap film by Zhang et al. [1–5]. They revealed that, for a single filament with its upstream end fixed and downstream end unconstrained in a regular fluid flow, it holds two distinct and stable dynamical states: a stretched-straight state and a flapping state. Meanwhile, for the fluid–structure interaction of a body between two filaments, two typical phenomena, which are according to the placed position of two filaments, have been reported [1,4,5]. For two filaments with their upstream ends fixed in a distance in the flow, there exist four different dynamical states depending on the distance of the two filaments. And for two filaments with their upstream ends fixed together, it is found that the flapping motion has different characteristics depending on the relative location of the filaments. Although laboratory experiments are the most effective method to study these motions, they have difficulties to capture some detailed characteristics and study the effects of some parameters.

With the fast development of computers, numerical simulations have become one of the important methods for investigating the FSI problems. However, developing an effective numerical algorithm for those problems presents many challenges: the mesh generation of irregular geometries with large deformation, high resolution grid and three-dimensional demand much computation time. In general, there are two approaches to solve FSI problems: the monolithic approach [6–8] adopt a similar discretization scheme to discretize the equations of a geometrically non-linear elastic structure and the incompressible viscous flow field, meanwhile the coupling condition are treated at the interface. Another is the partitioned approach [9], including loose (weak) coupling algorithm [10–13] and strong coupling algorithm [14–16]. The information between structure and flow field is exchanged only once per time step for a loose coupling, while a time step of the strong coupling algorithm is achieved by an iteration loop. To date, the arbitrary Lagrangian–Eulerian (ALE) method is found to be a rather convenient method in dealing with the moving boundaries [17] and it has been successfully applied to solve FSI problems [18]. However, the ALE method, which usually employs a body-fitted grid, needs to update the grid frequently with a large computational cost. To overcome this drawback, there were more attentions on the immersed boundary method (IBM) [19–26], which employs a Cartesian grid for solving the fluid flow and a Lagrangian grid to determine the moving boundary. The IBM is a handling scheme naturally and simply couples a fluid with the moving complex geometries through a distributed force, which is obtained at the Lagrangian points and distributed onto the fixed Cartesian grid by adding a corrective force term to the Navier–Stokes equations. Based on the idea of the IBM, Zhu et al. [22] simulated one flexible filament flapping in the uniform flow field firstly. The numerical results showed that the mass and length of the filament have a determining influence on the final stable state (rest or flapping) of the filament and also affect characteristics of flapping state, which are consistent with the findings of the laboratory experiments [1]. Subsequently, Zhu et al. presented a series of numerical investigations to study the motions of flexible filaments in the uniform flows including: the interaction of two elastic filaments placed in the parallel positions [23], a flexible filament tethered at its centre point in viscous flow field [24,27], and the interaction of two tandem deformable bodies in a viscous incompressible flow [26]. These studies allowed explained the mechanisms of the fluid–filament interactions found in the laboratory experiments given by Zhang et al. [1,2,5].

The usual approach to model incompressible macroscopic transport problems is to solve the Navier–Stokes equations by (semi-)implicit methods as the complementary Poisson equation for the pressure is elliptic. It has been generally known that Lattice Boltzmann Methods (LBM) is an efficient and simple method to obtain the solution of flow field [28,29]. In past decades, the LBM has been greatly developed and widely applied [30–39]. Owing to its simplicity and effectiveness, the LBM has been employed by many researchers to solve the FSI problems by coupling the IBM (hereafter denoting IB-LBM). For example, Feng and Michaelides were the first to apply the IB-LBM to solve fluid and particles interaction problems [40,41]. In his work, the interaction force between fluid and particles is computed by the penalty method. Consider that the penalty method introduces a user-defined spring parameter, Niu et al. [42] proposed a momentum exchange-based IB-LBM for simulating the particles moving in the incompressible flows. The momentum exchange-based IB-LBM method presents a very simple way to calculate the distributed force on the Lagrangian points on the body by using the momentum exchanging idea when two bodies are confronted. Recently, an explicit model for FSI problems using LBM and p-FEM was proposed by Geller et al. The solution of flow field is obtained by Lattice Boltzmann Method and a high-order Finite Element scheme is applied to discretize governing equations of the structure [43,44].

The IB-LBM has been used to simulate fluid–flexible-structure-interaction problems by many researchers [45–48]. However, these works have not taken into account the effects of the object's mass on the fluid–flexible-structure-interaction system. Tian et al. [49] introduced a modified penalty approach into the IB-LBM to simulate the elastic boundaries with a finite mass moving in the flow field. Unfortunately, this approach introduces artificial spring parameters to calculate the distributed force and causes many uncertainties in the calculation results. The momentum exchange-based IB-LBM, which was proposed by Niu firstly [42], can effectively avoid the above drawbacks.

In this paper, we use the momentum exchange-based IB-LBM to study an elastic object moving in the flow field. The present numerical algorithm is robust and highly efficient. A user-defined spring parameter is not introduced and the set of the distributed forces on the boundary is calculated based on the momentum exchange of the fluid and the moving boundary, which is more physically plausible.