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A Robust Immersed Boundary-Lattice Boltzmann Method for Simulation of Fluid-Structure Interaction Problems

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Abstract. A robust immersed boundary-lattice Boltzmann method (IB-LBM) is proposed to simulate fluid-structure interaction (FSI) problems in this work. Compared with the conventional IB-LBM, the current method employs the fractional step technique to solve the lattice Boltzmann equation (LBE) with a forcing term. Consequently, the non-physical oscillation of body force calculation, which is frequently encountered in the traditional IB-LBM, is suppressed greatly. It is of importance for the simulation of FSI problems. In the meanwhile, the no-slip boundary condition is strictly satisfied by using the velocity correction scheme. Moreover, based on the relationship between the velocity correction and forcing term, the boundary force can be calculated accurately and easily. A few test cases are first performed to validate the current method. Subsequently, a series of FSI problems, including the vortex-induced vibration of a circular cylinder, an elastic filament flapping in the wake of a fixed cylinder and sedimentation of particles, are simulated. Based on the good agreement between the current results and those in the literature, it is demonstrated that the proposed IB-LBM has the capability to handle various FSI problems effectively.

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Key words: Immersed boundary-lattice Boltzmann method, fractional step, suppression of force non-physical oscillation, fluid-structure interaction.

1 Introduction

Fluid-structure interaction (FSI) problems are constantly observed in both nature and engineering applications. Some examples are flapping motion of flags in the wind, deformation of red blood cells, transportation of solid particles, and so on. Many of these

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applications involve unsteady flows together with complex configurations, and their fundamental understanding is of critical importance. To numerically solve such problems, common approaches are to use either body-fitted meshes or fixed meshes. For the former approaches [1–3], the major difficulty is that a frequent mesh regeneration process is required that consequently increases the computational cost, particularly as complex and/or three-dimensional geometries are considered. In contrast, the latter approaches can avoid such difficulty due to the use of a regular fixed mesh for discretization of flow field. In these approaches, the effect of the embedded body on the surrounding fluid is taken into account in the form of an additional body force. Owing to such simplicity, they are very popular for FSI problems with arbitrary geometries. Thereinto, the immersed boundary method (IBM) is a famous example.

The IBM was originally developed by Peskin [4] for the purpose of simulating the blood flow in the human heart. Its basic idea is that the boundary of body can be represented by a set of Lagrangian points, and the body forces acting on the Lagrangian points that represent the effect of boundary can be distributed into the surrounding flow field. Subsequently, the whole flow field is discretized and solved on a regular Cartesian mesh. Therefore, a key issue of IBM is the treatment of body force. Hitherto, there are two implementations developed. One is the 'discrete forcing scheme' wherein the body force is either explicitly or implicitly applied to the discrete governing equations of flow field [5–7]. This scheme possesses the precise satisfaction of the boundary condition at the body surface by maintaining a sharp interface representation. However, its implementation for complex geometries may suffer some challenges because it needs to identify the mesh point where the body force is located. The other is the 'continuous forcing scheme' wherein a continuous forcing function, such as a discrete delta function, around the boundary is added to the governing equations [8–10]. This scheme can be directly implemented in any solver with relative ease, and the body interface might be diffused because of the introduction of interpolation.

From the methodological point of view, the IBM can be regarded as a technique for boundary treatment. Meanwhile, the flow field solution can be obtained by either solving the traditional Navier-Stokes (N-S) equations or using other approaches. One choice is the lattice Boltzmann method (LBM) that is an alternative to N-S solver with high simplicity and parallelism, and it has already been successfully applied to simulate various flow problems [11]. The coupling of IBM with LBM (i.e., IB-LBM) was first performed by Feng and Michaelides [12, 13], and then it was used to simulate particulate flows. Thereafter, this method has been refined continually and utilized to handle a variety of FSI problems [14–23]. Currently, there are two ways to treat the body force in the IB-LBM, i.e., explicit and implicit. In the explicit treatment that has been popularly employed, the body force is calculated in advance by using the penalty method [12, 15, 16, 19], direct forcing method [13] or momentum exchange method [14, 22]. As a consequence, the no-slip boundary condition is only approximately satisfied, which may induce some flow penetration to body. In the implicit treatment, on the other hand, the body force is first set as unknown and then is obtained by solving a formed matrix directly [17, 21] or ap-