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An immersed boundary-lattice Boltzmann flux solver and its applications to fluid–structure interaction problems

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ABSTRACT

An immersed boundary-lattice Boltzmann flux solver (IB–LBFS) for the simulation of two-dimensional fluid–structure interaction (FSI) problems is presented in this paper. The IB–LBFS applies the fractional-step method to split the overall solution process into the predictor step and the corrector step. In the predictor step, the intermediate flow field is predicted by applying the LBFS (lattice Boltzmann flux solver) without considering the presence of immersed object. The LBFS applies the finite volume method to solve N–S (Navier–Stokes) equations for the flow variables at cell centers. At each cell interface, the LBFS evaluates its viscous and inviscid fluxes simultaneously through local reconstruction of the LBE (lattice Boltzmann equation) solutions. In the corrector step, the intermediate flow field is corrected by the implicit boundary condition-enforced immersed boundary method (IBM) so that the no-slip boundary conditions can be accurately satisfied. The IB–LBFS effectively combines the advantages of the LBFS in solving the flow field and the flexibility of the IBM in dealing with boundary conditions. Consequently, the IB–LBFS presents a much simpler and more effective approach for simulating complex FSI problems on non-uniform grids. Several test cases, including flows past one and two cylinders with prescribed motions, are firstly simulated to examine the accuracy of present solver. After that, two strongly coupled fluid–structure interaction problems, i.e., particle sedimentations and vortex-induced vibrations of a circular cylinder are investigated. Good agreements between the present results and those in literature verify the capability and flexibility of IB–LBFS for simulating FSI problems.

1. Introduction

In recent years, fluid–structure interaction (FSI) problems have attracted growing attention due to their wide applications in scientific research and engineering. Essential examples include blood flows in a human heart (Peskin, 1977), vibrations of subsea pipelines and cables in deep sea (Singh and Mittal, 2005), flows around bionic fish and birds and cell transport in arteries and veins (Tian et al., 2014). To resolve such flow problems, many accurate and efficient numerical methods have been proposed, such as the body-fitted arbitrary-Lagrangian–Eulerian methods (ALE) and the Cartesian mesh solvers (Udaykumar et al., 2001; Glowinski et al., 2001; Xu and Wang, 2006; Gilmanov and Sotiropoulos, 2005). Among

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these methods, the immersed boundary method (IBM) (Gilmanov and Sotiropoulos, 2005; Mittal and Iaccarino, 2005; Fadlun et al., 2000; Feng and Michaelides, 2004, 2005; Goldstein et al., 1993; Zhu et al., 2011; Rosis et al., 2014a, 2014b; Suzuki and Inamuro, 2011; Niu et al., 2006; Chen et al., 2013; Wu and Shu, 2009; Sui et al., 2007; Dupis et al., 2008; Tian et al., 2011; Griffith et al., 2007), first proposed by Peskin (1977) for simulating the flow in a human heart, has been widely applied due to its simplicity and flexibility.

In general, the IBM uses two groups of independent meshes: the Cartesian Eulerian mesh for the flow field and the Lagrangian grid for implementation of boundary conditions. The basic idea of IBM is very simple. According to the no-slip boundary condition, the effects of the immersed boundary on the surrounding fluids are first modeled by restoring forces on the Lagrangian grid and then distributed to their surrounding Eulerian grid points. After distribution, the restoring forces on the Eulerian grid are added into governing equations as external forcing terms. In this manner, the IBM is able to simulate flows with complicated geometries on the simple Cartesian mesh, which avoids tedious re-meshing process and saves considerable computational cost and coding efforts. These distinctive features provide the IBM a high potential for simulating moving boundary and FSI problems in a much simpler and effective way. Due to high potential, many immersed boundary methods, such as the penalty forcing scheme (Peskin, 1977; Feng and Michaelides, 2004, 2005), the feedback forcing scheme (Goldstein et al., 1993; Zhu et al., 2011), the direct forcing scheme (Rosis et al., 2014a, 2014b; Suzuki and Inamuro, 2011), momentum exchange scheme (Niu et al., 2006; Chen et al., 2013), implicit boundary condition-enforced scheme (Wu and Shu, 2009), have been proposed.

In the successful development and applications of the IBM, a simple and efficient solver for the solution of flow field is necessary and essential. The popular approaches for the flow field in the IBM applications are the Navier–Stokes (N–S) equation solver (Peskin, 1977; Fadlun et al., 2000; Goldstein et al., 1993) and the lattice Boltzmann method (LBM) (Guo and Shu, 2013; Qian et al., 1992; Lai and Ma, 2012). Although they present a clear and rigorous physical foundation for incompressible flows, the N–S equations in primitive formulation suffers from some numerical difficulties in the solution process. The major difficulty comes from the velocity–pressure coupling due to the absence of the pressure in the continuity equation. To overcome this difficulty, the projection or pressure correction methods are usually applied, which will result in a pressure-Poisson or pressure correct equation. However, the slow convergence of Poisson equation degrades the computational efficiency of this kind of N–S solvers, especially for unsteady flow simulation. Another difficulty is the requirement of a staggered grid in the solution process, which brings much inconvenience and more effort in programming. As compared with the N–S solvers, the LBM has been proven to be a simple and efficient solver for simulation of incompressible fluid flows. Thanks to the distinctive merits of LBM, such as its simplicity, easy implementation and intrinsic kinetic and parallel nature, the combination of IBM and LBM, i.e. IB–LBM, could provide an efficient and flexible solver for FSI problems. This promising potential has driven the rapid development of IB–LBM (Rosis et al., 2014a, 2014b; Suzuki and Inamuro, 2011; Niu et al., 2006; Chen et al., 2013; Wu and Shu, 2009; Sui et al., 2007; Dupis et al., 2008; Tian et al., 2011) during the past decade. Although the distinctive advantages of the LBM are incorporated into the IB–LBM applications for some moving boundary flow problems, it has to admit that the drawbacks of the LBM, such as the lattice uniformity and tie-up between the time step and mesh spacing, are also retained in the IB–LBM. Since the standard LBM can only be applied on uniform grids, its application with IBM would inevitably need to use substantial grid points for complex FSI problems, especially in large flow domains. For applications on non-uniform grids, additional computational efforts should be introduced into the IB–LBM, such as multi-block LBM (Sui et al., 2007; Tian et al., 2011) and adaptive mesh refinement technique (Griffith et al., 2007). This is not a trivial job, which motives the present work to develop a simpler approach for complex FSI problems.

From the above review, it can be clearly seen that both the N–S solver and the LBM have their advantages and disadvantages in the IBM applications. Recently, a lattice Boltzmann flux solver (LBFS) (Shu et al., 2014a; Wang et al., 2014a, 2014b, 2014c) has been proposed for simulating both isothermal and thermal flows. The LBFS is a finite volume solver for direct update of the macroscopic flow variables at cell centers. The fluxes are evaluated at each interface by the local reconstruction of the standard LBM solutions. Due to the local application of the LBM, the LBFS is developed into a flexible and efficient solver for simulating incompressible flows on non-uniform grids, which not only successfully eliminates the previously mentioned drawbacks of the LBM and the N–S solver but also effectively combine their advantages. Due to the advantages of the LBFS in solving the flow field and the flexibility of the IBM in dealing with complex boundary conditions, it is interesting to explore the combination of the LBFS and IBM for simulating the complex FSI problems, which may produce a much simpler and more flexible solver. To achieve this goal, an immersed boundary-lattice Boltzmann flux solver (IB–LBFS) is proposed by combining the LBFS (Shu et al., 2014b) and the boundary condition-enforced IBM (Wu and Shu, 2009). In the solver, a fractional-step method is introduced to decouple the solution of the flow field and the implementation of boundary conditions. Two steps of predictor and corrector are included. In the predictor step, without considering the restoring force, the intermediate flow field is predicted by the LBFS. In the corrector step, the intermediate velocity field is corrected by applying the implicit boundary condition-enforced IBM (Wu and Shu, 2009). As a result, the no-slip boundary condition can be accurately satisfied at the end of each time step in the present IB–LBFS. It is noteworthy that the conventional IB–NS solver, which explicitly evaluates the restoring force at the beginning of each time step, cannot accurately satisfy the condition and may produce the unphysical streamline penetration phenomenon (Wu and Shu, 2009). Due to the application of the fractional-step technique, the external forcing terms are handled in a simpler and easier way in the IB–LBFS than those in IB–LBM. The IB–LBFS will be first validated by simulation of flows past stationary, transverse oscillating and two

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