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Immersed Boundary-Lattice Boltzmann Coupling Scheme for Fluid-Structure Interaction with Flexible Boundary

Yongguang Cheng[1], Hui Zhang[2,*] and Chang Liu[1]

[1] *State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China.*
[2] *School of Electrical Engineering, Wuhan University, Wuhan 430072, China.*

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Abstract. Coupling the immersed boundary (IB) method and the lattice Boltzmann (LB) method might be a promising approach to simulate fluid-structure interaction (FSI) problems with flexible structures and complex boundaries, because the former is a general simulation method for FSIs in biological systems, the latter is an efficient scheme for fluid flow simulations, and both of them work on regular Cartesian grids. In this paper an IB-LB coupling scheme is proposed and its feasibility is verified. The scheme is suitable for FSI problems concerning rapid flexible boundary motion and a large pressure gradient across the boundary. We first analyze the respective concepts, formulae and advantages of the IB and LB methods, and then explain the coupling strategy and detailed implementation procedures. To verify the effectiveness and accuracy, FSI problems arising from the relaxation of a distorted balloon immersed in a viscous fluid, an unsteady wake flow caused by an impulsively started circular cylinder at Reynolds number 9500, and an unsteady vortex shedding flow past a suddenly started rotating circular cylinder at Reynolds number 1000 are simulated. The first example is a benchmark case for flexible boundary FSI with a large pressure gradient across the boundary, the second is a fixed complex boundary problem, and the third is a typical moving boundary example. The results are in good agreement with the analytical and existing numerical data. It is shown that the proposed scheme is capable of modeling flexible boundary and complex boundary problems at a second-order spatial convergence; the volume leakage defect of the conventional IB method has been remedied by using a new method of introducing the unsteady and non-uniform external force; and the LB method makes the IB method simulation simpler and more efficient.

AMS subject classifications: 76M28, 74F10

Key words: Lattice Boltzmann method, immersed boundary method, fluid-structure interaction, flexible boundary, complex boundary.

*Corresponding author. *Email addresses:* `chengyg2004@yahoo.com.cn` (Y. Cheng), `hzhang@whu.edu.cn` (H. Zhang), `beryl1988@163.com` (C. Liu)

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1 Introduction

The immersed boundary (IB) method has been developing rapidly since it was first invented to simulate the heart valve flow by Peskin in 1972 [1]. Recently, it was viewed as a general method for computer simulations of biological systems interacting with fluids [2], and the successful simulations of three-dimensional human heart flows [3–5], insect flight [6], aquatic animal locomotion [7, 8], filament flapping dynamics [9, 10], blood cell aggregation [11, 12], biofilm processing [13] and parachute dynamics [14, 15] have exhibited its great potential and profound perspective. However, the existing versions of the IB method have some inadequacies, within which the solution of the fluid equations is not efficient enough and needs to be improved [16]. Because the IB method's fluid equations must be solved in a regular Cartesian grid, one may think of taking the lattice Boltzmann (LB) method as a substitute for the original spectral or finite-difference fluid flow scheme. The LB method [17] is a regular lattice-based scheme for fluid flow simulation, and its simplicity, efficiency, parallelism and aptness for many fluid flow problems have been extensively verified [17–23]. The fact that both the IB method and the LB method work on a regular grid or lattice makes the IB-LB coupling possible. Moreover, the superiority of the LB method for fluid flow simulation may improve the IB method's efficiency.

An IB-LB coupling scheme might be promising for simulating fluid-structure interaction (FSI) and moving boundary problems. Some preliminary but successful attempts have been conducted [10–12,24–28]. Feng in 2004 first published an IB-LB coupled scheme for simulating particle-fluid interaction problems [24]. Later, Peng upgraded the scheme by using a multi-block lattice and a multi-relaxation-time LB scheme to enhance stability and to implement local grid refinement [25]. Shu improved the convergence of the coupling scheme by correcting the velocity to enforce the physical boundary conditions [26]. Dupuis simulated the flow past an impulsively started cylinder [27]. Niu improved the calculation of the boundary force on the fluid [28]. The above works were aimed at rigid body-fluid interaction, and most of them used the flow past a cylinder or buoyant particles as the simulation example. On the other hand, for flexible boundary FSI simulations by the IB-LB coupling, Zhang studied the red blood cell aggregation process [11, 12] and Zhu proposed a 3D scheme for the sheet flapping phenomenon [10], showing profound perspective of the approach. To date, only a few works on the IB-LB coupled scheme for problems with flexible structures have been available.

This paper presents an IB-LB coupled scheme for flexible structure-fluid interaction and complex boundary problems. It is the preparation for the future 3D simulation of the human heart dynamics. The merits of the scheme are that it is suitable for rapid moving boundary and large pressure gradient FSI problems, and the volume leakage is relatively small. These will be verified by simulating typical problems. In the second section, the concepts of the IB and LB methods and the detailed coupling algorithm will be described. In the third section, three flow phenomena, respectively caused by the oscillating relaxation of a distorted balloon, the impulsive startups of a circular cylinder