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Three-Dimensional Simulation of Balloon Dynamics by the Immersed Boundary Method Coupled to the Multiple-Relaxation-Time Lattice Boltzmann Method

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Abstract. The immersed boundary method (IBM) has been popular in simulating fluid structure interaction (FSI) problems involving flexible structures, and the recent introduction of the lattice Boltzmann method (LBM) into the IBM makes the method more versatile. In order to test the coupling characteristics of the IBM with the multiple-relaxation-time LBM (MRT-LBM), the three-dimensional (3D) balloon dynamics, including inflation, release and breach processes, are simulated. In this paper, some key issues in the coupling scheme, including the discretization of 3D boundary surfaces, the calculation of boundary force density, and the introduction of external force into the LBM, are described. The good volume conservation and pressure retention properties are verified by two 3D cases. Finally, the three FSI processes of a 3D balloon dynamics are simulated. The large boundary deformation and oscillation, obvious elastic wave propagation, sudden stress release at free edge, and recoil phenomena are all observed. It is evident that the coupling scheme of the IBM and MRT-LBM can handle complicated 3D FSI problems involving large deformation and large pressure gradients with very good accuracy and stability.

AMS subject classifications: 76M28, 74F10

Key words: Immersed boundary method, multiple-relaxation-time lattice Boltzmann method, fluid-structure interaction, verification, balloon dynamics.

1 Introduction

Interactions between fluids and elastic objects are ubiquitous in nature, but efficient numerical techniques for investigating this kind of phenomena are challenging, however the immersed boundary method (IBM) has shown to be a powerful alternative model for simulating the problems. The IBM was originally developed by Peskin in 1972 to

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simulate flow patterns around natural heart valves [1]. Unlike the traditional numerical methods for fluid structure interaction (FSI) that have to treat body-fitted and moving grid with great effort at every time step, the IBM is very simple and convenient, because it uses regular and uniform algorithms for moving boundaries. In the IBM, an Eulerian description of the Navier-Stokes (N-S) equations is used for the fluid dynamics and an Lagrangian description of elastic structural mechanics is used for the objects immersed in the fluid; the grid for discretizing the immersed boundary need not to be coincident with the underlying fluid mesh; the interaction between fluid and boundary is implemented by a discrete Dirac delta function, which spreads the force of the distorted elastic boundary to the nearby fluid nodes and interpolates from the local fluid velocity to update the boundary position; no special effort is needed in treating boundary movements in the simulation. Since Peskin's pioneering work, great progress in algorithm improvements and applications has been made. Applications such as blood flow in the human heart [2], FSI of natural and prosthetic cardiac valves [3], swimming of bacterial organisms and aquatic animals [4, 5], platelet aggregation [6, 7], deformation of three dimensional capsules [8, 9], filament flapping dynamics [10, 11, 30] and parachute opening dynamics [13, 14], have exhibited its effectiveness and great potential for simulating realistic and sophisticated FSI problems involving complicated, fast moving, and strongly deforming boundaries. However the existing versions of the IBM leave something to be desired: boundary accuracy and numerical stability may be further improved.

Because the fluid flow equations in the IB methods must be solved in a regular Cartesian grid, it is natural to think of replacing the original fast Fourier transform or project method based solvers IBM by the newly developed lattice Boltzmann method (LBM) [15, 16]. The LBM is a regular lattice-based scheme for fluid flow simulations, and its easy implementation, intrinsic parallelism, and high accuracy for numerous fluid flow problems have been demonstrated by many works [17–19]. In the light of these advantages, introducing the LBM into the IBM to simulate FSI problems seems to be very attractive. The fact that both the IBM and LBM work on a regular lattice makes the IBM+LBM coupling possible and easy. The first work on IBM+LBM coupling was by Feng and Michaelides [20], who successfully simulated the sedimentation of many particles under gravity, and demonstrated the effectiveness of their IBM+LBM coupling scheme. Afterwards, some applications and improvements of the method were conducted. Zhang [7] simulated red blood cell aggregation. Cheng [21] analyzed the mitral valve flow. Tian [22] modeled the multiple elastic filament flapping. Dupuis [23] studied the flow past an impulsively started cylinder. Niu [24] improved the calculation of the boundary force on the fluid. Peng [25] carried out comparative study of the IBM+LBM and LBM bounce-back treatment of boundary. Kang [26] compared direct-forcing IBM+LBM methods for stationary complex boundaries. Cheng [27] improved the volume conservation and computational efficiency of the IBM+LBM coupling scheme by introducing a second-order treatment of the unsteady and non-uniform forcing terms into the LBM. Wu [28] made a velocity correction by using the external forcing term proposed by Guo [29] to guarantee the non-slip boundary condition. It should be noted that the works mentioned