Applied Mathematical Modelling 55 (2018) 502–521

Contents lists available at ScienceDirect

Applied Mathematical Modelling

journal homepage: www.elsevier.com/locate/apm

An immersed boundary-lattice Boltzmann method combined with a robust lattice spring model for solving flow–structure interaction problems

B. Afra [a], M. Nazari [a,*], M.H. Kayhani [a], A. Amiri Delouei [b], G. Ahmadi [c]

[a] Department of Mechanical Engineering, Shahrood University of Technology, Shahrood, Iran
[b] Department of Mechanical Engineering, University of Bojnord, Bojnord, Iran
[c] Department of Mechanical and Aeronautical Engineering, Clarkson University, Potsdam, NY 13699-5725, USA

ARTICLE INFO

Article history:
Received 17 September 2016
Revised 22 September 2017
Accepted 9 October 2017
Available online 16 October 2017

Keywords:
Immersed boundary method
Lattice Boltzmann method
Robust lattice spring model
Deformable body
Split-forcing algorithm

ABSTRACT

An immersed boundary (IB)-lattice Boltzmann method (LBM) combined with a robust lattice spring model (LSM) was developed for modeling fluid–elastic body interactions. To include the effects of viscous flow forces on the deformation of a flexible body, rotational invariant springs were connected regularly inside the deformable body with square lattices. Fluid–solid interactions were due to an additional force density in the lattice Boltzmann equation enhanced by the split-forcing approach. To check the validity and accuracy of the numerical method, the flow over a rigid plate and the deformation of a cantilever beam were investigated. To demonstrate the capability of the new method, different test cases were examined. The deformation of a two-dimensional flexible vertical plate in a laminar cross-flow stream at different conditions was analyzed. The simulations were performed for different boundary conditions imposed on the elastic plate, namely, fixed-end corners and fixed middle point. Different flow conditions such as "steady flow regime", "vortex shedding flow regime", and the limit of "rigid body motion" were examined using the new IB-LBM-LSM approach. A general formulation for evaluating the deformation of the elastic body was also introduced, in which the position of the LSM nodes (inside the body) was updated implicitly at each time step. Two dimensionless groups, namely capillary number (Ca) and Reynolds number (Re), were used for parametric study of the behavior of the flow around the deformable plate. It was found that for low Reynolds numbers ($Re < 50$) and when the middle of the plate was fixed, decreasing the capillary number led to a decrease in the drag coefficient. The fluctuation of the plate during the vortex shedding flow regime was also explored. It was found that when the middle of the plate was fixed, the critical Reynolds number for the initiation of vortex shedding increased. For $Re > 100$, the Strouhal number was observed to increase with the decrease in capillary number.

1. Introduction

Deformation problems occur when objects are immersed in a viscous fluid. In this condition; one can refer to the motion of red blood cells [1], interactions between heart leaflets and body fluid in biological systems [2,3], beating cilia in airways

* Corresponding author.
E-mail address: mnazari@shahroodut.ac.ir (M. Nazari).

https://doi.org/10.1016/j.apm.2017.10.014

that causes pumping the mucus layer including entrapped pollutant particles [4,5], fish swimming, self-propel of slender in micro-organisms [6], and reconfiguration of creatures in nature to lessen drag [7].

Different models are available for simulating the deformable body motion under the effect of viscous flow with some success. For example, Buxton et al. [8] simulated the breathing-mode behavior of an elastic shell that was filled with fluid by using a combination of lattice Boltzmann and lattice spring models (LBM and LSM, respectively). MacMeccan et al. [9] coupled finite element analysis and LBM to describe the linear deformation of RBCs in shear flow. Wu and Aidun [10] applied the external body force method in LBM combined with LSM to track RBC deformation when suspended in fluids. They simulated 120 deformable RBCs at 47% volume fraction that led to significant changes in the effective viscosity of the suspension at a constant shear rate. In the hybrid models specified above, the fluid and solid motion were separately evaluated; however, there are conventional approaches that solve the two-phase flows concurrently [2,11].

In general, because of the two different types of computational domains, the study of fluid–structure interaction problems is considered complex and costly. Therefore, the development of a straightforward and robust strategy that efficiently solves the fundamental coupling problem and reduces numerical instabilities has been the objective of many researchers [2,12–16]. Non-body fitted mesh methods, such as the immersed boundary method, are one of the most attractive interface tracking schemes. In particular, in the case of hydrodynamics with a flexible boundary, the boundary evolves into complex and unknown shapes. Thus, the re-meshing process leads to a high computational cost. Peskin [2] was the first to develop the immersed boundary method for simulating blood flow in the heart. He expressed the flow and structural domains in the Eulerian and Lagrangian frames, respectively. He substituted the immersed solid with normal and angular springs, for which the total force of the springs at each Lagrangian node is scattered into the Eulerian nodes, and the momentum equations are resolved with an additional density force. In this case, the rigid boundary maps into highly stiff springs. This method is called the feedback IBM [17,18], which requires user-defined parameters for evaluating the spring constants for different conditions. In this approach, the simulation of deformable particle requires a constitutive formula that relates external stresses to body deformation. There are two main differences between the LSM and the feedback-forcing IBM for the simulation of particle deformation: (1) using the LSM requires setting a collection of springs in the entire body, while in the IBM, deformation is portrayed by the deflection of a collection of springs just on the solid outer face. (2) For the LSM, the spring constant is analytically related to solid rigidity, while there is no direct relationship between these two variables in the feedback IBM [17]. However, the boundary force is calculated from the velocity and position of the interface. The IBM has been coupled with all traditional fluid solvers such as FVM and FDM [19,20]. Furthermore, a simple Cartesian computational domain is typically used in IBM; therefore, the LBM can be conveniently used for solving the fluid velocity associated with the IBM.

The LBM originates from the lattice gas automata (LGA) technique [21], which is based on the kinetic theory of gases. When a discrete particle number is used in this model, statistical noise will be generated. To remove this instability, instead of discrete Boolean variables, a distribution function is used [22]. Different types of lattice Boltzmann equation (LBE) have been developed, with many using the Bhatangar–Gross–Krook (BGK) model [23]. Collision and streaming operators are introduced for solving the LBE numerically. To recover the Navier–Stokes and continuity equations in mesoscale, the Chapman–Enskog expansion [24] is employed.

A combination of LBM and IBM has significant advantage in solving the flow structure interaction (FSI) problems, which was first attempted by Feng and Michaelides [12]. They used the IBM proposed by Lai and Peskin [25] and the LBM as the fluid solver to analyze the particle sedimentation under the laminar regime. Mohd-Yusof [26] introduced a new type of IBM that does not require choosing arbitrary parameters and forcing terms. In that approach (the so-called direct-forcing method), a forcing term is added to the discretized equations that implicitly imposes the non-slip boundary condition in the immersed boundary method. In general, the direct forcing method has two different schemes for boundary force calculation, namely sharp and diffuse interface schemes. In the sharp interface scheme [27], the forcing points do not necessarily coincide with the interface, and they can be perched out of the boundary [19,20]. The boundary force on the forcing point is calculated by the linear interpolation from the boundary and fluid velocities in an arbitrary direction. It has been shown that the sharp scheme causes instability, especially for the moving boundary problem because of the interpolation [28,29].

In the diffuse interface scheme proposed by Silva et al. [30], the force density is calculated from the velocity difference between the desired velocity and the non-forcing velocity on the boundary points. Values of non-forcing velocity on the boundary points are obtained by interpolating the local fluid velocity on the boundary points. In addition, the calculated force on these points is distributed through the fluid neighboring points. Interpolation is applied by the discrete delta function, which was proposed by Peskin [31]. Depending on the extent of the interpolation area around each boundary point, the diffuse interface is divided into various types, namely two-point, four-point, and higher in which there are proportional delta functions [32]. For example, Delouei et al. [33] showed that for a stationary flow over a cylinder, the four-point diffuse interface has better agreement with experimental data. The application of IB-LBM based on the direct forcing method results in first-order accuracy because the momentum changes depend only on the last time step. Later, Guo et al. [34] proposed another IB-LBM based on the split forcing method in which the momentum exchange depends not only on the last time step but also on the force density at the present time. This approach increases the IB-LBM to second-order accuracy, which is important for non-uniform and unsteady problems.

Although there are a number of earlier studies on fluid–elastic solid interactions [35,36], there remains a need for the development of more accurate and computationally more efficient approaches that allow detailed and fast simulations. Direct numerical simulation techniques such as IB-LBM can provide insight into the mechanisms of FSIs. To the best of our