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A Boundary Condition-Implemented Immersed Boundary-Lattice Boltzmann Method and Its Application for Simulation of Flows Around a Circular Cylinder

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Abstract. A boundary condition-implemented immersed boundary-lattice Boltzmann method (IB-LBM) is presented in this work. The present approach is an improvement to the conventional IB-LBM. In the conventional IB-LBM, the no-slip boundary condition is only approximately satisfied. As a result, there is flow penetration to the solid boundary. Another drawback of conventional IB-LBM is the use of Dirac delta function interpolation, which only has the first order of accuracy. In this work, the no-slip boundary condition is directly implemented, and used to correct the velocity at two adjacent mesh points from both sides of the boundary point. The velocity correction is made through the second-order polynomial interpolation rather than the first-order delta function interpolation. Obviously, the two drawbacks of conventional IB-LBM are removed in the present study. Another important contribution of this paper is to present a simple way to compute the hydrodynamic forces on the boundary from Newton's second law. To validate the proposed method, the two-dimensional vortex decaying problem and incompressible flow over a circular cylinder are simulated. As shown in the present results, the flow penetration problem is eliminated, and the obtained results compare very well with available data in the literature.

AMS subject classifications: 76M28, 76M25

Key words: Immersed boundary method, lattice Boltzmann method, velocity correction, Lagrange interpolation, no-slip boundary condition.

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1 Introduction

Nowadays, one of the most challenging issues in computational fluid dynamics is the simulation of incompressible flows around complex geometries or moving boundaries. One approach that has been proven particularly effective in handling a variety of these problems is the immersed boundary method (IBM).

IBM was originally developed by Peskin [1] in 1970s to simulate the blood flow in a two-dimensional model of heart. It uses a fixed Cartesian mesh for the flow field, which is composed of Eulerian nodes. Meanwhile, the physical boundary immersed in the fluid is represented by a set of Lagrangian points. The basic idea of IBM is that the boundary is treated as deformable but with high stiffness. The deformation or moving of the boundary will yield a force that tends to restore the boundary to its original shape or position. The restoring force on the boundary is then distributed into the surrounding nodes (Eulerian nodes) as the body force. Subsequently, the governing equation of flow field with a body force is solved over the whole fluid domain including both inside and outside of the boundary.

Based on the work of Peskin [1], various modifications and refinements have been made. As a result, a number of variants of this approach were proposed and applied. Among the remarkable works, Goldstein et al. [2] proposed a model named virtual boundary method which permits simulations with complex geometries. They employed feedback forcing to represent the effect of solid body. The feedback force, which can be easily computed via the velocities of fluid and boundary, is added to the momentum equation to bring the fluid velocity to zero at the desired points. The main drawback of virtual boundary method is that it contains two user-defined parameters that need to be tuned according to the flow. Lai and Peskin [3] presented a second-order accurate immersed boundary method to simulate the flow past a circular cylinder. The interaction between the fluid and the immersed boundary is modeled using a well-chosen discretized approximation to the Dirac delta function. However, this method does not truly have the second-order of accuracy due to the use of first-order Dirac delta function. Tseng et al. [4] proposed a ghost-cell immersed boundary method for flow in complex geometry. This approach imposes the specified boundary condition by extrapolating the variable to a ghost node inside the body. High-order extrapolation is used to preserve the overall accuracy. Lima E Silva et al. [5] proposed a version named physical virtual model, which is based on the conservation laws, and simulated an internal channel flow and the flow around a circular cylinder. In this model, the restoring force is calculated by applying the momentum equations at the boundary points and then distributed to the surrounding Eulerian grid.

Due to its simplicity and efficiency, the lattice Boltzmann method (LBM) has been broadly used to simulate complex flows as an alternative to the Navier-Stokes (N-S) equations-based solvers. It is a particle-based numerical technique, which studies the dynamics of fictitious particles. Same as the IBM, the Cartesian mesh is usually used in the standard LBM. This common feature motivates the coupling of two methods, which