Advances in Applied Mathematics and Mechanics
Adv. Appl. Math. Mech., Vol. **4**, No. 3, pp. 311-324

DOI: 10.4208/aamm.10-m1171
June 2012

Simulation of Incompressible Viscous Flows by Local DFD-Immersed Boundary Method

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Received 28 April 2011; Accepted (in revised version) 26 September 2011

Available online 30 April 2012

Abstract. A local domain-free discretization-immersed boundary method (DFD-IBM) is presented in this paper to solve incompressible Navier-Stokes equations in the primitive variable form. Like the conventional immersed boundary method (IBM), the local DFD-IBM solves the governing equations in the whole domain including exterior and interior of the immersed object. The effect of immersed boundary to the surrounding fluids is through the evaluation of velocity at interior and exterior dependent points. To be specific, the velocity at interior dependent points is computed by approximate forms of solution and the velocity at exterior dependent points is set to the wall velocity. As compared to the conventional IBM, the present approach accurately implements the non-slip boundary condition. As a result, there is no flow penetration, which is often appeared in the conventional IBM results. The present approach is validated by its application to simulate incompressible viscous flows around a circular cylinder. The obtained numerical results agree very well with the data in the literature.

AMS subject classifications: 76 Fluid mechanics; 35 Partial differential equations

Key words: Local domain free discretization (local DFD), immersed boundary method (IBM), incompressible flow, flow past a circular cylinder.

1 Introduction

Immersed Boundary Method (IBM) has been becoming more and more popular in the numerical simulation of incompressible viscous flows since it was firstly proposed by Peskin in 1970s for the study of blood flow in the heart valve [1]. The original IBM

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uses a fixed Eulerian mesh for the flow field, and a set of Lagrangian points to represent the boundary of objects immersed in the fluid. The basic idea of IBM is that the physical boundary is treated as deformable with high stiffness. A small distortion of the boundary will yield a force which tends to restore the boundary into its original shape. The balances of such forces are distributed into the Eulerian mesh points and the Navier-Stokes (N-S) equations with a body force are solved on the whole domain, including exterior and interior of the object. After the work of Peskin [1], numerous research works have been made to improve IBM. Goldstein et al. [2] proposed a model named virtual boundary method which permits simulations with complex geometries. Lai and Peskin [3] presented a so-called second-order accurate IBM with adoption of a well-chosen Dirac delta function. Linnick and Fasel [4] used the fourth-order compact finite-difference schemes for approximation of spatial derivatives in the IBM application. Lima E Silva et al. [5] proposed a version named physical virtual model, which is based on the conservation laws, and simulated a channel flow and the flow around a circular cylinder. Feng and Michaelides [6] firstly presented the immersed boundary-lattice Boltzmann method (IB-LBM) to simulate the motion of rigid particles in the flow field, where the solution of flow field is obtained by the newly-developed lattice Boltzmann method (LBM) [7]. Later, Niu et al. [8] proposed the momentum exchange-based IB-LBM for simulation of several incompressible flows, and Peng et al. [9] developed the multi-block IB-LBM for simulation of flows around a circular cylinder and an airfoil.

The major advantage of IBM is its simplicity and easy implementation because it decouples the solution of governing equation with the implementation of boundary conditions at immersed boundaries. This means that the governing equation can always be solved on a regular domain without considering the presence of solid boundary immersed in the flow field. The effect of solid boundary to surrounding fluids is through the introduction of body force in the governing equation. On the other hand, it should be indicated that the conventional IBM suffers two major drawbacks. One is the flow penetration to the immersed boundary. This is because in the IBM, the non-slip boundary condition is not enforced, and is only approximately satisfied at the converged state. As a consequence, some streamlines may penetrate the immersed boundary. The flow penetration means some mass exchange through the boundary, which will cause the momentum exchange and lead to numerical error of force calculation. Another drawback is the low order accuracy nearby the immersed boundary due to the use of Dirac delta function interpolation. In the IBM, the distribution of restoring force at the boundary (Lagrangian) nodes to the Eulerian mesh points and interpolation of flow velocity at the Eulerian mesh points to the boundary nodes are through the Dirac delta function, which only has the first order of accuracy. To remove the drawback of flow penetration, Shu et al. [10] did some analysis and found that unsatisfying of non-slip boundary condition in IBM is in fact due to pre-calculated restoring force. Using the fractional step technique, they concluded that, adding a body force in the momentum equations is equivalent to make a correction in the velocity field. To enforce the non-slip boundary condition, the velocity correction