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A New Explicit Immersed Boundary Method for Simulation of Fluid-Solid Interactions

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Abstract. A new Explicit Immersed Boundary method (IBM) is presented in this work by analyzing and simplifying the system of equations developed from the implicit boundary condition-enforced immersed boundary method. By this way, the requirement to solve the matrix system has been bypassed. It makes the solver be computationally less expensive, especially when large number of Lagrangian points are used to represent the solid boundary. The lattice Boltzmann Flux solver (LBFS) was chosen as the flow solver in this paper as it combines the advantages of both Lattice Boltzmann (LB) solver and Navier- Stokes solver. However, it should be indicated that the new IBM can be incorporated into any flow solver. Comprehensive validations demonstrate that the new explicit scheme bears comparable numerical accuracy as the previous implicit IBM when having a geometry with curvature. The new method is computationally much more efficient than the previous method, especially for moving boundary problems.

AMS subject classifications: 35Q30, 76D05

Key words: Lattice Boltzmann flux solver, immersed boundary method, explicit, moving boundary, arbitrary Eulerian Lagrangian.

1 Introduction

Fluid-solid interaction (FSI) problems are ubiquitous in both natural phenomena and industries. Investigations into such problems are very important in both academic and engineering perspectives.

There are two main classes in FSI solvers, depending upon how meshing is done. One is the boundary conforming method, in which the mesh conforms to the solid body. Implementation of boundary condition would be very simple and straightforward in this

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category of methods. However, it encounters obstacles for problems with complex geometries or multiple immersed objects. The other class of solvers is called boundary non-conforming method, like the Fictitious particle method [1], Smoothed Profile method [2], Cartesian grid method [3] and Immersed boundary method [4]. In these methods, the Eulerian mesh is fixed, over which the fluid equations are resolved. The presence of solid boundary is realized by applying a forcing term in the fluid equations. The Immersed Boundary Method (IBM), which was first introduced by Peskin [5] for numerical simulation of blood flow in heart, is a popular method in this category due to its simplicity and flexibility. Essentially, IBM employs two sets of grids–the fixed Eulerian mesh over which the fluid equations are resolved and the varying Lagrangian points which are located on the surface of immersed objects. The restoring forces acting at the Lagrangian points are calculated to interpret boundary effect of the immersed objects and then distributed back to the Eulerian mesh. These distributed forces show up as external body forces in the fluid flow equation. The advantage of IBM is that it removes the need for grid transformation or unstructured grid and avoids the tedious re-meshing algorithm when tackling complex geometries or moving boundary problems.

Since the work of Peskin [5], IBM has been developed into several variants. The first approach is called the penalty forcing method which evaluates the body force on the Lagrangian points by constitutive Hooke's law [6–9]. When interpreting rigid bodies, very high stiffness should be adopted to avoid spurious results [10–12]. The limitation of this approach is the artificial setting of stiffness utilized in the computation, which is case-dependent and thus lacks physical robustness. The direct forcing scheme refers to another version of immersed boundary method which resolves the momentum equation at Lagrangian points to update the body forces exerted at these locations [13–15]. Momentum Exchange-based IBM is another simple scheme, where the density distribution functions are interpolated to the boundary points using Lagrangian interpolated polynomials, and bounce back rule is implemented to establish no-slip condition [16,17]. Although being explicit schemes helps to facilitate implementation, the above penalty forcing, direct forcing and the momentum exchange schemes reveal unphysical penetration of streamlines in applications, implying that they were not able to exactly impose the no-slip boundary condition.

Recognizing that limitation, Wu and Shu [18] proposed another strategy to fulfill the no-slip boundary condition, which is the boundary condition–enforced immersed boundary method. In this method, the velocity correction term was initially considered unknown and then resolved implicitly through a set of algebraic equations that interpret the no-slip boundary condition. The obtained velocity correction term can then be used to retrieve the body force by employing the Newton's second law. By this way, the no-slip boundary condition is exactly imposed, and the unphysical penetration of streamlines is successfully removed.

Although the implicit scheme is proved to be accurate in simulating fluid-solid interaction and has been used extensively to study several FSI problems, it is also noticed that it trades in the computational efficiency. This limitation originates from the implicit