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# Comparative Study of Implicit and Explicit Immersed Boundary-Lattice Boltzmann Methods for Simulation of Fluid-Structure Interactions

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**Abstract.** This work aims to provide guidance for selection between the implicit and explicit immersed boundary methods (IBMs). The implicit method ensures satisfaction of the boundary condition in one correction step (Wu and Shu, J. Comput. Phys., 228 (2009), pp. 1963–1979). However, it requires formation of a relatively complex matrix. The computational time of this method for moving boundary problems is also a concern, because matrix operations are required at each time step. On the other hand, the explicit multi-direct forcing (MDF) (Luo et al., Phys. Rev. E, 76 (2007), 066709) methods are more straightforward. Nevertheless, the detailed comparison between the two methods is lacked in the literature. In this work, the implicit method, the MDF method, MDF method with under/over-relaxation parameters are compared in detail through simulation of stationary and moving boundary problems. It is found that the implicit method generally outperforms the explicit methods, in respects of maintaining both accuracy and computational efficiency. The present study suggests that it can be worthy to form the matrix and solve the equation system implicitly in IBM for both stationary and moving boundary problems.

**AMS subject classifications**: 74F10

**Key words**: Fluid-structure interactions, immersed boundary method, lattice Boltzmann method.

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## 1 Introduction

Immersed boundary method (IBM [1,2]), owning to its computational efficiency and simplicity, has been widely applied to simulate fluid-structure interactions (FSI) [3]. In IBM, the governing equations are solved on a fixed Cartesian grid, and the boundary is represented by a Lagrangian grid. This feature greatly reduces the requirement for grid generation. To reflect the influence of boundary, a restoring force is first evaluated on the

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boundary and then distributed back to the flow field through discrete delta function. Attribute to this decoupling strategy, IBM possesses high computational efficiency. The actual efficiency and accuracy of an IBM depend mostly on the way to calculate the forcing term. Thus a large body of work has been done [3] to improve the way of forcing evaluation. In the pioneering work of Peskin [1], Hooke's law was used to link the restoring force and body deformation, in which a user-defined coefficient was involved. To eliminate the arbitrary coefficients, direct forcing method was introduced by Mohd-Yusof [4] and also applied by Fadlun et al. [5]. In this method, the Navier-Stokes (N-S) equations are used to compute the force on the boundary. The direct forcing method is improved with regard to forcing oscillation by Uhlmann [6]. The boundary condition is also better satisfied through a multi-direct forcing (MDF) approach by Luo et al. [7]. In these IBMs, the forcing term is evaluated explicitly and the no-slip boundary condition is approximately satisfied. To enforce the no-slip boundary condition, a boundary condition-enforced IBM has been proposed by Wu and Shu [8]. In this method, the forcing term is calculated in an implicit manner. It is determined in a way that ensures the velocity at the boundary point satisfies the no-slip boundary condition. Their results showed that the no-slip boundary condition was well satisfied. The streamline penetration that is observed in the previous works is also effectively eliminated. The method has been successfully applied to investigate various solid-fluid interactions [9, 10]. However, the matrix formation involved in this implicit method may increase complexity as compared to the explicit methods. To avoid this, an alternative is the explicit multi-direct forcing method introduced previously [7, 11]. In these methods, the forcing term is determined iteratively. Thus, the satisfaction of boundary condition can be improved compared with the direct forcing methods. Nonetheless, computational efficiency may be undermined, depending on the number of iteration required. To balance the accuracy and efficiency, the iteration number is usually fixed [11, 12].

In sum, to enforce the boundary condition in IBM, one can use the implicit matrix method. It guarantees the satisfaction of boundary conditions in one step correction. The deficiency of this method is the additional complexity to form the matrix. Another concern is that, for moving boundary problems, it may be computationally costly since matrix operations are necessary in each time step. On the other hand, a more straight forward way is to use explicit MDF method. Compared with the direct forcing method, it enhances the satisfaction of boundary condition by evaluating the forcing term iteratively. The computational cost, however, might be undermined due to the added iteration procedures. Moreover, because the iteration number is usually fixed, the extent of satisfaction of the boundary condition is not very clear. Although various versions of IBMs have been proposed, it is noted that there is few detailed comparison between these two useful types of methods in the literature. It is worth to perform such a study to provide guidance for selection of IBMs. This work aims to address this issue by a concrete comparison, in respects of the accuracy and efficiency, between the implicit IBM [8] and the explicit MDF. In the present work, the IBMs are combined with the lattice Boltzmann methods (LBM) for the flow field simulation. LBM originates from the mesoscopic kinet-