

Virtual Body-Fitted Grid-Based Immersed Boundary Velocity Correction Method for Simulation of Incompressible Flows with Moving Boundaries

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Abstract. In this work, a virtual body-fitted grid is introduced and combined with the implicit velocity correction-based immersed boundary method (IBM) for simulation of incompressible flows with moving boundaries. The original implicit velocity correction-based IBM to this kind of problem requires the matrix inversion operation to be repeated at each time step, resulting in significant computational resources and time when the Gaussian elimination method is used for solution, whose computational complexity is $\mathcal{O}(M^3)$. The present method introduces a virtual body-fitted grid that moves together with the immersed boundary to overcome the above defect. As with the original implicit velocity correction-based IBM, the fractional step technique, which includes the prediction step and the correction step, is applied in the present method. Note that the correction step is implemented on the virtual grid in the present method instead of the Eulerian mesh in the original method. Since the relative positions between virtual grid points and Lagrangian points are changeless, the matrix in the correction step can be pre-calculated and stored, avoiding the need to update it at every time step. Although, within this approach, three additional steps including the marking virtual grid points and covered Eulerian points, and two interpolations between the Eulerian mesh and the virtual grid must be conducted at each time step, the computational effort is still greatly reduced as the computational complexity of these steps is $\mathcal{O}(M)$. A numerical experiment of flow around a transversely oscillating cylinder is first performed, demonstrating the improved efficiency, especially when

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the number of Lagrangian points is large. As validation, the flow over a flapping elliptical wing and a fluid-structure interaction (FSI) problem of vortex-induced vibrations of a circular cylinder are simulated. The numerical results are found to be in line with reference results, verifying the ability of the proposed method to simulate complex moving boundary problems.

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Key words: Immersed boundary method, velocity correction, virtual body-fitted grid, incompressible flows, moving boundaries.

1 Introduction

Numerical simulation of flow around moving boundaries with complex geometry has always been a challenge to traditional computational fluid dynamics (CFD) approaches which employ body conformal grids. For large displacement and deformation of objects, complicated body-fitted mesh generation needs to be made at every time step, which requires high computational effort. Recently, the immersed boundary method (IBM) [1] has attracted great attention since it only uses the Cartesian grid to simulate flow problems, so that the difficulties related to tedious mesh generation are eliminated. The IBM was originally proposed by Peskin [2] to model the blood flow in the heart. It uses two groups of independent meshes: the Cartesian Eulerian grid for the flow field and the Lagrangian grid for the solid boundary. The Lagrangian grid consists of discrete points immersed in the fixed Eulerian one. The effects of the immersed boundary on the fluid domain are then realized by adding a body force to the governing equations. In fact, IBM separates the boundary treatment from the mesh generation, which makes it easy to simulate the flow around complex or moving boundary objects.

A key issue in IBM is to reasonably predict the body force to satisfy the no-slip boundary condition. In the original IBM, Hooke's law is used to calculate the body force through the difference between the boundary velocity and the local fluid velocity, which is commonly referred to as the penalty forcing method [2, 3]. Based on this, several variants of IBM have been developed. For example, in the feedback forcing scheme proposed by Goldstein et al. [4], the force term is estimated by a model called virtual boundary formulation. In the direct forcing method presented by Fadlun et al. [5–7], the force term is computed by the local solution of Navier-Stokes (N-S) equations at the boundary point and there are no free constants needed to be set. Lima E Silva et al. [8] proposed the physical virtual model based only on the laws of conservation. There are no ad hoc constants in this model, but the process includes tedious derivative approximation and interpolation of pressure and velocity. In addition, there are several implicit methods, where the body force is determined implicitly. Taira and Colonius [9] introduced a fully implicit IBM using the projection method. The pressure and boundary force are determined implicitly from the modified Poisson equation, and then the non-divergence-free and no-slip