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Hybrid Diffuse and Sharp Interface Immersed Boundary Methods for Particulate Flows in the Presence of Complex Boundaries

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Abstract. A coupling framework that leverages the advantages of the diffuse and sharp interface immersed boundary (IB) methods is presented for handling the interaction among particles and particles with the static complex geometries of the environment. In the proposed coupling approach, the curvilinear IB method is employed to represent the static complex geometries, a variant of the direct forcing IB method is proposed for simulating particles, and the discrete element method is employed for particle-particle and particle-wall collisions. The proposed approach is validated using several classical benchmark problems, which include flow around a sphere, sedimentation of a sphere, collision of two sedimenting spheres, and collision between a particle and a flat wall, with the present predictions showing an overall good agreement with the results reported in the literature. The capability of the proposed framework is further demonstrated by simulating the interaction between multiple particles and a wall-mounted cylinder, and the particle-laden turbulent flow over periodic hills. The proposed method provides an efficient way to simulate particle-laden turbulent flows in environments with complex boundaries.

AMS subject classifications: 76T99, 76F65, 76M20
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1 Introduction

Particle transport in a carrier fluid is often encountered in engineering and environmental applications. Examples of such flows include transmission of droplets during a cough [1,

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2], suspension and sedimentation of aspherical particles [3, 4], sediment transport [5] and dispersion of contaminants [6]. Approaches for simulating particle-fluid interaction can be classified into two categories according to whether the particles are modeled or resolved. The particle-modeled methods include the fully Eulerian method in which only one-way interaction is considered [4,5], the Eulerian-Eulerian method [7,8] in which the governing equations of the fluid phase and the particle phase are both solved by using the Eulerian approach, the point-particle Eulerian-Lagrangian method [9] in which the particles are treated as point sources to the fluid momentum and are evolved via a given drag law. The immersed boundary (IB) method [10], which can resolve the geometry of particles, belongs to the particle-resolved category.

The classic IB method was proposed by Peskin to simulate blood flows [10]. Up to date, various IB methods have been proposed [11–13], which can be classified into the diffuse interface and the sharp interface IB methods. The diffuse interface IB methods regularize the discontinuous across the fluid-structure interface by using kernel functions, which include the regularized Dirac delta functions [10, 14–18], the reproducing kernel particle method delta function [19] and the moving-least-squares reconstructions [20,21]. Different variants of the diffuse interface IB method also differ in how the forces on the IB are computed. In the classical IB method [10], the IB forces on the flexible boundary are computed via the constitutive law, e.g., Hook's law. When applying such methods to rigid boundaries, spring constants of very high magnitudes have to be employed, causing issues of numerical instability. To solve this problem, the diffuse interface direct forcing IB method [14], which calculates the forces on the boundary by satisfying the no-slip boundary conditions, was then proposed and developed [17]. As an alternative to the diffuse interface IB methods, the sharp interface IB methods include the curvilinear immersed boundary (CURVIB) method [22], the immersed interface method [23–26], the Lagrange-multiplier based fictitious domain methods [27], the cut cell methods [28, 29], and the embedded boundary methods [30, 31], which differ in the ways of applying the boundary conditions. In the cut cell method, the cells cut by the boundary are reshaped according the actual geometry, where the boundary conditions are directly imposed. In the immersed interface method, the boundary conditions are applied based on stress discontinuities via jump conditions for the velocity, the pressure and their derivatives, which enables simulating also interface problems not restricted to fluid-solid boundaries. In the CURVIB method and others, the boundary conditions are imposed by reconstructing the velocity (and pressure) field near the boundary.

Different approaches have been developed to satisfy the no-slip boundary condition on the IB more accurately for the diffuse interface IB method. Su et al. [32] proposed to take into account the effect of force distribution process in the determination of forces on the IB by solving a linear equation with coefficients forming a banded matrix so that the no-slip boundary condition can be completely satisfied. Wang and Zhang [33] extended the matrix inversion idea to the discrete stream function flow solver. Wang et al. [34] introduced an iterative direct forcing IB method to avoid the penetration of streamlines across the boundary. To minimize the effect of the Dirac delta function on the simulated