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Combined MPM-DEM for Simulating the Interaction Between Solid Elements and Fluid Particles

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Abstract. How to effectively simulate the interaction between fluid and solid elements of different sizes remains to be challenging. The discrete element method (DEM) has been used to deal with the interactions between solid elements of various shapes and sizes, while the material point method (MPM) has been developed to handle the multi-phase (solid-liquid-gas) interactions involving failure evolution. A combined MPM-DEM procedure is proposed to take advantage of both methods so that the interaction between solid elements and fluid particles in a container could be better simulated. In the proposed procedure, large solid elements are discretized by the DEM, while the fluid motion is computed using the MPM. The contact forces between solid elements and rigid walls are calculated using the DEM. The interaction between solid elements and fluid particles are calculated via an interfacial scheme within the MPM framework. With a focus on the boundary condition effect, the proposed procedure is illustrated by representative examples, which demonstrates its potential for a certain type of engineering problems.

AMS subject classifications: 65Z05, 76M28, 74F10

Key words: Multiphase flow, solid-fluid interaction, material point method (MPM), discrete element method (DEM).

1 Introduction

Interaction between a large number of solid elements (bodies or particles) and surrounding fluid occurs in many natural and engineering settings such as sediment transport in

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rivers and coastal oceans, debris flows during flooding, cuttings transport in petroleum-well drilling, mineral particle size reduction in grinding mills, as well as powder handling and pneumatic conveying in pharmaceutical industries [1]. In the category of dense granular flow, the collisions between solid elements and shear drag from surrounding fluid play a dominant role. As for the study of the interaction between solid elements, discrete element method (DEM) is one of the most efficient approaches, which has found a firm place in powder mechanics and rock mechanics [2–4]. One of the key challenges of the DEM, as highlighted in a review paper by Weerasekara et al. [2], is the need for adequately simulating the fine particles in engineering applications. The fine particles represent a reasonable volume of the charge, and modify the collision and transport behaviors of the coarse particles. Due to their small size, the number of the fine particles is tremendously large, which the DEM is unable to handle.

As for the interaction between solid elements and fluid, many efforts have been made in the past based on computational fluid dynamics (CFD), such as combined DEM and moving particle semi-implicit method [5], and combined DEM and CFD [6–9]. The smoothed-particle hydrodynamics (SPH) method has been developed to simulate the motion of fluid [10, 11]. The SPH method was originally introduced to simulate the problems in astrophysics, which involve fluid particles moving arbitrarily in the absence of boundaries [12, 13]. One type of combined DEM-SPH simulation is based on one-way coupling, namely, one phase contributing to the motion of others while the reaction from others is ignored [14, 15]. Recent research focus has been on the two-way coupling [16, 17]. The verification and validation of the combined DEM-SPH has been recently conducted [18]. However, the SPH solution is unstable or not convergent in some cases [19,20]. Hence, further improvement is required on the SPH, or an alternative approach must be found.

It is proposed in this paper that the material point method (MPM) be combined with the DEM to simulate the interaction between solid elements of different sizes and surrounding fluid particles. The MPM is an extension of the particle-in-cell (PIC) method in CFD to the field of computational solid dynamics (CSD), and is a particle method formulated with the same weak formulation as that used for the finite element method (FEM) [21]. Because the deformation history is recorded with material points for history-dependent constitutive equations, the MPM is able to handle the problems with large deformation, failure evolution and multi-phase interactions, such as impact, penetration, perforation, and fluid-structure interaction with strong shocks, as demonstrated in previous studies [22–31]. In addition, the MPM has been combined with the FEM to improve the computational efficiency [32]. Another approach to improve the computational efficiency is to combine the MPM with the adaptive mesh refinement (AMR) techniques. This approach has been adopted to simulate fluid-structure interaction problems [33]. The MPM has also been employed in multi-scale simulation [34]. By taking advantages of both the MPM and DEM, hence, an effective spatial discretization procedure might be designed to better simulate the interactions among various kinds of solid elements with surrounding fluid particles.