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A Hybrid Fluid-Solid Interaction Scheme Combining the Multi-Component Diffuse Interface Method and the Material Point Method

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Abstract. We propose a hybrid scheme combing the diffuse interface method and the material point method to simulate the complex interactions between the multiphase compressible flow and elastoplastic solid. The multiphase flow is modelled by the multi-component model and solved using a generalized Godunov method in the Eulerian grids, while the elastoplastic solid is solved by the classical material point method in a combination of Lagrangian particles and Eulerian background grids. In order to facilitate the simulation of fluid-solid interactions, the solid variables are further interpolated to the cell center and coexist with the fluid in the same cell. An instantaneous relaxation procedure of velocity and pressure is adopted to simulate the momentum and energy transfers between various materials, and to keep the system within a tightly coupled interaction. Several numerical examples, including shock tube problem, gas-bubble problem, air blast, underwater explosion and high speed impact applications are presented to validate the numerical scheme.

AMS subject classifications: 76L05, 74H15, 76T30, 68U20, 47E05

Key words: Multiphase flow, elastoplastic solid, diffuse interface method, material point method, fluid-solid interaction.

1 Introduction

The dynamical fluid-solid interaction (FSI) problems involving large deformations and phase changes span a wide range of areas including air blast, underwater explosions,

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high-speed impacts, and so on. Due to the great discrepancy of the constitutive relations between the fluid and solid, the interactions between fluid and solid must be treated carefully to maintain a robust and efficient behavior.

The numerical simulation of the FSI problem is still very challenging and mainly consists of two difficulties, the interface capture and the interaction between distinct mediums. Several numerical methods have been carried out to solve these difficulties, such as the Lagrangian method [1–3], Eulerian method [4–11], arbitrary Lagrangian Eulerian (ALE) method [12–14] and so on. The Lagrangian method has been widely applied in structural analyses due to its capability of modelling the history-dependent material and tracking the material interface, but it suffers from mesh distortion which would reduce the numerical accuracy and efficiency dramatically. Unlike the Lagrangian method, the Eulerian method employs a stationary grid and allows arbitrary distortion of materials and phase interfaces. Several Eulerian approaches, such as the volume of fluid (VOF) method [15, 16], level set method [17, 18], moment of fluid (MOF) method [19–21], front-tracking method [22, 23] and diffuse interface method [24–32] are used extensively to capture the interface. The ALE method defines an independent framework for each material and keeps the velocity of the material interface equal to the local material velocity, so the advantages of both Lagrangian method and Eulerian method are presented. The major numerical difficulty of the ALE method is to develop an effective and efficient mesh moving scheme for complex multi-dimensional problems. In the above methods, the governing equations of the fluid and solid are solved on a single grid, which ensures the velocity consistency and avoids the penetration naturally.

Until now, the Eulerian-Lagrangian coupling method [33, 34] in which the fluid is solved on a stationary Eulerian grid while the solid is solved on a moving Lagrangian grid is the most dominant scheme for the FSI problems, since the Lagrangian method possesses advantages in simulating the solid structures with history-dependent variables while the Eulerian method can handle the multiphase fluid flows with large deformations more efficiently. Recently, the material point method (MPM) [35–39] which can combine the benefits of both the Lagrangian method and the Eulerian method has received a great increasing attentions and is widely applied in solid dynamics with large deformations, such as high speed impacts, underground explosion problems, and so on. The MPM discretizes a material domain into a set of Lagrangian particles moving through an Eulerian background grid. The Eulerian background grid eliminates the mesh distortion problem and the Lagrangian particles track the phase interface and free surface of the material domain automatically.

The major disadvantage of the MPM is the frequent transformations of variables between the particles and grid nodes, which require more computational resources and have difficulties in constructing high-order schemes, compared to the high-order Eulerian schemes and high-order FEM schemes. Some efforts have been devoted to couple the particle methods and the grid methods. Guillkey et al. [40] developed an approach to solve the full-physics FSI problems using the implicit continuous Eulerian descrip-