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Diffuse interface immersed boundary method for multi-fluid flows with arbitrarily moving rigid bodies

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ABSTRACT

We present an interpolation-free diffuse interface immersed boundary method for multiphase flows with moving bodies. A single fluid formalism using the volume-of-fluid approach is adopted to handle multiple immiscible fluids which are distinguished using the volume fractions, while the rigid bodies are tracked using an analogous volume-of-solid approach that solves for the solid fractions. The solution to the fluid flow equations are carried out using a finite volume-immersed boundary method, with the latter based on a diffuse interface philosophy. In the present work, we assume that the solids are filled with a "virtual" fluid with density and viscosity equal to the largest among all fluids in the domain. The solids are assumed to be rigid and their motion is solved using Newton's second law of motion. The immersed boundary methodology constructs a modified momentum equation that reduces to the Navier–Stokes equations in the fully fluid region and recovers the no-slip boundary condition inside the solids. An implicit incremental fractional-step methodology in conjunction with a novel hybrid staggered/non-staggered approach is employed, wherein a single equation for normal momentum at the cell faces is solved everywhere in the domain, independent of the number of spatial dimensions. The scalars are all solved for at the cell centres, with the transport equations for solid and fluid volume fractions solved using a high-resolution scheme. The pressure is determined everywhere in the domain (including inside the solids) using a variable coefficient Poisson equation. The solution to momentum, pressure, solid and fluid volume fraction equations everywhere in the domain circumvents the issue of pressure and velocity interpolation, which is a source of spurious oscillations in sharp interface immersed boundary methods. A well-balanced algorithm with consistent mass/momentum transport ensures robust simulations of high density ratio flows with strong body forces. The proposed diffuse interface immersed boundary method is shown to be discretely mass-preserving while being temporally second-order accurate and exhibits nominal second-order accuracy in space. We examine the efficacy of the proposed approach through extensive numerical experiments involving one or more fluids and solids, that include two-particle sedimentation in homogeneous and stratified environment. The results from the numerical simulations show that the proposed methodology results in reduced spurious force oscillations in case of moving bodies while accurately resolving complex flow phenomena in multiphase flows with moving solids. These studies demonstrate that the proposed diffuse interface immersed boundary method, which could be related to a class of penalisation approaches, is a robust and promising alternative to computationally expensive conformal moving mesh algorithms

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as well as the class of sharp interface immersed boundary methods for multibody problems in multi-phase flows.

1. Introduction

Fluid flows interacting with solid bodies are ubiquitous in several realms of engineering that include naval structures, chemical processing and gaseous combustion among others. The numerical modelling of such flows are challenging since different sets of governing equations must be satisfied in fluid and solid domains with their coupling at the interface is pivotal for meaningful solutions. The simulations become even more difficult when the bodies are in motion, either imposed or induced by the flow around them. Conventional approaches tackle such problems by using Arbitrary Lagrangian–Eulerian methods [1], which work with body conforming grids. However, these methods are computationally expensive owing to moving/deforming meshes and in cases of significant displacement/deformation necessitate continuous re-meshing. One could circumvent this problem, in a general scenario, using overset meshes [2] but these also incur significant cost, including those of identifying overlapping volumes and transferring solutions by interpolation. A simple and interesting alternative to ALE and overset approaches is to employ a fixed background mesh with the stationary/moving solid(s) “immersed” into it. This philosophy, pioneered in early seventies by the seminal work of Peskin [3] is now classified under the broad category of Immersed Boundary (IB) methods.

Different classifications of the IB methods are possible, but they are widely distinguished as continuous and discrete forcing based approaches [4]. Discrete forcing approaches can themselves be classified as being sharp interface IB and diffuse interface IB methods. The key difference between the sharp and diffuse interface approaches lie in the fact that the former retains the immersed geometry as a “sharp” interface while the latter would smear the interface over a few cell widths (typically two or three). The sharp interface IB methods are typically favoured over the entire range of Reynolds numbers, since the “spreading” effect in diffuse interface IB could become detrimental for high Re computations. For the same reasons, continuous forcing approaches are less desirable for turbulent simulations since they inherently do not preserve the sharpness of the interface. The notable efforts in the category of sharp interface IB include the ghost-cell finite difference approach in [5], the cut-cell finite volume approach in [6] and the hybrid Cartesian IB (HCIB) of [7]. Interestingly, while all of these preserve a sharp interface, they enforce the boundary conditions within the IB framework in completely different ways. All three approaches however involve interpolations to determine the solution in the vicinity of the immersed boundary. The ghost-cell approach defines “ghost” cells inside the body while HCIB does not include cells inside the body. The cut-cell approach is distinct in that it requires cell reshaping near the vicinity to ensure strict mass and momentum conservation, which could however become computationally expensive for three-dimensional geometries. Moreover, while the ghost-cell and cut-cell methods involve bilinear/trilinear interpolations, the HCIB employs an effectively uni-dimensional interpolation for problems in any space dimension [8]. Despite the similarities and differences in the sharp interface approaches, they have found widespread application in a range of problems including phonation [9], biofluid dynamics [10], dune morphodynamics [11] and multiphase flows [12].

Diffuse interface IB, as the name suggests, comprises of all methods that necessarily smear the interface. It is therefore easy to see that all continuous forcing methods and a few discrete forcing methods fall into this class of IB methods. There also exist several variants of the classical IB approaches that can be encompassed within this category. A notable variant is the fictitious domain method [13], which employs the idea of Lagrangian multipliers with the rigidity constraint enforced for rigid solids [14]. This approach has been used by several researchers [15,16] for fluid–structure interaction problems. Another interesting alternative is the Brinkman penalisation or volume penalisation [17–19], which considers the rigid solid as a porous medium of very low porosity and enforces the boundary condition through a masking function. Nakayama and Yamamoto [20] proposed a smooth profile method for particulate flows while the approach of Xiao [21] used a colour function to distinguish and track solids in a domain consisting of fluids. Pan [22] proposed a diffuse interface methodology based on volume-of-solid approach, where the solid fraction is employed to construct a single momentum equation that is solved everywhere in the domain. This methodology, which is inspired by the volume-of-fluid approach in multiphase flows, has been applied to single phase flows past stationary and moving bodies [22] and more recently investigated for flows with heat transfer in [23].

It is pertinent to discuss the advantages and limitations of the methods in either category so that potential users can make a judicious choice of the IB approach for their applications. Sharp interface IB methods enforce the boundary conditions exactly since the sharpness of the geometry is preserved and the body tracked using Lagrangian markers. These methods can handle Dirichlet, Neumann and Robin BCs with equal ease, but lead to spurious oscillations in time histories of integrated quantities (such as lift and drag) for moving bodies. There have been limited but in-depth studies on the mechanisms behind these unphysical oscillations and means of suppressing/eliminating them. While these oscillations do reduce with increasing grid resolution and larger time steps, use of extremely fine meshes is not a computationally viable option and the choice of time step is largely dictated by the flow physics and numerical stability. It is important to note that the spurious force oscillations is a critical issue for problems involving fluid–structure interactions and necessitates special treatments such as the use of hybrid stencils [24], field extension [25] or resorting a cut-cell conservative scheme