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A 3D, fully Eulerian, VOF-based solver to study the interaction between two fluids and moving rigid bodies using the fictitious domain method

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ABSTRACT

We present a three-dimensional (3D) and fully Eulerian approach to capturing the interaction between two fluids and moving rigid structures by using the fictitious domain and volume-of-fluid (VOF) methods. The solid bodies can have arbitrarily complex geometry and can pierce the fluid–fluid interface, forming contact lines. The three-phase interfaces are resolved and reconstructed by using a VOF-based methodology. Then, a consistent scheme is employed for transporting mass and momentum, allowing for simulations of three-phase flows of large density ratios. The Eulerian approach significantly simplifies numerical resolution of the kinematics of rigid bodies of complex geometry and with six degrees of freedom. The fluid–structure interaction (FSI) is computed using the fictitious domain method. The methodology was developed in a message passing interface (MPI) parallel framework accelerated with graphics processing units (GPUs). The computationally intensive solution of the pressure Poisson equation is ported to GPUs, while the remaining calculations are performed on CPUs. The performance and accuracy of the methodology are assessed using an array of test cases, focusing individually on the flow solver and the FSI in surface-piercing configurations. Finally, an application of the proposed methodology in simulations of the ocean wave energy converters is presented.

1. Introduction

Fluid–structure interaction (FSI) can be found in many diverse areas encompassing sediment transport in rivers, fluidized beds, blood flow in arteries, power plant condensers, and ocean wave energy converters (WECs). In this paper, we present a computational framework to model FSI between two fluids and a moving rigid structure. The framework is quite general and applicable to many diverse FSI applications. However, our focus is on WECs. WECs have been traditionally modeled using the potential flow theory, where both linear [1,2] and nonlinear [3–6] models have been developed. A review on theory and applications of both types of models can be found in [7]. However, these methods cannot handle large topographical changes in the free-surface, e.g., breaking of waves around structures. Moreover, such methods employ Morison's equation [8] to account for viscous drag. Empirical relations for the viscous drag coefficient exist only for simple structure geometries. Complex geometries will require additional wave tank tests.

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Phenomena like viscous layer separation, turbulence, wave-breaking and overtopping are critical to correct numerical prediction of WEC response and can only be captured by solving the full Navier–Stokes (N–S) equations, including the viscous term. Approaches that employ the full N–S solutions to compute FSI include body conformal methods [9–13], immersed boundary (IB) methods [14,15], and fictitious domain (FD) methods [16,17]. A detailed review on different numerical modeling techniques of FSI can be found in [18]. In body conformal methods, the mesh is updated every time step to conform to the structure boundary or the free interface. The method becomes especially challenging if the boundary/interface is arbitrarily complex and undergoes large deformation. That issue is circumvented in IB and FD methods where the mesh for solving the N–S equations does not have to conform to the boundary/interface. In the IB method first developed by Peskin [14], a forcing term is added to the N–S equations. In another variant of the IB method developed by Mohd-Yusof [19], the effect of immersed boundary is introduced by imposing velocity boundary condition at the grid points located in the vicinity of the interface. In the IB approach, the forces on the structure are computed by explicit integration of pressure and shear stresses at the immersed interface, e.g., [20]. In this regard, Hu and Joseph [21] and Fekken [22] observed that using an explicit scheme to compute hydrodynamic forces on the structure is unstable if mass (m) of the moving structure is less than the virtual mass (m_v) of the surrounding fluid accelerated by the motion of the structure, i.e., if $m < m_v$. The explicit scheme will be unstable in spite of small time steps. To avoid this problem, Hu and Joseph [21] suggested alternately solving the equations for the structure and fluid in an iterative fashion until a convergence criterion is satisfied. The iterative procedure makes the scheme computationally expensive. Hesla's [23] combined weak formulation of the fluid–structure evolution obviates this iterative procedure. The formulation called the *fictitious domain method* was developed by Glowinski et al. [24] using the distributed Lagrangian multiplier and later made computationally fast by Patankar et al. and Patankar [25,26]. The fast method of Patankar et al. was employed in a finite volume framework by Sharma and Patankar [17]. In the fast fictitious domain method, the structure is considered as a fictitious fluid and the N–S equations are solved in the entire computational domain. Rigid body velocity is then imposed in the solid domain by conserving linear and angular momenta. The method was used by [27–29] to study FSI. In the present work, we employ the same method to compute FSI between two fluids and a moving rigid body.

Most of the previous work with FD method involved a structure completely submerged in fluid, e.g. [17,24,27,29–31]. Of these, [29] and [30] used a fully Eulerian approach for computing both fluid and structure motions. FD method has been applied in 2D to surface piercing floating structures in [28,32–34]. In 3D, [16,35,36] employed the FD method to surface piercing floating particles, where the free surface was represented by the level set function. The particle motion, however, was treated in a Lagrangian fashion. We present a fully Eulerian fictitious domain methodology to compute FSI in surface piercing configurations, i.e., rigid structures interacting with two immiscible incompressible fluids. Here, the kinematics of the solid boundary and the interface between the two fluids are resolved by using the volume-of-fluid (VOF) method through two separate color functions. Such representation allows us to handle arbitrarily shaped and complex solid bodies. The proposed methodology employs a single fully Eulerian finite volume grid for moving the structure and the two fluids. The Eulerian implementation of the FD method offers some advantages:

- It obviates the need for transfer functions, otherwise needed in Lagrangian treatment of the rigid body motion, to interpolate between Eulerian background grid and the Lagrangian nodes attached to the rigid body.
- Relying on the Eulerian transport schemes, e.g., the VOF method of Youngs [37,38], simplifies appreciably the six degree-of-freedom (DOF) position update of the rigid body. Otherwise, in a Lagrangian framework, update of the rotational positions of a non-spherical body becomes a rather cumbersome task involving either Euler's angles or quaternions. Recently, van Wachem et al. [39] implemented quaternion rotation to study the FSI involving non-spherical particles.
- Phase change processes can be easily handled by an Eulerian approach where the solid phase is represented by a color function such as VOF [29].

There are some challenges in implementing a fully Eulerian FD method to surface piercing configurations. In such configurations, there can exist computational cells that contain three phases (solid and the two fluids). Such cells require special treatment to reconstruct the interfaces and transport mass. We use the 3D error-minimization VOF method formulated by Pathak and Raessi [40] to reconstruct the phase interfaces and transport mass in three-phase cells. An alternative approach can be the moment-of-fluid (MoF) method first proposed by Ahn and Shashkov [41], which requires additional information in the form of cellwise centroid position of each phase. Recently, Li et al. [42] presented a MoF approach to track centroids along with volume fractions. The method [40] adopted in the present work requires only the available volume fraction distribution to perform interface reconstruction in three-phase cells. Furthermore, the density ratio among the three phases can be arbitrarily large. If not treated properly, non-physical deformations can be observed at the phase interfaces [43,44]. We employ the consistent scheme proposed by Rudman [45] that can handle simulations involving large density ratios. In this scheme, mass and momentum are transported in a tightly coupled consistent fashion. The formulation is explained in Section 3.3.

In several previous studies, e.g., [22,46], involving free surfaces, the N–S equations are solved only for the water phase. The effect of air is considered via pressure and shear stress boundary conditions. Such approach might not be appropriate for modeling phenomena like wave-breaking. Iafrati [47] showed significant dissipation of energy occurring in the air phase via formation of large scale dipoles during wave-breaking. The methodology proposed in the present paper solves the full N–S equations in both air and water phases making it suitable for modeling phenomena like breaking of waves around