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Modeling free surface flows in presence of an arbitrary moving object

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ABSTRACT

In this study, a numerical algorithm is developed for simulating the interactions between a liquid and a solid object in presence of a free-surface. The presented model is the fast-fictitious-domain method integrated into the volume-of-fluid (VOF) technique used for tracking the free surface motion. First, the governing equations are solved everywhere in the computational domain including the solid object. Next, a rigid body motion is projected onto the region occupied by the solid. The evaluation of the acting forces on the solid object and the application of the no-slip boundary condition on the solid–liquid interface are performed implicitly. In the model developed in this study, the no-slip condition is imposed by attributing a high viscosity to the solid region. The model is validated by a comparison of the simulation results with those of the available experiments in the literature for a sphere during its entry into a liquid free surface and for the free fall of one and two circular particles inside a liquid. For all cases considered, the results are in good agreement with those of the experiments and other numerical studies.

1. Introduction

The free surface deformation in presence of a moving solid object has been studied experimentally and theoretically for more than a century. However, this phenomenon is not well understood due to complex effects of solid–liquid momentum, the cavity formation behind the solid object and capillary effects at the contact line between the surface of the solid and liquid. The interaction between a solid body and a liquid medium has a wide application in many industries such as the water entry of a solid; and designing ships, flying boats, seaplanes, etc.

Worthington (1908) was one of the first researchers who systematically studied vertical water entry of spherical objects. Many later studies were performed to improve the knowledge regarding the liquid–solid interaction. Gilbarg and Andersok (1948) discussed the influence of atmospheric pressure, solid velocity and surface tension on the entry of spheres into water. They found that any increase in atmospheric density and solid velocity can affect the closure of the splash. The surface tension effect on the splash closure becomes important in cases where the solid radius and velocity, and the atmospheric density are small (Gilbarg and Andersok, 1948). May (1951) discussed the effect of different surface conditions of a sphere on the cavity formed during its water-entry. In a later publication (May, 1952), he conducted many experiments to discuss the effect of different parameters on the cavity formation behind the object. Abelson (1970) conducted experiments to study pressure drop behind a solid object moving inside a liquid. Moghisi and Squire (1981) performed an experimental investigation of the initial force of the impact on a sphere striking a liquid surface. They modified a correlation presented by Shiffmanm and Spencerd (1945) for the drag coefficient of a sphere during its initial entry into a liquid. Kuwabara et al. (1987) reported quantitative information about the liquid entry of smooth spheres and cylinders.

The classical view of impacts on free surfaces relies solely on solid and liquid inertia. From the recent experimental works that investigated different aspects of the solid object impact into a free surface, we can mention those performed by Lee et al. (1997), Thoroddsen et al. (2004), Grumstrup et al. (2007) and Lee and Kim (2007). In a strong contrast to the classical viewpoint, Duez et al. (2007) showed that the wettability of the impacting solid, highly affects the splashing characteristics. Motivated by Duez et al. (2007), Aristoff et al. (Aristoff and Bush, 2009; Aristoff et al., 2010) conducted experimental–theoretical studies for water entry of hydrophobic spheres and vertical cylinders. They presented a regime diagram for hydrophobic spheres with the same wetting properties based on nondimensional parameters affecting the cavity formation behind the spheres. In addition, they developed a theoretical model for predicting important parameters involving the depth and time of pinch-off, depth of sphere at the pinch-off time and volume of the cavity behind the sphere.

Direct numerical simulations (DNS) of fluid–solid interaction can provide more insight for this complicated phenomenon. There are two general approaches used by researchers to overcome this challenging field of study; approximate method simulations and direct numerical simulations. Approximate methods available in

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the literature such as potential flow, Stokes flow and point-particle approximation all simplify the computations by ignoring one or more of the important effects like viscosity, wakes, and stagnation and separation points. A complete review of the approximate methods is presented by Esmaeeli and Tryggvason (1998) and Hu (1996). However, in this study we focus on the direct numerical simulation of fluid–solid interaction methods.

The first category of DNS methods introduced for simulating the fluid–solid interaction is based on unstructured grids where solid zones are not considered in the computational domain and the object surface are treated as boundary conditions. As the solid body moves inside the fluid the geometry of the fluid computational domain changes. Therefore, a re-meshing is inevitable in each time step (Eulerian methods) or after a large distortion of the generated grid (Lagrangian or Arbitrary Lagrangian–Eulerian methods). The re-meshing is seen by most researchers as a process that should be avoided. Many studies reported in the literature used this technique in simulating the fluid–solid interaction. Hu and Joseph (1992) used an Eulerian method in which the computational domain is re-meshed in each time step and the solution of the previous time level is mapped onto the new mesh. Next, the Navier–Stokes equations and the implicitly discretized Newton's equations for particle velocities are solved on the new mesh iteratively. He applied this method for sedimentation of one and two cylinders in a 2D channel. Hu (1996) adopted an arbitrary Lagrangian–Eulerian (ALE) technique to simulate the motion of the particles. He avoided a re-meshing in each time step, however, when unacceptable element distortion was detected, a new grid was generated and the flow fields were projected from the old grid to the new one. He applied this technique successfully for simulation of 2D solid–liquid mixture flows. Johnson and Tezduyar (1996) reported the first 3D finite element computation of fluid–particle interactions to simulate the movement of a number of spheres ranging from two to five inside a liquid. As the number of spheres increased, the mesh size and the frequency of re-meshing were also increased. Using a stabilized space–time technique and a redesigned automatic mesh generation strategy Johnson and Tezduyar (1997) substantially reduced the required memory and computational time for mesh generation and successfully simulated the falling of more than one hundred spheres in a liquid-filled tube. In other studies, they reported the first simulation of 1000 falling spheres in a tube (Johnson and Tezduyar, 1999) and sedimentation of 128 spheres in a spatially periodic flow (Johnson and Tezduyar, 2001). Tezduyar (2001) provided a detailed review of different finite element methods based on unstructured grids for flow problems with moving boundaries. He also introduced Mixed Interface-Tracking/Interface-Capturing Technique (MITICT) where the fluid–solid interfaces are represented with an interface-tracking (moving-grid) technique, and fluid–fluid interfaces (or free surfaces) with an interface-capturing (fixed-grid) technique. The MITICT provides high-resolution fluid mechanics computations at the boundary layer of the fluid–solid interfaces, and computations free from mesh deformation at the fluid–fluid interfaces. The MITICT was successfully tested for simulation of an oscillating cylinder (Akin et al., 2007) and a falling sphere (Cruchaga et al., 2007) in presence of a free surface, using different combinations of interface-tracking and interface-capturing techniques.

The second category of direct numerical simulations is based on fictitious-domain method. The main advantage of this method is that the fluid flow equations are enforced everywhere in the computational domain including fluid and solid zones. This conceptual framework leads to a simple geometry and time independent computational domain which can be discretized by a structured and fixed grid mesh. Eliminating the re-meshing requirement and dropping the need for unstructured grids results in a considerable reduction of the required time for computations especially when dealing with a large number of solid objects. Numerical techniques for simulating fluid–solid interactions using a fixed-grid discretization scheme have been developed considerably over the past decade. Based on this methodology Glowinski et al. (1999) introduced a new Lagrange-multiplier based fictitious-domain method for the direct numerical simulation of fluid–solid interaction and used it successfully for sedimentation, fluidization and many other applications (Glowinski et al., 1999, 2001; Glowinski, 2003). The method of Glowinski et al. (1999) motivated other researchers (Carlson et al., 2004; Patankar, 2001; Patankar et al., 2000; Singh et al., 2003) in fluid–solid interaction simulation to further modify his method. Sharma and Patankar (2005) inspired by these works used the fast computation technique of Patankar (2001) in a control volume context for the direct numerical simulation of rigid particulate flows. In this method, the computational domain encompasses both the fluid and solid, and governing equations are solved everywhere in the computational domain. The rigid body motion is then obtained by integrations in the solid zones due to the fact that the total linear and angular moment in each individual solid zone should be conserved. This computationally fast and effective framework for treating the motion of solid objects has been applied in many other investigations such as Apte et al. (2009), Apte and Patankar (2008), Ardekani et al. (2008), Ardekani and Rangel (2008), Coquerelle and Cottet (2008), Martin et al. (2009), Patankar and Sharma (2005), Sharma et al. (2005) and Shirgaonkar et al. (2009).

The fictitious-domain methods also have been used for direct numerical simulation of water entry problems (Xiao, 1999; Hu and Kashiwagi, 2004; Zhu, 2006). Lin (2007) presented a two dimensional model based on cut-cell technique in a fixed grid system integrated into the VOF method for tracking the free surface motion. In this model, the solid object is assumed to have a prescribed motion. The moving body problem is then recast into an equivalent problem where the solid is held constant and the fluid motion is superimposed with the same velocity of the solid in the opposite direction. Besides this drawback, the Lin's model (Lin, 2007) relies on the fact that the gas phase is not considered, rather a void region is assumed outside the liquid phase. Do-Quang et al. (Do-Quang and Amberg, 2009, 2010) presented a numerical study on the influence of solid surface wettability on the splash of a solid sphere impacting a liquid free surface. In their studies, the sphere is considered to be fixed and the computations are made in the reference frame of the sphere. Next, the liquid inlet velocity to the domain of computations is set equal to that of the falling velocity of the solid in each time step. This treatment for the sphere motion cannot be implemented for general motion of the solid objects. Yang and Stern (2009) used a sharp interface immersed-boundary formulation and a level-set/ghost-fluid method for solid–liquid and liquid–gas interface treatments, respectively. In immersed-boundary method of Yang and Stern (2009), the forces acting on the flow field domain due to the solid object presence have to be evaluated explicitly in the governing equations. These forces need to be applied to the nodes located on the vicinity of the liquid–solid interface (also known as forcing points). In another work (Yang and Balaras, 2006), they introduced further complexities when solving for the moving object problems due to the fact that the role of the forcing points near the interface changes from one time step to the other.

In this study, a numerical method is presented which can simulate the water entry of solid objects. This method is capable of handling unprescribed motion of the solids without solving any additional equation in the computational domain. The method is based on the fast-fictitious-domain method presented by Sharma and Patankar (2005) in which the governing equations are solved everywhere in the computational domain including the solid object and the evaluation of the acting forces on the solid are