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Numerical Simulation of Water Entry and Exit Problems by an Adaptive Cartesian Grid Method

Yunxing Zhang, Wenyang Duan, Shan Ma and Kangping Liao
College of Shipbuilding Engineering, Harbin Engineering University
Harbin, Heilongjiang, China

In this paper, a two-dimensional three-phase flow model for simulating wave–body interactions is developed. Based on the conventional two-phase flow model in which gas and liquid are involved, the solid body is considered the third phase so that wave-body interactions are considered to be three-phase problems. Furthermore, an adaptive mesh refinement grid is adopted to reduce the computational cost. Benchmark cases of water entry and exit of a circular cylinder and of water entry of a free-falling V-shaped wedge are used to validate the model. Acceptable agreements are obtained between the present results and data from other sources.

INTRODUCTION

As one of the most violent interactions between solid bodies and free surfaces, wave–body interactions play an important role in many engineering fields. Computational fluid dynamics (CFD) techniques are nowadays widely utilized to investigate the hydrodynamics of these problems. However, there are still many difficulties in numerical simulating wave-body interactions. A typical problem is how to track the body surface and enforce the boundary condition, especially when the body is not in stationary. Besides, computational cost is always a bottleneck in CFD.

For a body-fitted grid in which the grid is aligned with the body surface, the enforcement of boundary conditions is simple, although the tracking of the body could be complicated. The arbitrary Lagrangian Eulerian (ALE) method is widely utilized for this grid (Donea et al., 2004). The grid follows the motion of the body with grid stretch or reconstruction to keep align with the body surface. The method would not be so stable when the motion of the body is large. For a large motion of the body, the overset grid could be a better choice, although the conservation of the overset grid is not easy to preserve (Ferziger and Perić, 2002).

The non-body-fitted methods based on a Cartesian grid are a good alternative. On a Cartesian grid, the solid body is considered the third phase, and the methods for capturing/tracking the interface in multiphase flow could be adopted. The volume of fluid (VOF) method (Hu and Kashiwagi, 2004; Ghasemi et al., 2014) and level-set method (Yang and Stern, 2009) were used to capture the body. Usually, the immersed boundary (IB) method is adopted for the treatment of boundary conditions (Yang and Stern, 2009).

Adaptive mesh refinement (AMR) was proposed by Berger and Oliger (1984). Since then, the method had been widely adopted to reduce the computational cost in CFD simulation. For the single-phase flow, the method was combined with the immersed boundary method for fluid-structure interactions in compressible or incompressible flows (Roma et al., 1999; Vanella et al., 2010; Liu and Hu, 2018). For the two-phase flow without a body, the method was used to simulate various interfacial flows including bubble flows or waves (Popinet, 2009; Zuzio et al., 2018; Nangia, Griffith et al., 2019).

When a body exists in a two-phase flow such as a wave-body interaction, the implementation of the AMR grid could be even more complicated. Related research that considers wave-body interactions with AMR are still not so many because of such complications. Nangia, Patankar and Bhalla (2019) developed a robust solver for modeling wave-structure interactions. Two level-set functions were adopted for tracking gas-liquid interfaces and body surface with the distributed Lagrange multiplier method to represent the body boundary condition. In this paper, we try to develop a robust model for wave-body interactions with AMR. The model is based on the two-phase flow model developed by Zhang et al. (2020) in which the Cartesian grid with AMR is utilized. Different from Nangia, Patankar and Bhalla (2019), two VOF functions are utilized for tracking the free surface and body surface. Furthermore, a sharp interface method is adopted to treat the boundary condition of the body.

In this paper, a two-dimensional three-phase flow model is developed for the numerical study of wave-body interactions. The VOF method is adopted to capture the free surface and body surface, and the IB method is utilized for treating the boundary condition of the body. An AMR grid is adopted to reduce the computational cost. The rest of this paper is organized as follows: The numerical methods are provided first, followed by the validation of the model. Benchmark cases of water entry and water exit of a circular cylinder, as well as a free-falling V-shaped wedge, are used to validate the present numerical model. Finally, conclusions and future work are drawn.

NUMERICAL METHODS

Governing Equations

The incompressible viscous two-phase flow with surface tension neglected is governed by the following continuity equation and Navier–Stokes equations:

$$\frac{\partial u_i}{\partial x_i} = 0$$
$$\frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{1}{\rho}\frac{\partial \tau_{ij}}{\partial x_j} + f_i \quad (1)$$

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KEY WORDS: Cartesian grid, three-phase problem, water entry, adaptive mesh refinement.