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Numerical simulation of fluid–structure interaction using a combined volume of fluid and immersed boundary method

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Abstract

In this work, a combined immersed boundary (IB) and volume of fluid (VOF) methodology is developed to simulate the interactions of free-surface waves and submerged solid bodies. The IB method is used to account for the no-slip boundary condition at solid interfaces and the VOF method, utilizing a piecewise linear interface calculation, is employed to track free surfaces. The combined model is applied in several case studies, including the propagation of small-amplitude progressive waves over a submerged trapezoidal dike, a solitary wave traveling over a submerged rectangular object, and wave generation induced by a moving bed. Numerical results depicting the free-surface evolutions and velocity fields are in good agreement with either experimental data or numerical results obtained by other researchers. In addition, the simplification of the initial free-surface deformation used in most tsunami earthquake source study is justified by the present model application. The methodology presented in the paper serves as a good tool for solving many practical problems involving free surfaces and complex boundaries.

Keywords: Moving bed; Immersed boundary method; Volume of fluid method; Wave–structure interaction; Wave generation

1. Introduction

Interactions between water waves and submerged marine structures are important in the solution of many coastal engineering problems. With rapid advances in computing technology, more researchers and engineers are using numerical simulations to better understand the fluid–structure interactions. However, it is difficult to study numerically complex free-surface evolutions and irregular boundaries. The challenge is even higher if the structure is in motion.

Over the past two decades, many accurate numerical schemes based on potential theory have been developed for the simulation of free-surface flows. Grilli et al. (1994) and Ohyama and Nadaoka (1994), for example, made use of the boundary integral method (BIM) to study the scenarios of a solitary wave run-up and the wave transformation over a submerged object. The wave transformation was accurately predicted, but phenomena such as flow separation and vortex generation were ignored. To capture these essential features of flow–structure interactions, it would be necessary to solve the Navier–Stokes (N–S) equations.

Lin and Li (2002) made use of a σ-coordinate transformation to map a irregular physical domain to a computational domain of rectangular shape. Lin (2006) developed a three-dimensional (3D) multiple-layer σ-coordinate model to simulate surface wave interaction with various types of structures, including submerged, immersed, and floating structures. In general, such methodologies are capable of producing accurate predictions of free-surface displacements. A limitation, however, is the modeling of free surface of arbitrary configuration, such as in the case of wave breaking. Compared to the application of the coordinate transformation technique, it is still more convenient to carry out numerical simulations of wave–structure interactions in a Cartesian coordinate system. Due to the complexity in modeling a general irregular solid boundary, many studies were limited to simpler cases such as wave flows over a submerged rectangular obstacle

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(e.g., Tang and Chang, 1998; Huang and Dong, 2001; Chang et al., 2001). In the study of a progressive water wave propagating over a submerged trapezoidal dike, Huang and Dong (1999) divided the varying bed topography into a series of small rectangular steps and used a modified marker and cell (MAC) method to capture the free surface. Having compared their simulated free-surface evolutions with experimental data, they attributed the discrepancy, especially behind the object, to this solid boundary approximation.

General schemes for the modeling of complex fluid–solid boundaries have been proposed. In a RIPPLE model, to simulate two-dimensional (2D) incompressible fluid flows with arbitrary free surfaces and internal obstacles, Kothe and Mjolsness (1992) used the idea of two-phase flow to treat solid boundaries. In particular, one phase was fluid and another phase was solid having infinite density and zero velocity. The free-surface interface was modeled with a volume of fluid (VOF) method based on the Hirt–Nichols algorithm (Hirt and Nicholes, 1981). The accuracy of the numerical solutions near the solid boundary was however not demonstrated conclusively. Lin and Liu (1998) coupled the RIPPLE model with the κ–ε turbulence model and applied it to calculate breaking waves on a sloping beach. The free-surface profile, mean velocities, and turbulent kinetic energy distribution obtained with the numerical model compared well with those obtained in laboratory measurements. Recently, similar models were used by Shen et al. (2004) to simulate cnoidal waves propagating over a submerged bar. They concluded that more efforts were required for the development of models.

In general, the complexity of the problem increases when the wave–structure interaction problem includes structure movements. Based on potential flow, steady-flow problems have been solved in a coordinate system which is fixed to the moving object (e.g., Forbes and Schwartz, 1982; Forbes, 1988; King and Bloor, 1990). Lowery and Liapis (1999) obtained the transient free-surface profiles that were caused by a moving semi-circular bottom obstruction in the time domain. Water waves generated by underwater landslides have been numerically investigated by Grilli and Watts (1999) and Grilli et al. (2002) using boundary element methods. In a similar study, Heinrich (1992) solved 2D N–S equations and added a source function to the continuity and momentum equations to represent moving boundary effects. However, the no-slip boundary condition was not satisfied on the moving body surface. Wu (2004) further extended Heinrich's model to simulate the 3D wave generation induced by landslides.

It is noted that, to ensure that no-slip boundary conditions are satisfied at solid boundaries, an immersed boundary (IB) method could be used. The IB method was originally developed by Peskin (1972) to simulate blood flows in mitral valves, and was later introduced to solve problems in incompressible fluid flows (e.g., Goldstein et al., 1993; Verzicco and Orlandi, 1996; Saiki and Biringen, 1996; Mohd-Yusof, 1997; Fadlun et al., 2000; Lai and Peskin, 2000; Kim et al., 2001; Balaras, 2004). The method was recently reviewed by Mittal and Iaccarino (2005), with an extensive bibliography. The IB method has the advantage of simplified grid generation and its inherent simplicity to study a moving body (Mittal and Iaccarino, 2005) on fixed Cartesian meshes. Moreover, the IB method with an appropriate treatment can bring about the convenience of computing forces acting on a submerged body, namely drag and lift forces in two dimensions. These advantages further suggest that the IB method could be utilized to study problems involving moving structures with wave–structure interactions.

In this paper, a combined IB–VOF model is presented to study wave–structure interactions. The IB method is applied to handle solid object boundaries, while the VOF method, which was introduced by Hirt and Nicholes (1981), is used to capture free surfaces. In Section 2, the numerical model is described. The capability of the model is demonstrated in Section 3 through several case studies, including the propagation of small-amplitude progressive periodic waves over a trapezoid, a solitary wave passing over a submerged rectangular object, and the wave generation induced by a moving bed. The usefulness of the combined IB–VOF model is summarized in Section 4.

2. Numerical model description

2.1. Mathematical formation of the model

In the 2D wave–structure interaction, the flow of an incompressible viscous fluid is governed by the N–S equations:

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = \frac{1}{\rho}\frac{\partial p}{\partial x_i} + v\nabla^2 u_i + g_i, \tag{1}$$

and the continuity equation:

$$\frac{\partial u_i}{\partial x_i} = 0, \tag{2}$$

where u_i, $i = 1$, 2 are the velocity components along the coordinate axes x_i, p is the pressure, t the time, ρ the water density, $v = \mu/\rho$ the kinematic viscosity coefficient of the water, and g_i the body force, including the gravitational acceleration. In what follows, the velocity and the coordinate axes will be written interchangeably as (u_1, u_2) or (u, w) and (x_1, x_2) or (x, z).

The effect of a solid body on the flow is to act a force on the fluid and that force is induced by the no-slip boundary condition on the rigid body surface. In the IB method, the solid body is replaced with a proper force being imposed on the body surface (shown in Fig. 1). Consequently, the N–S Eq. (1) becomes

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + v\nabla^2 u_i + g_i + f_i \tag{3}$$

in the absence of the object; f_i are the force components which are zero everywhere except on the body surface.

For the completeness of the problem setup, appropriate initial and boundary conditions are required. In this study,