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Numerical simulation of nonlinear dispersive waves propagating over a submerged bar by IB–VOF model

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ABSTRACT

It is a good test for a numerical model to simulate progressive waves propagating over a submerged bar with a relatively high ratio of slopes. In this paper, the combined IB–VOF model is used to predict nonlinear dispersive waves propagating over a submerged bar with both slopes of 1:2. The predicted free surface elevations are compared with the experimental data and numerical results presented by other researchers. The comparison shows that the IB–VOF model is able to provide satisfactory wave profiles in the shallow water with strong nonlinear effects and in the wave transmitted region with strong wave dispersion in particular. Moreover, the wave evolution behind the submerged bar is described in detail, including the spatial wave profile modulation, spectral analysis of the time-series waves, flow velocity and pressure fields, and kinetic energy distribution. The effect of fluid viscosity on the numerical simulations is also studied, and it is found that the effect on the wave evolution considered in this paper is not significant. Finally, the hydrodynamic force acting on the bar is calculated using the IB–VOF model.
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1. Introduction

It is well known that regular waves decompose into shorter waves when they propagate over a submerged bar. The phenomenon of decomposition has been observed in the laboratory experiments (e.g. Beji and Battjes, 1993; Ohyama et al., 1995) and revealed by numerical simulations as well (e.g. Huang and Dong, 1999; Ohyama and Nadaoka, 1994; Ohyama et al., 1995; Lin and Li, 2002; Shen et al., 2004; Wu and Yuan, 2007; Shen and Chan, 2008; Young and Wu, 2009). It is observed that the numerical simulations agree favorably with the experiments on wave evolution over a submerged mildly sloping bar. However, numerical solutions by various models are not so satisfactory for a bar with relatively steep slopes, particularly for wave evolution behind the bar. Therefore, it is worthwhile to further investigate this problem.

In Ohyama et al. (1995), three different wave-propagation models, namely fully nonlinear, Stokes second order and Boussinesq with an improved dispersion relation, were applied to investigate nonlinear dispersive wave evolution over a submerged bar, with the same slope ratio of 1:2. The fully nonlinear models were able to provide better solutions than other models when compared with the experimental measurements. However, further investigations of pressure and velocity fields were required by the authors in engineering applications. Ertekin and Becker (1998) simulated cnoidal waves propagating over the same bar by solving the Green–Naghdi equations for an inviscid fluid. The comparison between their predictions and the experimental data showed that the higher harmonics were not exhibited in the simulations and the wave height was underestimated as well. A further study of this problem was suggested. A non-hydrostatic numerical model based on the incompressible Euler equations was developed by Zijlema and Stelling (2005). A boundary-fitted co-ordinate system was employed in the vertical direction to achieve high resolution near the bottom and the free surface as well. The model was applied to two cases of wave propagation considered by Ohyama et al. (1995). Overall agreement with the experiments were obtained, though less accurate results were found at positions located in the transmitted wave region and insufficient mesh resolution was ascribed by the authors.

All of these numerical models have neglected the viscous effect and thus energy dissipation due to fluid viscosity was not considered. Particularly, the free surface evolution may be affected when the fluid flow separates from the blunt object, giving rise to vortices in the wake behind it. Francis and Kim (1994) carried out laboratory experiments to investigate the flow separation effects by conducting periodic water waves travelling over a submerged rectangular obstacle, and found that the transmission process was significantly modified by the separated flow. However, the numerical simulation of progressive waves over a rectangle by Huang and Dong (1999) showed that the impact of the separated vortices on the free surface was ignorable.

In Shen et al. (2004), a two-equation $k-\varepsilon$ turbulence model was used to simulate the cnoidal waves propagating over the same relatively steep bar. The free surface was captured by a VOF (volume of fluid) method in first order accuracy, while the irregular

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solid boundary was treated by a partial-cell method. A visible discrepancy was observed in the comparison of free surface evolution between their numerical results and experimental measurements, particularly, in the transmitted waves behind the bar. High harmonic waves were not well discovered in their simulations. A more refined turbulence model was suggested by the authors to improve their model.

In brief, it is found that the above-mentioned numerical methods are generally able to predict wave decompositions over the bar. However, a relatively large discrepancy of the wave evolution behind the bar was observed in the comparison between numerical results and experimental measurements. Various reasons were attributed to the discrepancy and different suggestions were proposed to improve the numerical models. Therefore, it is worthwhile for a well-developed numerical model to study the detailed evolution of waves passing over the submerged bar, including the spatial wave evolution, spectral analysis of wave series in time, velocity and pressure fields, and kinetic energy distribution as well.

In this work, the IB–VOF model (Shen and Chan, 2008) is employed to simulate periodic progressive waves propagating over the submerged bar with a slope ratio of 1:2. In the IB–VOF model, the IB (immersed boundary) method is used to deal with the solid boundaries and the VOF method, in second order accuracy, is used to capture the free surface movement. One advantage of the IB method is that the irregular solid boundary can be handled in the Cartesian coordinate system. The IB method had been successfully used to simulate an oscillating circular cylinder in fluid at rest (Shen et al., 2009) and oscillating flows over a bed-mounted circular cylinder as well (Shen and Chan, 2010a). Recently, the well-developed IB–VOF model was applied to the study of a progressive periodic wave travelling over a circular cylinder close to the bed by Shen and Chan (2010b).

In Section 2, the mathematical model and numerical method are briefly introduced. In Section 3, the IB method is validated first by simulating an oscillating flow around a circular cylinder, and then the numerical sponge layer is tested. Finally, the IB–VOF method is applied to the waves propagating over the submerged bar. The summary and concluding remarks are given in Section 4.

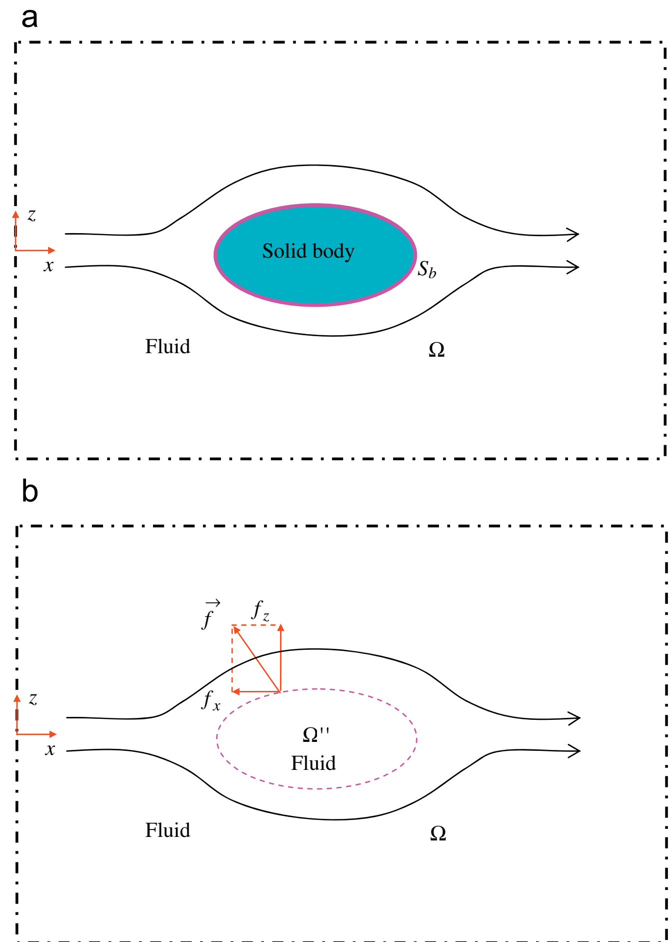

Fig. 1. Illustration of flow around rigid body in IB method: (a) original flow domain Ω; (b) submerged object is replaced by same fluid with a proper force unit applied on surface S_b. Domain Ω'' is enclosed inside body.

2. Mathematical model and numerical scheme

The 2D flow of an incompressible viscous fluid around an immersed solid object (Fig. 1) is governed by the Navier–Stokes equations

$$\frac{\partial u_i}{\partial t}+\frac{\partial u_i u_j}{\partial x_j}=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+\nu\nabla^2 u_i+g_i \quad (1)$$

and the continuity equation

$$\frac{\partial u_i}{\partial x_i}=0 \quad (2)$$

where $u_i, i=1,2$ are the velocity components in the direction along with the coordinate axes x_i, p is the pressure, t the time, ρ the fluid density, $\nu=\mu/\rho$ the kinematic viscosity coefficient of the water, μ the dynamic viscosity coefficient, and g_i the gravitational acceleration. In what follows, the velocity and the coordinate axes will be written interchangeably as (u, w) and (x, z). For the completeness of the problem description, appropriate initial and boundary conditions must be prescribed. These conditions will be described in each case study.

In the framework of the IB method, the solid body is replaced by an imposed force distribution over the body surface. Consequently, the N–S equation (1) may be written as

$$\frac{\partial u_i}{\partial t}+\frac{\partial u_i u_j}{\partial x_j}=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+\nu\nabla^2 u_i+g_i+f_i \quad (3)$$

where f_i are the imposed force terms that are zero everywhere except on the body surface.

In the IB method, the hydrodynamic forces acting on the submerged stationary object can be determined simply by integrating the x- and z-components of the imposed force densities (Shen et al., 2009), i.e.

$$F_x=-\rho\iint_{\Omega'} f_x\,dV \quad (4)$$

$$F_z=-\rho\iint_{\Omega'} f_z\,dV \quad (5)$$

in the enclosed domain of $\Omega'=\Omega+\Omega''$, where Ω'' represents the closed domain inside the solid body (shown in Fig. 1(b)).

The VOF method was introduced by Hirt and Nichols (1981) and the free surface could be simulated in terms of the distribution of the discrete grid volume fraction. The method consists of two steps, namely the interface reconstruction and the volume fraction advection. In the IB–VOF method, a technique of piecewise linear interface calculation with second order accuracy was employed.

The N–S equations are solved numerically by the SIMPLEC-type two-step computational method. The intermediate velocity is computed first; then a pressure is obtained by solving a Poisson equation, which is derived by enforcing the continuity constraint; the final velocity is updated by simple algebraic operations. Please refer to Shen and Chan (2008) for the detailed numerical scheme, including the determination of force term f_i and the implementation of the VOF method for the free surface.

In the numerical simulation of wave-structure interaction, it is very important to define the outflow boundary conditions to

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