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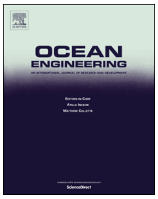

Development of a numerical circular wave basin based on the two-phase incompressible flow model

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ABSTRACT

Fully nonlinear oblique waves are reproduced in a circular wave basin using a viscous three-dimensional numerical model based on the two-phase flow model. The numerical model is conducted in cylindrical coordinates and the finite volume method (FVM) is used to discretize the Navier–Stokes equations on the zonal embedded grids. The free surface is captured using the volume of fluid (VOF) method. Oblique waves are generated by a wave generator inside the computational domain, which is implemented by adding a source term to the continuity equation. The outgoing waves are numerically dissipated by an artificial damping zone at the outer edge of the circular wave basin.

To demonstrate the advantages of the present model, numerical simulations of oblique incident waves are carried out, and the results for the regular waves are compared with the theoretical results. It is found that the effective area in the circular wave basin is significantly enlarged and its performance rarely depends on the incident angle of the oblique waves. In addition, by integrating the mass function of the oblique waves, this model can be used to simulate multi-directional waves. In this paper, this method is used to simulate two crossed waves.

1. Introduction

Wave direction, one of the main properties of ocean waves, plays an important role in the application of the hydrodynamic loads acting on coastal and ocean structures. To settle this issue, experimental facilities with a relatively wide wave basin have been widely used. In the three-dimensional wave basin, the snake-type wave generators which are located along one or more of the basin walls are implemented to reproduce the directional waves (Dean and Dalrymple, 1984). However, the ineffective dissipation of reflected waves from wave generators, side walls and structures will deform the wave field after a certain amount of time, resulting in a limited effective zone for experimental studies. To enlarge the effective experimental area, based on the concept that regular waves can be generated by the periodic movement of infinite long wave paddles, Funke and Miles (1987) and Dalrymple (1989), considering the side wall reflection, practically increased the effective area for oblique wave generation. Hiraishi et al. (1995) replaced the two side walls of the wave basin with a serpent wave generator, and proposed a multi-face absorbing wave generator. And Ito et al. (1996) successfully reproduced the multi-directional waves with the multi-face wave generator.

On the other hand, over the past decades, a number of numerical wave basin models have been developed for dealing with problems involving waves, and the snake-type wave generator has been widely applied to analyze multi-directional and oblique waves in these models. For instance, Williams and Crull (2000) proposed a three-dimensional semi-infinite wave basin for oblique waves using the boundary element based potential theory model. And Shih et al. (2009) proposed a three-dimensional numerical wave basin for the investigation of multi-directional waves using the multi-face wave generator. In order to predict the three-dimensional fully nonlinear wave fields, Park et al. (2003, 2004) presented an incompressible Navier–Stokes solver. In their model, the marker-density function method is applied to treat the fully nonlinear kinematic free surface condition.

Although the multi-face wave generator can significantly enlarge the effective area in a rectangular wave basin, Hiraishi et al. (1995) found that its performance was still affected by the incident direction of waves. The effect of the incident direction to the effective zone was also reported by Williams and Crull (2000). Therefore, to simulate the real multi-directional waves without the effect of the wave incident direction, Tanaka et al. (1994) proposed a new concept to generate three-dimensional waves with a circular wave basin. The results of their theoretical and experimental studies indicated that oblique

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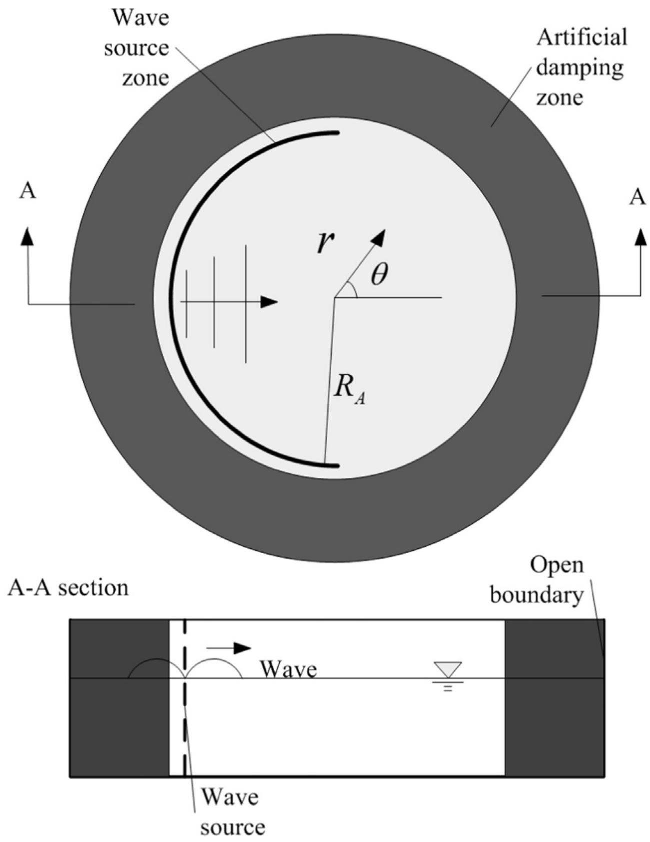

Fig. 1. Schematic sketch of the circular basin.

waves with an arbitrary incident direction could be generated with an internal wave generator. As the side boundary of the circular wave basin was considered as the open boundary in their model, the outgoing waves could freely transit across the boundary without reflection. Through comparisons with the traditional rectangular basin, it was observed that the effective area in the circular wave basin was significantly enlarged in the oblique wave generations. Moreover, Naito (2006) presented a small scale circular wave basin with the absorbing wave generators arranged in a circle at the wall of the basin. In his study, the physical model was capable of generating small amplitude waves.

Previous studies on the circular wave tank have mainly been conducted using the physical and theoretical analyses. To better understand the fully viscous free surface movements in the circular wave tank, herein, a Navier–Stokes solver is developed based on a self-developed code. The finite volume method (FVM) is used to discretize the control equations in cylindrical coordinates and the VOF method is applied to capture the free surface. In this model, as shown in Fig. 1, the oblique waves are generated with a semi-circle wave generator and outgoing waves are numerically dissipated with a damping zone at the outer edge of the computational domain. A mass source function is applied as the non-reflection wave generator and added to right side of the continuity equation as a mass source. The wave mass source is only nonzero at the semi-circle wave source zone. Moreover, the momentum equations are modified by a friction term, which acts as the damping factor and is only active at the damping zone.

2. Governing equations

Wave motions can be investigated with the two-phase flow model governed by the modified Navier–Stokes equations based on the single fluid assumption, which accounts both the differences of the material properties and the surface tension. To simulate the circular wave basin, the continuity and Navier–Stokes equations are solved in the cylindrical coordinates by adapting the wave generating and damping methods. In this work, the continuous equation is rewritten with a mass source term to generate waves, and the momentum equations are rewritten with a source term to dissipate outgoing waves.

2.1. Wave generation method in cylindrical coordinates

One of the most important challenges in numerical wave simulations is establishing a well-designed wave generator that neither disturbs the wave field nor re-reflects the reflected waves. The internal wave source method, developed to solve this problem, has been used by Kawasaki (1999) and Lin and Liu (1999) in a two-dimensional numerical wave model with a mass source acting as a wave generator. To incorporate the internal wave source method, the continuity equation in cylindrical coordinates is modified as follows:

$$\frac{1}{r}\frac{\partial ru}{\partial r}+\frac{1}{r}\frac{\partial v}{\partial \theta}+\frac{\partial w}{\partial z}=Q(r,\theta,z,t), \tag{1}$$

where u, v, and w are the velocity components respectively in the r, θ, z directions, and $Q(r,\theta,z,t)$ is the mass source term that is only nonzero in the wave source zone. The semi-circle wave source zone is settled according to the direction of the incident wave θ_i, as shown in Fig. 2.

The wave source term in the circular wave basin can be derived from the wave potential $\phi(r,\theta,z,t)$ according to a certain wave theory. Brorsen and Larsen (1987) gave the formula for the mass source term as

$$Q(r,\theta,z,t)=2\int_{-h}^{\eta}\int_{\theta_i-\pi/2}^{\theta_i+\pi/2}u(R_A,\theta,z,t)dzd\theta/V_s=2\int_{-h}^{\eta}\int_{\theta_i-\pi/2}^{\theta_i+\pi/2}\frac{\partial\phi(R_A,\theta,z,t)}{\partial r}dzd\theta/V_s, \tag{2}$$

where $V_s=\Delta r\int_{-h}^{\eta}\int_{\theta_i-\pi/2}^{\theta_i+\pi/2}dzd\theta$, is the total volume of the wave source zone; Δr is the cell size in the radial direction and the coefficient 2 means waves are transported in both directions from the internal wave source zone.

2.2. Momentum equations

Lin and Liu (2004) dissipated the outgoing waves with a numerical damping zone using an additional friction term in the momentum equations. In the present model, the additional friction term is only applied in the vertical direction. Therefore, the modified momentum equations in cylindrical coordinates are written as

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial r}+\frac{v\partial u}{r\partial\theta}+w\frac{\partial u}{\partial z}-\frac{v^2}{r}=-\frac{1}{\rho}\frac{\partial p}{\partial r}+$$

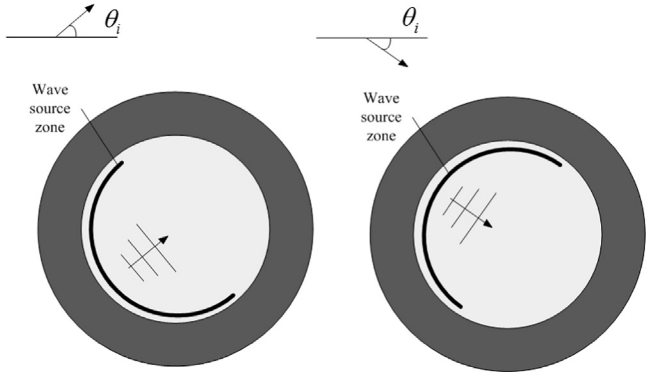

Fig. 2. Setup of the wave source zone $\theta_i-\pi/2\le\theta\le\theta_i+\pi/2$ (θ_i is the wave incident angle).