Ocean Engineering 42 (2012) 93–101

Contents lists available at SciVerse ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Regular and irregular wave impacts on floating body

Yong Li, Mian Lin *

Institute of Mechanics, Chinese Academy of Sciences, No. 15 West Road, North 4th Ring Road, Beijing 100190, China

ARTICLE INFO

Article history:
Received 13 January 2011
Accepted 2 January 2012
Editor-in-Chief: A.I. Incecik
Available online 25 January 2012

Keywords:
Floating body
Irregular wave
Wave impact
Numerical wave tank
Finite volume method

ABSTRACT

Fully nonlinear wave–body interactions for a stationary floating structure under regular and irregular waves for different water depths, wave heights and periods are studied in a 2-D numerical wave tank. The tank model is based on Reynolds-averaged Navier–Stokes equations and renormalization group k–ε model. The equations are discretized based on the finite volume method. The pressure implicit splitting of operators scheme is employed to treat the pressure–velocity coupling and a compressive interface capturing scheme is used to capture the free surface on mashes of arbitrary topology. The calculated results for regular wave simulation, irregular wave propagation and wave impacts on floating body are compared with the theoretical/experimental data and the numerical results agree well with analytical/experimental solutions. The mean and maximum wave impacts, including rotational moment, on body are obtained. The effects of water depth, wave height and period on forces and moment have been investigated and the calculated results for irregular waves are compared with those induced by regular waves.

1. Introduction

Recently, many types of floating structures, such as floating breakwater, jacket platform and man-made island, have been used in coastal and ocean engineering. The safety of these structures has a significant relation to the wave impacts. The structures usually suffer from strong nonlinear loadings under waves, especially under irregular waves. Therefore, prediction of nonlinear regular and irregular wave forces on floating structures is an important topic.

There are many correlative studies on the interactions between the water waves and structures with different types, including the fully submerged structures (Clement and Mas, 1995; Boo, 2002; Koo et al., 2004; Vengatesan et al., 2006, etc.), vertical cylinders/plates (Li and Lin, 2001; Pradip and Sukamal, 2006; Wang and Wu, 2010, etc.), the surface-piercing bodies (Nojiri and Murayama, 1975; Tanizawa and Minami, 1998; Fang and Chen, 2001; Koo and Kim, 2007a, 2007b; Li and Lin, 2010, etc.) and so on.

Many researchers studied the interaction problem based on theory and experimental analyses. Pradip and Sukamal (2006) introduced a solution of shallow water wave force, using small amplitude linear wave theory on two-dimensional (2-D) vertically submerged circular thin plates under different configurations. The total horizontal force and moment with respect to the wave amplitude were obtained at different water depths and wave periods. Hanssen and Torum (1999) experimentally studied the breaking wave forces on tripod concrete structure on shoal using Morison's equation. Ren and Wang (2003) studied the irregular wave slamming on structure members with large dimension in the splash zone. The time-domain and frequency-domain analyses results of the irregular wave impact pressure on the subface of the structure were presented.

Some of the other researchers investigated the interaction problem using numerical wave tank. In Boo's work (2002), a time-domain numerical scheme was used to simulate the linear irregular waves in numerical tank and the linear and nonlinear irregular wave diffraction forces acting on a submerged structure was predicted. Koo and Kim (2007a) studied the wave body interactions for stationary floating single and double bodies using a potential-theory-based fully nonlinear 2-D numerical wave tank. Li and Lin (2010) investigated the fully nonlinear wave–body interactions for a surface-piercing body in finite water depth with flat/slop bottom topography. A 2-D numerical regular wave tank was built, which mainly based on the spatially averaged Navier–Stokes equations and the k–ε model was used to simulate the turbulence of flow. Clauss et al. (2010) studied the fully nonlinear interactions between water waves and vertical cylinder arrays in a numerical tank, which based on a finite element method (FEM).

Among studies presented above, the problems on interaction between water waves and floating bodies have been interested recently. The regular wave and/or current had been considered by some authors (Koo and Kim, 2007a, 2007b; Li and Lin, 2010, etc.). It is important to understand nonlinear interactions between irregular waves and surface-piercing structures, compared with

* Corresponding author. Tel.: +86 10 8254 4206.
E-mail addresses: linmian@imech.ac.cn, liyong@imech.ac.cn (M. Lin).

0029-8018/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.oceaneng.2012.01.019

regular waves. In present paper, using a fully nonlinear 2-D numerical wave tank, the wave forces and rotational moment on a floating structure are investigated for regular and irregular waves at different water depths, wave heights and periods.

With the development of computer technology and computation algorithm, the numerical wave tank has been developed to be a promising tool to investigate various wave-related problems. In order to study the problem of wave propagation, a fully nonlinear numerical wave tank was presented by Zhang et al. (2006). In their studies, desingularized boundary integral equation method was coupled with the mixed Eulerian–Lagrangian formulation. Li (2008) described a numerical tank for regular and irregular wave propagation based on the Navier–Stokes equations and a spatial fixed σ-coordinate was used to transform the equations from the sea bed to the still water level.

In present works, the numerical tank is built based on Reynolds-averaged Navier–Stokes (RANS) equations and renormalization group (RNG) k–ε two-equation model. The wave tank is verified firstly and the simulated results are compared with the theoretical/experimental solutions. Then, mean and maximum wave forces and rotational moment are calculated. The force spectra are obtained by fast Fourier transform (FFT), though which the forces and moment are transformed from the time-domain to frequency-domain.

2. Mathematical formulation

2.1. Governing equations

The governing equations are the RANS equations, which can be written as follows:

$$\frac{\partial}{\partial x_j}(u_j)=0, \tag{1}$$

$$\frac{\partial}{\partial t}(u_i)+\frac{\partial}{\partial x_j}(u_ju_i)=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+\frac{1}{\rho}\frac{\partial}{\partial x_j}\left[\mu_{eff}\left(\frac{\partial u_j}{\partial x_i}+\frac{\partial u_i}{\partial x_j}\right)\right]-D_iu_i+g_i \tag{2}$$

where $x_j(j=1,2)$ represents the coordinate component, u_j is the fluid velocity, p is the pressure, ρ is the density, g is the acceleration of gravity, D_i is the damping coefficient and the damping term D_iu_i is added to the momentum equation directly. $\mu_{eff}=\mu+\mu_f$, μ is the molecular viscosity, μ_f is the turbulent eddy viscosity, $\mu_f=C_\mu\rho k^2/\varepsilon$. k is the turbulent kinetic energy, ε is the turbulent energy dissipation rate. In present paper, the RNG $k-\varepsilon$ two-equation model is adopted to estimate the turbulence

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_j}(\rho u_jk)=\frac{\partial}{\partial x_j}\left[\alpha_k\mu_{eff}\frac{\partial k}{\partial x_j}\right]+P_k-\rho\varepsilon, \tag{3}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_j}(\rho u_j\varepsilon)=\frac{\partial}{\partial x_j}\left[\alpha_\varepsilon\mu_{eff}\frac{\partial \varepsilon}{\partial x_j}\right]+C^*_{1\varepsilon}P_k\frac{\varepsilon}{k}-\rho_fC_{2\varepsilon}\frac{\varepsilon^2}{k} \tag{4}$$

where

$$P_k=\mu_f\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j},\ C^*_{1\varepsilon}=C_{1\varepsilon}-\frac{\eta(1-\eta/\eta_0)}{1+\beta\eta^3},$$

$$\eta=(2S_{ij}S_{ij})^{0.5}\frac{k}{\varepsilon},\ S_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right).$$

The values of constants in RNG k–ε model are shown in Table 1.

Table 1
Values of constants in turbulent model.

Constant	C_μ	α_k	α_ε	$C_{1\varepsilon}$	$C_{2\varepsilon}$	η_0	β
Value	0.0845	1.39	1.39	1.42	1.68	4.38	0.012

In order to capture the water–air free surface, an Eulerian method named the volume of fluid (VOF) method is adopted. The equation for the volume fraction is

$$\frac{\partial\alpha}{\alpha t}+\frac{\partial}{\partial x_j}(u_j\alpha)=0 \tag{5}$$

where α is the volume fraction of water and $1-\alpha$ represents the volume fraction of air. Volume fraction of each liquid is used as the weighting factor to get the mixture properties, for the density and molecule viscosity

$$\rho=\alpha\rho_w+(1-\alpha)\rho_a, \tag{6}$$

$$\mu=\alpha\mu_w+(1-\alpha)\mu_a \tag{7}$$

where ρ_w and ρ_a represent the density of water and air, respectively. μ_w and μ_a are molecule viscosity coefficient of water and air, respectively.

2.2. Boundary conditions

The entire study domain is shown in Fig. 1. There are totally five types of boundary associated with the governing equations, including inlet, outlet, structure, bed and atmosphere. In addition, in order to absorb the wave energy reflection from end-wall and re-reflection from input boundary, artificial damping zones are located at the two ends of domain.

Boundary conditions associated with regular and irregular waves are prescribed along the inlet of computational domain. The pressure and turbulence quantities, such as k and ε, are set to be zero normal gradients. To simulate wave-structure interaction steadily for a long time, a special damping scheme is employed in front of the inlet boundary, which can be used to prevent the re-reflection from the left boundary. For the left damping zone, the velocity in this area is modified by $u_i=u_i^m+D_i'(u_i-u_i^m)$ at the end of each time step. This damping scheme is employed to damp out only the reflected waves from the structure while preserving the incident waves. Similar treatment methods are used by many researches for wave-structure interaction problem (Koo and Kim, 2007a, 2007b; Li et al., 2007, etc.). In the damping scheme, u_i^m is the theoretical wave velocity and D_i' is the dissipative coefficient, which can be written as (Troch and Rouck, 1998)

$$D_i'=\sqrt{1-\left(\frac{l-x}{l}\right)^2}, \tag{8}$$

where l is the length of damping zone. Troch and Rouck (1998) found that the elliptic type damping function performs better than the linear type and the cosine type.

At the outlet, non-reflective boundary condition combines damping zone and the radiation boundary condition. The velocity is specified by Sommerfeld radiation condition (SRC), expressed by

$$\frac{\partial u}{\partial x}+\frac{1}{c}\frac{\partial u}{\partial t}=0, \tag{9}$$

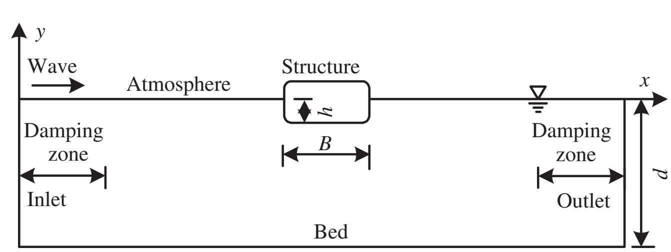

Fig. 1. Sketch of a fixed floating body.