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Numerical simulation of wave interacting with a free rolling body

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ABSTRACT: *The present study numerically models the interaction between a regular wave and the roll motion of a rectangular floating structure. In order to simulate two-dimensional incompressible viscous two-phase flow in a numerical wave tank with the rectangular floating structure, the present study used the volume of fluid method based on the finite volume method. The sliding mesh technique is adopted to handle the motion of the rectangular floating structure induced by fluid-structure interaction. The effect of the wave period on the flow, roll motion and forces acting on the structure is examined by considering three different wave periods. The time variations of the wave height and the roll motion of the rectangular structure are in good agreement with experimental results for all wave periods. The present response amplitude operator is in good agreement with experimental results with the linear potential theory. The present numerical results effectively represent the entire process of vortex generation and evolution described by the experimental results. The longer wave period showed a different mechanism of the vortex evolution near each bottom corner of the structure compared to cases of shorter wave periods. In addition, the x-directional and z-directional forces acting on the structure are analyzed.*

KEY WORDS: Wave; Roll motion; Numerical wave tank; Viscous two-phase flow.

INTRODUCTION

In the past several years offshore structures have been moved to deeper water, due to increasing interest in the development of subsea resources. Offshore structures can undergo large-amplitude motion due to harsh environments and extremely steep waves. Responses of floating bodies such as ships or offshore structures to incident waves are one of the main concerns in ocean engineering.

Offshore structures have been investigated in terms of six degree of freedom motion to evaluate design that can meet safety standards. As a result, there is an increasing interest in the use of numerical simulation to study the interaction between waves and structures. One of the most critical aspects of motions of a structure is roll, which is of practical interest for both safety and comfort reasons.

Roll motion, unlike other motions, is highly nonlinear because of the roll damping effect. However, the ability to predict roll motion lags considerably behind that of motions such as heave and pitch. Potential flow theories, based on the assumptions that the flow is inviscid and irrotational, can introduce large errors. They fail to account for viscous damping, flow separation, and vortex generation (Wehausen, 1971).

This shortfall is normally compensated by introducing a viscous roll damping coefficient. Traditionally, hydrodynamic coefficients used in the prediction of rolling motions have been obtained from empirical formulas based on experimental test results (Himeno, 1981; Ikeda and Himeno, 1981). However, it is not easy to find a proper viscous damping coefficient, or to generalize data for roll damping.

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Despite some difficulties, numerous numerical methods have been developed to simulate viscous flow. Faltinsen and Pettersen (1987) studied the separated flow and vortex generation of a blunt body and rectangularly shaped body using the vortex tracking method. Scolan and Faltinsen (1994) investigated separated flow from bodies with sharp corners using the vortex in cell method. Yeung and Vaidhyanathan (1994) considered separated flows near a free surface using the random vortex method. Unfortunately, these numerical methods require a priori knowledge of the boundary layer separation point, and are therefore difficult to apply for various problems.

Recently, many researchers have used techniques based on the solution of Reynolds averaged Navier-Stokes (RANS) equations (Korpus and Falzarano, 1997; Sarkar and Vassalos, 2000; Chen et al., 2002; Wilson et al., 2006). These methods naturally incorporate the effects of viscosity with a turbulence model, and can easily be extended to various practical problems.

Most of the above publications are concerned with problems, either with fixed bodies or forced motion. Studies of the interaction between waves and free-rolling bodies are still very limited in the available literature.

Jung et al. (2004a) experimentally investigated wave interactions with a fixed rectangular structure using particle image velocimetry (PIV) to simulate the condition of a barge in a beam sea. The mean velocity field was demonstrated along with the generation and evolution of vortices on both sides of the structure. In subsequent studies, Jung (2004b) and Jung et al. (2005) released the roll motion of the structure to investigate the two-dimensional flow characteristics of wave interactions with free-rolling rectangular structures using PIV.

In this study, we simulated the coupled interaction between a wave and a rectangular structure in rolling motion. The main purpose of the present study is the verification of a numerical method that describes wave and body interaction. The time variations of wave height and the roll motion of the rectangular structure were validated by comparison with experimental results of Jung et al. (2004a). The characteristics of flow, roll motion and the forces acting on the structure were analyzed for different wave periods.

NUMERICAL DETAILS

Numerical approach

The present two-dimensional problem of wave-structure interaction is governed by the Navier-Stokes equations and continuity equation. Once the Reynolds averaging approach for turbulence modeling is applied, the Navier–Stokes equations can be written in Cartesian tensor form as

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho \overline{u'_i u'_j}\right) + F_i \tag{2}$$

where x_i are Cartesian coordinates, u_i are the corresponding velocity components, p is the pressure, ρ is the density, μ is the viscosity, and F_i is an external body force (e.g. gravity). Also, $-\rho\overline{u'_i u'_j}$ is the Reynolds stress term that was closed by using the standard $k-\varepsilon$ turbulence model (Launder and Spalding, 1972).

The equations of motion of a rectangular structure are expressed as follows,

$$\vec{F} = m\frac{d\vec{V}}{dt} \tag{3}$$

$$\vec{L} = \frac{d}{dt}\left(I_0\vec{\omega}\right) \tag{4}$$