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Numerical study of roll motion of a 2-D floating structure in viscous flow*

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Abstract: In the present study, an open source CFD tool, OpenFOAM has been extended and applied to investigate roll motion of a 2-D rectangular barge induced by nonlinear regular waves in viscous flow. Comparisons of the present OpenFOAM results with published potential-flow solutions and experimental data have indicated that the newly extended OpenFOAM model is very capable of accurate modelling of wave interaction with freely rolling structures. The wave-induced roll motions, hydrodynamic forces on the barge, velocities and vorticity fields in the vicinity of the structure in the presence of waves have been investigated to reveal the real physics involved in the wave induced roll motion of a 2-D floating structure. Parametric analysis has been carried out to examine the effect of structure dimension and body draft on the roll motion.

Key words: OpenFOAM, CFD, potential-flow theory, roll motion, 2-D floating structure, regular waves, wave forces, viscous flow

Introduction

The hydrodynamic motions of ships and floating structures in the presence of waves need to be carefully examined during the early stage of structure design to ensure the stability characteristics or energy efficiency of the structure. In reality, a ship or floating structure experiences motion in all six degrees of freedom (DoF) simultaneously, but only roll motion will be investigated in this paper. Roll motion is the most critical motion leading to ship or platform capsizes compared to other five degrees of freedom motion of a ship or platform[1,2]. The roll motion of a ship or floating structure can be determined by solving an ordinary differential equation which contains three coefficients, the virtual mass moment of inertia for rolling, the damping coefficient and the restoring moment coefficient. The value of these three coefficients can be determined experimentally or by using mathematical methods. Among them, the damping coefficient has been considered to play the most significant role in the roll motion calculation and should be determined accurately. Model test has been one of the most common approaches used to estimate the roll damping. Generally, the body is rolled to a chosen angle and then released in calm water. The recorded roll time history is used to determine the equivalent linearized roll damping by assuming that the dissipated energy due to the nonlinear and equivalent linear damping is the same. Jung et al.[3] carried out several experiments in a 2-D wave tank to study the roll motion of a rectangular barge and concluded that the roll damping in some wave conditions helps the barge to roll. Wu et al.[4] conducted an experimental investigation to study the nonlinear roll damping of a ship in the presence of both regular and irregular waves. The recorded roll time history in calm water obtained by Wu et al.[4] had the similar trend with that obtained by Jung et al.[3].

Physical experimentation is expensive and not always practical. Numerical methods, including potential flow theory, empirical formula and viscous flow theory, have also been widely used for the prediction of the roll motion. Potential flow theory like strip theory is applied to investigate wave induced roll motion based on the assumption that the motion of a floating structure by waves is linear. Lee et al.[5] used strip theory to investigate the roll damping of a ship in beam seas and the hydrodynamic radiation damping of

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a rectangular barge, respectively. The potential flow theory has been used to predict the motion of the structure in surge, heave, pitch, sway and yaw to a reasonable degree of accuracy without any empirical correction or recourse to experiments. However, it is found that the wave damping derived from the linear potential flow theory is inadequate for an accurate prediction of the roll motion since the effect of viscous damping could be as significant as those of wave damping in roll[6].

One of the compensating methods is to introduce an artificial or empirical damping coefficient in the computation using potential flow theory to take into account the viscous effect. Chakrabarti[6] divided the total roll damping coefficient into several components, such as friction, eddy, wave damping, lift etc.. Wave damping is derived from linear potential flow theory while other components can be computed by empirical formulas. This prediction method has been applied successfully by inviscid-fluid models coupling with the strip theory[7].

The applicability of the empirical formulas is limited by the fact that the empirical coefficients are derived from extensive model tests or field measurements. Viscous models based on Navier-Stokes equations are becoming increasingly popular in engineering predictions for providing more accurate and realistic results. Zhao and Hu[8] developed a viscous flow solver, based on a constrained interpolation profile (CIP)-based Cartesian grid method, to model nonlinear interactions between extreme waves and a box-shaped floating structure, which is allowed to heave and roll only. Bangun et al.[9] calculated hydrodynamic forces on a rolling barge with bilge keels by solving Navier-Stokes equations based on a finite volume method in a moving unstructured grid. The roll decay motion of a surface combatant was predicted by Wilson et al.[10] using an unsteady Reynolds-averaged Navier-Stokes (RANS) method. The RANS method was employed by Chen et al.[11] as well to describe large amplitude ship roll motions and barge capsizing.

OpenFOAM, an open-source CFD package, is proved to provide accurate numerical predictions when applied to nonlinear wave interactions with fixed structures. Morgan et al.[12,13] has extended the OpenFOAM and reproduced the experiments on regular waves propagation over a submerged bar successfully with up to 8th order harmonics correctly modelled. The extended OpenFOAM has been applied to model nonlinear wave interactions with a vertical surface piercing cylinder and a single truncated circular column by Chen et al.[14] and Sun et al.[15], respectively. The accuracy of the models was validated by comparing with experiments. A built-in dynamic solver interDyMFoam was extended by Ekedahl[16] to simulate wave-induced motions of a floating structure. The model diverged after about 10 s for the case with a coarse mesh due to numerical discrepancies or low mesh quality. According to Yousefi et al.[17], OpenFOAM can also be applied to simulate the flow field around a hull, taking into account maneuverability, wave and free surface effects and it is gaining increasing popularity due to its excellent computational stability.

In this paper, the nonlinear interactions between regular waves and a 2-D rolling rectangular barge have been studied numerically and the results are compared with the experimental measurements collected by Jung et al.[3]. The extended OpenFOAM model developed by Chen et al.[14] is selected here for the two-phase flow modeling as well as wave generation and absorption. Two difficulties have been solved in order to extend its capability of simulating the roll motion of floating structures by waves: determining the wave-induced motion of the floating structure and moving or deforming the mesh according to this motion. The wave-induced roll motions, hydrodynamic forces on the barge, velocities and vorticity flow fields in the vicinity of the structure in the presence of waves have been investigated in this paper. Parametric analysis has been carried out to study the effect of the structure size and draft on the roll motion.

1. Numerical methods

1.1 *Flow Fields*

The extended OpenFOAM model developed by Chen et al.[14] has been selected here for the two-phase flow modelling based on the unsteady, incompressible Navier-Stokes equations. The waves are generated by introducing a flux into the computational domain through a vertical wall and the wave reflections at the end of the wave flume are dissipated by a numerical beach in the extended OpenFOAM model.

1.1.1 Governing equations

The flow fields are solved using the laminar form of the Navier-Stokes equations for an incompressible fluid as follows:

$$\nabla \cdot \boldsymbol{U} = 0 \tag{1}$$

$$\frac{\partial \rho \boldsymbol{U}}{\partial t} + \nabla \cdot (\rho \boldsymbol{U}\boldsymbol{U}) - \nabla \cdot (\mu \nabla \boldsymbol{U}) - \rho \boldsymbol{g} = -\nabla p - \boldsymbol{f}_\sigma \tag{2}$$

in which $\boldsymbol{U}$ is the fluid velocity, p is the fluid pressure and $\boldsymbol{f}_\sigma$ is the surface tension. ρ and μ are the fluid density and the dynamic viscosity, respectively.

The free surface is tracked by using the volume of fluid (VOF) method and indicated by the volume