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Numerical Simulation of Wave-induced Roll of a 2-D Rectangular Barge Using OpenFOAM

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Highlights:

- A new solver based on OpenFOAM has been developed and used for the simulation of the roll motion of a 2-D box barge in beam sea conditions. A series of new results for the effect of wave height, structure size and draft on roll motion will be discussed in the workshop.
- It is found that viscous effect not only can damp out the roll but also can increase the roll motion.

1. Introduction

Stability against capsizing is one of the key factors to be considered for ship design. The roll motion is the most critical motion leading to ship capsizes compared to other five degrees of freedom motion of a ship [1]. Moreover, there are wave energy converters aiming to extract wave energy through its roll motion in waves, such as tuned roll wave energy extractor.

The potential flow theory is not adequate to describe the motion of structures in roll because fluid viscosity is not considered. One of the compensating methods is to introduce an artificial damping coefficient in the computation to take account into the viscous effect [2]. Yet, it is difficult to determine the roll-damping coefficient for a ship or floating structure properly due to its highly nonlinear feature and cross-sectional variation. The applicability of the empirical formulas is limited by the fact that the empirical coefficients are derived from extensive model tests or field experiments [2]. The viscous models based on Navier-Stokes equations are becoming increasing popular in engineering predictions for providing more accurate and realistic results. OpenFOAM, an open-source CFD package, is proved to have provided accurate numerical predictions when applied to non-linear wave interactions with fixed structures [3]-[6].

In this paper, the capability of OpenFOAM in simulating the roll motion of a floating structure in beam sea conditions is validated by comparing to the experimental results obtained by Jung et al. [7]. A new solver based on OpenFOAM has been developed for simulating motions of floating structures in waves. The roll motions of a 2-D rectangular barge, velocities and vorticity flow fields in the vicinity of the structure under wave actions have been investigated in this paper.

2. Validation and results discussions

Experimental study on the roll motion of a box barge in beam sea conditions has been described in Jung et al. (2006). A glass-walled wave tank (35 m × 0.9 m × 1.2 m) was used for the tests with a constant water depth of 0.9 m. A rectangular structure (0.3 m × 0.9 m × 0.1 m) with a draft that equals one-half of its height was hinged at the center of gravity of the structure and it was only allowed to roll under wave actions (1 degree of freedom). The experimental setup can be seen in Fig. 1. Regular waves with wave period between 0.5 *s* and 1.2 *s* were tested in the experiments. And for the wave periods: T = 0.7, 0.93, 1.2 and 2.0 *s*, the experiments were carried out with several different wave heights to study the effect of wave height on the roll motion.

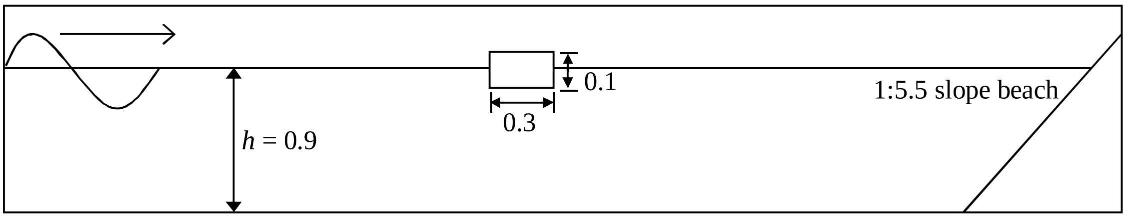

Fig. 1 Sketch of wave tank (unit: m)

In the numerical simulations, a new solver based on OpenFOAM-2.1.0 has been developed to simulate the motions of free floating structures. A damping zone is added in the computational domain to avoid reflection at the downstream end of the numerical tank.

The dynamic characteristics of the box barge including natural frequency (ω_N) and damping coefficient (ξ) are identified by using free decay test. The box is initially rotated to 15 degree and then released in the calm water condition. The time series of the successively decaying roll amplitude have been recorded and analyzed to obtain the natural frequency and damping factor [8]. The values for both experimental and numerical results are listed in Table 1.

Table 1 Dynamic characteristics of a 2D rectangular barge

Case	ω_N rad/sec	Error %	ξ	Error %
Numerical results	6.856	1.1%	0.077	27%
Experimental results	6.78	-	0.106	-

The natural frequency matches well with experiments while there is a relative large discrepancy for damping coefficient which is likely due to 2-D flow assumption and frictional damping of hinges introduced in experiments.

The investigation of the dynamic responses of the roll motion of the box is followed. Variations of the magnification factors (φ/kA, also called the response amplitude operators, in which φ is the angle of roll, k is wave number and A is wave amplitude) of the box with the dimensionless wave frequencies (ω/ω_N) were first examined. The numerical results have been compared with the experimental data and the solutions based on linear potential flow theory, shown in Fig. 2. It can be seen that the numerical results agree well with experiments in general. However, the roll motion calculated using linear potential flow theory is significantly over-predicted near the natural frequency due to the assumption that the fluid is inviscid and irrotational. Additionally, at lower frequencies, the potential flow theory underestimates the magnification factors compared to the experimental and numerical results. The possible reason is that the viscous effect neglected in potential flow theory helps to increase the roll at lower frequencies. The effect of wave height on the roll motion has been studied over a few frequencies (ω/ω_N = 1.328, 1, 0.775). It is found that the magnification factors decrease with the increase of wave height at the natural frequency while the magnification factors have the similar values at different wave heights for wave frequencies away from the natural frequency, which means that the nonlinear effect on the roll damping is significant only for the natural frequency.

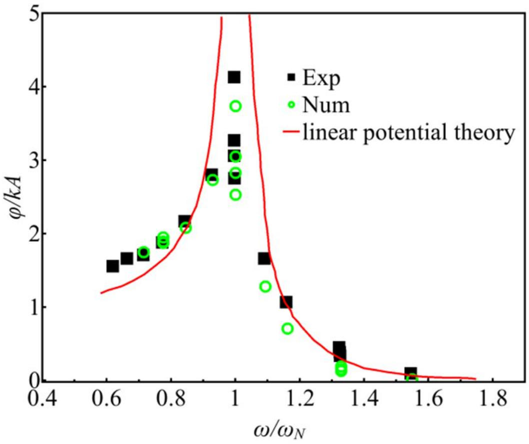

Fig. 2 Magnification factors for roll motion of 2-D box barge

The velocity and vorticity fields of T = 1.2 s (ω/ω_N = 0.775) wave close to both sides of the 2-D barge are shown in Fig.3. The barge reaches its maximum clockwise motion at Fig. 3(a) and experienced counter-clockwise motion from Fig. 3(b) - Fig. 3(c). It can be seen from Fig. 3 (a) and 3(b) that after a short period of time, the negative vortex (black) diffuses and a positive vortex (white) appears. The positive vortex helps the box to roll due to its position being "ahead" of the rolling direction. The barge reaches its maximum counter-clockwise position at Fig. 3 (d) and experiences clockwise motion from Fig. 3(e) – Fig. 3(f). Similar to the counter-clockwise motion, the positive vortex diffuses quickly and negative vortex appears which helps to increase the clockwise motion. In other word, the viscous effect helps increase the roll motion at lower frequencies which is observed in Fig. 2.l.

3. Conclusions

From the preliminary results, we conclude that the newly developed model based on OpenFOAM can accurately predict the roll motion of a rectangular structure by waves. And the investigation on the velocity and vorticity fields reveals that the viscous effect not only can damp out the roll motion but also can help the structure to roll. Further examples of the validation and the effect of the structure size on the roll motion will be presented on the workshop.

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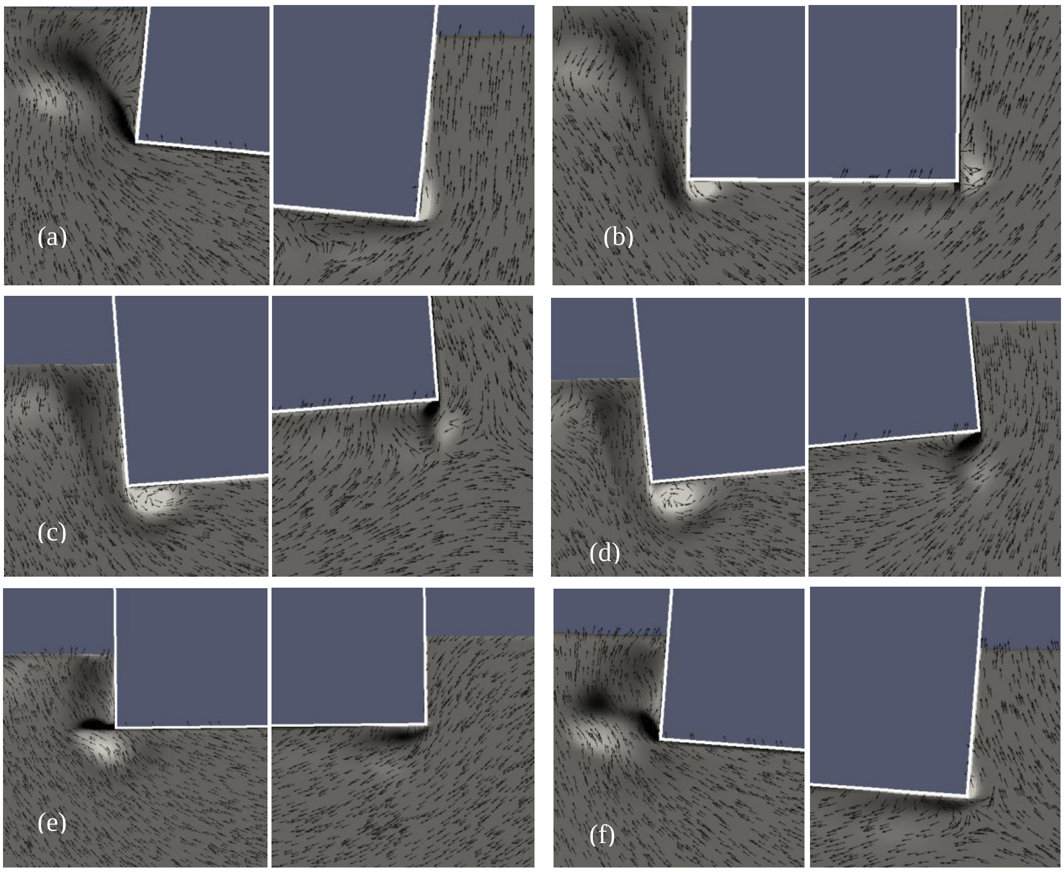

Fig. 3 Velocity and vorticity flow fields of T = 1.2 s waves (ω/ω_N = 0.775)