Numerical Study on Focused Wave Interactions with a Moored Floating Structure

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ABSTRACT

Accurate prediction of the motion of a wave energy converter and the loads acting on it is of great significance in the design procedure. In this work, the interaction between focused waves and a hemispherical-bottomed buoy is simulated using the in-house CFD solver naoe-FOAM-SJTU. The time histories of three focused waves at several positions are presented and compared with experimental data from the CCP-WSI working group. The effects of wave steepness on motion responses of the hemispherical-bottomed buoy and the loads in the mooring system are presented and discussed.

KEY WORDS: Wave-structure interactions; naoe-FOAM-SJTU solver; focused wave; wave force; mooring loads

INTRODUCTION

Under extreme wave conditions, strong non-linear impact phenomena such as severe wave run-up, relative motion and green water may occur, which will cause a large local impact load on wave energy converters (WECs). Exploring interaction between waves and WECs have great importance for the design and protection of WECs. So accurate prediction of the motion of a WEC and the loads acting on it is of great significance in the design procedure. Numerous researchers have done experimental and numerical studies on this problem.

Previously, Savin et al. (2012) experimentally measured lateral force acting on the funnel under two sea states. Two measurements were taken by two separate measuring systems with slightly different timing. The development of the method could be used for evaluation of the forces from waves acting on the WEC. Azimuth-inclination angles and snatch load on a tight mooring system are mainly discussed in their work. Hann et al. (2015) concerned experimental measurements of the interaction of a taut moored floating body, representing a WEC in survivability mode, with extreme waves. Focused wave groups, based initially on NewWave theory, were used to generate the extreme waves, with crest amplitude exceeding the mooring's design capacity. They discussed the influence of wave steepness effect on model response and mooring load using a focused wave groups. Goteman et al. (2015) considered the survivability of a 1:20 scale point-absorbing WEC model in extreme wave tests with focused waves embedded in regular waves and irregular waves. Experimental results of the forces were presented. Mai et al. (2016) performed experiments to examine wave-structure interactions for a series of simplified FPSO-shaped bodies.

Besides experimental investigation on wave interaction with floating structures, numerical methods have also been widely used in dealing with this problem. Wolgamot and Fitzgerald (2015) reviewed efforts that have been made to analyze wave energy converter behavior and performance using nonlinear hydrodynamics methods. They affirmed the potential advantages of solving the wave-structures interaction by CFD methods. Sykes et al. (2009) provided a preliminary assessment of the validity of employing a BEM code to predict the displacement and associated hydrodynamic properties of a simple floating OWC. Bredmose and Jacobsen (2010) computed extreme wave loads from breaking waves on a monopile foundation within a 3D CFD model. The wave impacts were obtained by application of focused wave groups to the amplitudes of a JONSWAP spectrum. The CFD results were compared to loads estimations obtained from the Morison equation. Westphalen (2011) applied two commercial Navier-Stokes solvers to solve wave-wave and wave-structure interaction problems leading to the final application of simulating a single float of the WEC. Pakozdi et al. (2011) simulated a long crested breaking wave and its impact on a cylinder and deck structure in order to find out the feasibility of the numerical reconstruction of such events, by Star-CCM++. In their study, the nonlinear wave propagation over long distance was simulated accurately and efficiently by solvers based on potential flow theory. Li and Lin (2012) studied fully nonlinear wave-body interactions for a stationary floating structure under regular and irregular waves for different water depths, wave heights and periods in a 2-D numerical wave tank. Palm et al. (2013) presented incompressible Navier-Stokes simulations of the dynamics of a floating WEC coupled to a high-order finite element solver for cable dynamics by open source code OpenFOAM. Ransley et al. (2015) used a numerical tool based on OpenFOAM to simulate focused wave impacts on generic WEC hull forms. Two floating structures: a fixed truncated surface-piercing
cylinder and a floating hemispherical-bottomed buoy with a linear spring mooring were simulated. The results have been validated against the experimental data. Ransley (2015) also discussed the development of a numerical wave tank and its capability of simulating the coupled behavior of WECs and the moorings under extreme wave loading. Palm et al. (2016) numerically simulated a moored floating vertical cylinder in six DoFs based on OpenFOAM. The coupling was implemented between the native six DoF motion solver of OpenFOAM and an in-house mooring code, MooDy. Bharath et al (2016) applied a non-linear, viscous volume of fluid RANS model to simulate the diffraction and radiation problems for a single heaving submerged spherical WEC. The CFD work undertaken could be extended to the study of arrays of generic WECs and to develop a greater understanding of WEC interactions in various array configurations. Wagner et al. (2016) performed hydrodynamic analysis of oscillation of a submerged plate (WEC) due to nonlinear shallow water waves. Lou (2017) studied the coupled fluid-structure interaction (FSI) of a WEC and evaluated the design of a WEC mooring system. Palm et al. (2018) analyzed the nonlinear forces on a moored point-absorbing WEC in resonance at prototype scale (1:1) and at model scale (1:16). They recommended that both RANS and Euler simulations could be used during numerical validation against experimental model scale tests in order to separate the viscous drag influence from the induced drag. Consequently, this approach could be used to quantify the effects of scale on wave energy converters. Paci (2018) created an open source numerical model able to simulate every kind of harbour and offshore structure, both fixed and floating. The code called IHFOAM was developed based on OpenFOAM and was able to reproduce a physical wave tank and could be used during the design phase as an integration to physical tests. Lim et al. (2018) carried out prediction of the long-term extreme response (surge motion) of a simple moored floating offshore structure using polynomial chaos expansion.

All methods mentioned above including experimental methods, potential flow theory and CFD methods can predict the loading and dynamic response of WECs in large nonlinear waves (Coe and Neary, 2014). Well-targeted validation work has the potential to better determine which of these methods is best suited to each stage of a WEC survival analysis. So a systematic approach must be employed to the survival aspect of WEC design.

Present work is part of the comparative study on focused wave interactions with floating structures. The objective of the present work is to investigate the interaction between focused waves and a hemispherical-bottomed cylinder. In this paper, present CFD calculations are performed by the in-house CFD solver n Saoe-FOAM-SJTU. The time history of focused wave at target location was compared with the experimental data provided by CCP-WSI working group. The results show that the current approach can be an alternative tool to generate focused waves according to experiment. The free surface elevation in the vicinity of the structure is captured by 13 wave gauges. The effects of wave steepness on motion of the floating structure and the load in the mooring system are presented and discussed. Under our present in-house CFD solver, the floating structure with mooring system through nonlinear wave can be solved and analyzed accurately.

NUMERICAL METHODS

Governing Equations

Based on the open source platform OpenFOAM, the CFD solver n Saoe-FOAM-SJTU is designed for computing viscous flows around ocean structures (Wang et al., 2016; Zhao and Wan, 2016; Wang and Wan, 2018; Zhao et al., 2018). Compared to the OpenFOAM standard solver, the n Saoe-FOAM-SJTU solver is complemented with a wave generation and damping module, a wave probe module, a 6DoF motion module, a mooring system module and turbulence models. It can be used to simulate wave-structure interaction. The governing equations of incompressible viscous fluids in n Saoe-FOAM-SJTU solver are as follows:

\[ \nabla \cdot \mathbf{U} = 0 \]  
\[ \frac{\partial \rho \mathbf{U}}{\partial t} - \nabla \cdot (\rho \mathbf{U} \mathbf{U}) = \nabla \cdot \sigma + \mathbf{f}_d + f_s + \mathbf{f}_w + \mathbf{f}_m + \mathbf{f}_t + \mathbf{f}_\sigma \]  

where \( \mathbf{U} \) and \( \mathbf{U}_d \) are the velocity field and the velocity of grid nodes, respectively, \( \rho_d \) is the dynamic pressure and \( \rho \) is the total pressure, \( \rho \) is the mixed density of the two phases water and air. \( \mu_{eff} \) is the effective dynamic viscosity, in which \( \nu \) and \( \nu \) are kinematic viscosity and eddy viscosity, respectively. \( f_s \) is the surface tension, which impacts the free surface. \( f_w \) is a source term, added to generate the sponge layer for wave absorbing.

Numerical Wave Tank

The numerical simulations in this work are performed in a numerical wave tank based on the in-house n Saoe-FOAM-SJTU solver. VOF method (Hirt and Nichols, 1981) with artificial bounded compression techniques is adopted to capture the free surface. Three wave making modules including piston-type wave maker, flap-type wave maker and velocity inlet are extended to the in-house n Saoe-FOAM-SJTU solver (Shen et al., 2015; Wang et al., 2015; Wang and Wan, 2016). The velocity inlet (Dirichlet-type boundary conditions) is adopted to generate the irregular waves according to the existing wave theory in this work. To avoid wave reflection, a sponge layer is setup at the outlet of the computational domain by adding a source term \( f_s \) into Eq. (2). With the dynamic grid technique, the full 6DoF motion solver is used to simulate the motion of the buoy.

Moorings System

Moorings system is important for the prediction of the WEC motion. In order to model the mooring system in the CFD simulation, an equivalent spring system for 6DoF motion is implemented to n Saoe-FOAM-SJTU solver. Thus, the motion can be modeled by means of a mass-spring-damping system. The natural frequency of this mass-spring system can be given as:

\[ f_s = \frac{1}{2\pi} \sqrt{\frac{k}{m + \Delta m}} \]

where \( k \) is the equivalent stiffness of the mass-spring system, \( m \) is the mass of the WEC, \( \Delta m \) is the added mass of the WEC submerged in water. For natural rotation frequency, it can be described as:

\[ f_w = \frac{1}{2\pi} \sqrt{\frac{k}{J + J_a}} \]

where \( k \) is the equivalent rotation stiffness of the mass-spring system, \( J \) is the moment of inertia of the WEC, \( J_a \) is the added moment of inertia of the WEC submerged in water. Each spring line can be defined by four physical parameters: pretension, stiffness, anchor and fairlead.

Discretization Schemes

The finite volume method (FVM) is adopted to discretize the RANS and VOF transport equations in OpenFOAM. Van Leer scheme is applied for VOF equation. The merged PISO-SIMPLE algorithm is used to solve the coupled equation of velocity and pressure. The
convection terms are solved by a second-order TVD limited linear scheme, and the diffusion terms are approximated by a second-order central difference scheme.

GEOMETRY AND TEST CONDITIONS

Present work is part of the comparative study on focused wave interactions with floating structures. The physical experiments were performed in the COAST Laboratory Ocean Basin at Plymouth University, UK. The wave tank is 35 m × 15.5 m and has 24 flap-type, force feedback-controlled wave makers with a hinge depth of 2 m. The water depth at the wave makers is 4 m with a linear slope to the working area, where is 3.0 m deep. There is a parabolic absorbing beach at the end of the tank (Fig. 1). Fig. 2 indicates the layout of 13 wave gauges and in the current study.

Fig. 1 Physical wave tank

A hemispherical-bottomed buoy with the radius of the hemisphere and the cylinder equal to 0.25 m is placed at wave gauge 5. The height of the cylindrical section is also 0.25 m. The draft of the buoy is 0.322 m and z position of CoM is -0.141 m. Fig. 3 shows the physical model in both experiments and numerical simulations. The mooring attachment is located at the bottom-most point of the hemisphere on the axial line. The mooring used is a linear spring with a stiffness of 67 N/m and a rest length of 2.224 m. The pretension in the mooring is 32.07 N.

Fig. 3 Geometry of the physical model

The velocity inlet method is adopted to generate the focused waves in this work. The focused waves are generated based on a JONSWAP spectrum. Table 1 shows the wave parameters for both empty wave tank simulation case and floating buoy case. Those three cases are different on wave steepness. Each wave was created by COAST using linear superposition of 244 wave fronts with frequencies evenly spaced between 0.101563 Hz and 2 Hz and a theoretical focus location \( x = 14.8 \) m from the wave generation boundary.

Table 1. Wave parameters for each test

<table>
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<th>CCP-WSI ID</th>
<th>An</th>
<th>fp</th>
<th>h</th>
<th>Hs</th>
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<td>(hz)</td>
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<td>0.274</td>
<td>0.128778</td>
</tr>
<tr>
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<td>0.4</td>
<td>3.0</td>
<td>0.274</td>
<td>0.193167</td>
</tr>
<tr>
<td>3BT3</td>
<td>0.32</td>
<td>0.4</td>
<td>3.0</td>
<td>0.274</td>
<td>0.206044</td>
</tr>
</tbody>
</table>

Numerical Models

Using the CFD solver nase-FOAM-SJTU, the focused wave is simulated without and with the floating hemispherical-bottomed buoy. According to the physical experiment, the numerical domain was set to \( 0 < x < 27 \) m, \(-4 < y < 4 \) m, \(-4 < z < 2 \) m. The computational domain is shown in Fig. 4. Fig. 5 shows the computational mesh around the hemispherical-bottomed buoy. The total grid number is about 2.31 million for the case without the buoy and 2.97 million for the case with the buoy. Wave generation in the physical wave tank is made with a velocity inlet method. The wave generation boundary is located at \( x = 0 \) m. The hemispherical-bottomed buoy is placed at \( x = 14.8 \) m away from the inlet. The boundary conditions are as follows: Velocity inlet boundary condition is adopted. Zero-Gradient condition is applied at the outlet. Slip boundary condition was considered at the bottom and at side boundaries. Non-slip boundary condition was set at the buoy surface. The turbulence was modelled by laminar. The time step is 0.005 s for empty tank cases and 0.0008 s for cases with the floating hemispherical-bottomed buoy.

RESULTS AND DISCUSSION

Grid Convergence Study
Firstly, a grid convergence study has been carried out to validate the accuracy of the current numerical model. For case 1BT3, four different meshes are adopted in grid convergence study. The total grid number of coarse mesh, medium mesh, fine mesh and finer mesh is 1.75M, 2.31M, 3.52M, and 7.13M, respectively. The time step is 0.005 s in each case. As shown in Fig. 6(a) and Fig. 6(b), the focused wave crest of coarse mesh is obviously lower than other cases and the error of wave phase is larger than other cases. This mesh is not sufficient for the simulation of focused wave in this work. As the grid is refined, the focused wave amplitude approaches the experimental data monotonically. The wave amplitude of medium mesh shows little difference with fine mesh case and finer mesh case, as shown in Fig. 6(b). The error of focused wave amplitude between medium mesh and experimental data is within 3%. To save computational resource, the medium mesh is used for the remaining simulations in the present work.

To validate wave generation and propagation in naoe-FOAM-SJTU solver, the numerical results are compared with experimental data provided by CCP-WSI. The time histories of wave elevations at 13 wave gauges along the wave tank are presented for the three cases are presented in Fig. 7, Fig. 8 and Fig. 9, respectively. The time history of free surface elevation at the focused location \( x=14.8 \, \text{m} \) without hemispherical-bottomed buoy is investigated. As can be seen, the numerical results show good with experimental data, especially at the focused location \( x=14.8 \, \text{m} \) (wave gauge 5). A sharp wave crest can be found at the focused time in both experiment and numerical simulations. After the focused time, the amplitude of surface elevation decreases, as the energy content of the wave decreases. Moreover, as shown in Fig. 7- Fig. 9, with the increasing of the wave steepness, non-linear phenomenon of focused wave is more obvious. The focused wave crest of case 3BT3 is sharper than the other two cases. The wave amplitude at wave gauge 5 is within 3% of the experimental value for the three cases. For all wave gauges, the numerical results of wave elevation after focused time are larger than the experimental data. This may due to different wave generation methods between experiment and numerical simulation. However, the concerned wave crest and wave trough at focused time are almost consistent with experiment. It can be observed that the main crests at some wave gauges (e.g. wave gauge 2) are larger than the experimental results. This is more obvious for steeper wave case. And the oscillation of the surface before and after the largest crest is more evident than the experimental results. This may be caused by the effect of oblique bottom of wave tank. In our naoe-FOAM-SJTU, the water depth can be only set as constant 3 m in wave generation dictionary, while in experimental setup, the water depth changes from 4 m to 3 m in the front of wave tank \( (x = 0-7.8 \, \text{m}) \). This can result in over-estimation of wave elevation at some locations. The results indicate that the focused wave in experiment is well replicated by naoe-FOAM-SJTU solver.

**Wave Elevation without Hemispherical-bottomed Buoy**

To validate wave generation and propagation in naoe-FOAM-SJTU solver, the numerical results are compared with experimental data provided by CCP-WSI. The time histories of wave elevations at 13 wave gauges along the wave tank are presented for the three cases are presented in Fig. 7, Fig. 8 and Fig. 9, respectively. The time history of free surface elevation at the focused location \( x=14.8 \, \text{m} \) without hemispherical-bottomed buoy is investigated. As can be seen, the numerical results show good with experimental data, especially at the focused location \( x=14.8 \, \text{m} \) (wave gauge 5). A sharp wave crest can be found at the focused time in both experiment and numerical simulations. After the focused time, the amplitude of surface elevation decreases, as the energy content of the wave decreases. Moreover, as shown in Fig. 7- Fig. 9, with the increasing of the wave steepness, non-linear phenomenon of focused wave is more obvious. The focused wave crest of case 3BT3 is sharper than the other two cases. The wave amplitude at wave gauge 5 is within 3% of the experimental value for the three cases. For all wave gauges, the numerical results of wave elevation after focused time are larger than the experimental data. This may due to different wave generation methods between experiment and numerical simulation. However, the concerned wave crest and wave trough at focused time are almost consistent with experiment. It can be observed that the main crests at some wave gauges (e.g. wave gauge 2) are larger than the experimental results. This is more evident for steeper wave case. And the oscillation of the surface before and after the largest crest is more evident than the experimental results. This may be caused by the effect of oblique bottom of wave tank. In our naoe-FOAM-SJTU, the water depth can be only set as constant 3 m in wave generation dictionary, while in experimental setup, the water depth changes from 4 m to 3 m in the front of wave tank \( (x = 0-7.8 \, \text{m}) \). This can result in over-estimation of wave elevation at some locations. The results indicate that the focused wave in experiment is well replicated by naoe-FOAM-SJTU solver.
Fig. 7 Wave elevation at different wave gauges for case 1BT3

Fig. 8 Wave elevation at different wave gauges for case 2BT3
Wave interaction between focused waves and Hemispherical-bottomed Buoy

Fig. 10 shows a series of snapshots of free surface around the hemispherical-bottom buoy during the interaction between focused wave crest and the buoy. When the wave encounters and passes the buoy, buoy moves in heave, surge and pitch with relatively large amplitude. This may have great influence on mooring loads. Strong nonlinearity including run-up and diffraction in the vicinity of the buoy can be found. The mooring effect is also included in the simulation as shown in the Fig. 10.

Buoy Motion Responses

To analyze the buoy’s motion response, the time histories of surge, heave and pitch motion are presented in Fig. 12-Fig. 14, respectively. Generally, the motion in surge, heave and pitch increases with the increasing wave steepness. For surge motion, the displacement of the buoy can reach almost one radius of buoy, which is about 67% larger than the other two cases. The heave motion of the buoy shows similar effect. The displacement is close to one radius for case 2BT3 and 3BT3. As shown in Fig. 14, the second peak of pitch motion is larger than the first peak.
CONCLUSIONS

Present work is part of the comparative study on focused wave interactions with moored floating structures from CCP-WSI working group. This paper applied the in-house CFD solver naoe-FOAM-SJTU to simulate interaction between focused wave and a hemispherical-bottomed buoy. The focused waves with three different steepnesses in empty wave tank are firstly simulated. The time history of focused wave in experiment is well reproduced by naoe-FOAM-SJTU solver, although the oscillation of the surface before and after the largest crest is more evident than the experimental results. This may due to the effect of the slope in the front of the tank. Then a moored hemispherical-bottomed buoy is placed in the numerical wave tank. The effects of wave steepness on motion of the buoy and the wave load are discussed. The incident wave steepness will affect both wave forces and buoy's motion. The first peak and second peak of wave force increases with the increasing steepness. As expected, the same effect can be observed in buoy's motion. The results show that under our present in-house CFD solver, the focused wave interaction with moored floating structures can be solved accurately.

ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China (51879159, 51409075, 11432009, 51579145), Chang Jiang Scholars Program (T2014099), Shanghai Excellent Academic Leaders Program (17XD1402300), Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning (2013022), Innovative Special Project of Numerical Tank of Ministry of Industry and Information Technology of China (2016-23/09) and Lloyd’s Register Foundation for doctoral student, to which the authors are most grateful.

REFERENCES


