Numerical Study of Focused Waves Acting on a Fixed FPSO-Shaped Body

Yuan Zhuang and Decheng Wan*
State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean and Civil Engineering
Shanghai Jiao Tong University, Shanghai, China

This paper applies our in-house solver, naoe-FOAM-SJTU to study focused waves acting on a fixed FPSO-shaped body. This benchmark test follows the settings of experiments conducted in the Ocean Basin at Plymouth University’s COAST Laboratory. The different headings and different wave steepness are considered to figure out how the focused waves act on the fixed model. The values of wave height in different positions of the empty wave tank are obtained through computations and verified by experimental results. The scattered wave height and impact pressure on the hull are provided. The results of the wave and the corresponding pressure on the hull are compared with CCP-WSI Blind Test Workshop to ensure the accuracy of the calculation. The influence factor of incident wave angle and wave steepness is discussed.

INTRODUCTION

For offshore structures, it is essential to study the hydrodynamic loads on those structures operating in the hostile environment. On the one hand, the designation and operation need to avoid structure damage and loss on work stoppage, thus the severe sea states must be considered. Dangerous extreme waves like focused waves may impact marine architectures that are dispatched to a particular place for a long-term production operation. Under these conditions, the FPSO may suffer damage on ship bow. On the other hand, the wave—wave interaction may transfer high-frequency energy to the structure. Those wave-induced high frequencies may cause nonlinear structure behaviors. Therefore, it is necessary to investigate offshore structures in hostile sea states.

It is known that the focused wave has significant characteristics of randomness. Thus, the real sea state statistics can hardly be recorded. One striking case is the “New Year Wave,” which happened in the central North Sea at Statoil Draupner Platform on Jan 1st, 1995. The peak crest elevation reached 18.5 m, while the significant wave height there is 12 m (Bihs et al., 2017). Because focused waves only rarely appear in nature currently, the main approaches to study its generation and hydrodynamic properties are experimental and numerical methods. As the potential method cannot solve the extreme sea states with strong nonlinear phenomena, the advantages of computational fluid dynamics (CFD) method arouse widespread concern in shipbuilding engineering. However, the range of model fidelity still remains considerably uncertain when simulating the interaction of waves with offshore structures when using numerical methods. To deeply understand these issues, the wave—structure interaction and the wave evolution of the focused waves are studied in this paper.

Experiments are usually carried out in water flumes using wave paddles to generate focused waves. By adopting a focused wave group, many irregular wave components in a spectrum will focus at the designated time and place simultaneously. Previous methods included frequency focusing method (Chaplin, 1996) and modified phase and amplitude wave maker control signal to make optimized focused waves (Schmittner et al., 2009). Nevertheless, the effectiveness of their linear wave theory decreased when the wave groups were high nonlinearity. Stagonas et al. (2014) implemented an empirical iterative methodology which can generate focused waves at designated time and space with any height. By controlling the frequency spectrum and phase of the wave components, the extreme wave profile can be formed in a short time and focused at the designated time and location, this making the physical experiments and numerical simulation more efficient. Several experiments have been done to investigate the focus waves and the interaction between wave and structure. Ning et al. (2009) conducted experimental and numerical studies on a series of steep focused wave groups in a water flume. By using high order boundary element method, their calculation results fitted the experimental results well, even for the waves near to breaking. As for high-order boundary element method, a domain decomposition technique is implemented by Bai and Taylor (2007) to make this method more efficient. To investigate the wave—structure interaction, a simplified FPSO model was set in the Ocean Basin at Plymouth University’s COAST Laboratory (Mai et al., 2016). This experiment took the model length, and focused wave steepness and incident wave angles into account. Results were given and analyzed with a general phase-based harmonic separation method. In addition, based on the experiment of COAST laboratory, several numerical methods are used for further research. Based on the fully nonlinear potential theory (FNPT), Ma et al. (2015) used the Quasi Arbitrary Lagrangian Eulerian Finite Element Method (QALE-FEM) combined with modified time domain self-correction technique. The results are in good agreement with the experimental results. Hu, Greaves, and Raby (2016) and Hu, Mai, et al. (2016) then took advantage of the computational fluid dynamics to do corresponding numerical simulations using open source code OpenFOAM. The comparison of calculation results shows OpenFOAM is reliable to solve the hydrodynamic problems of wave—structure interaction. Yan et al. (2015) applied unidirectional focusing waves and a cylinder based on QALE-FEM with FNPT and OpenFOAM coupled with potential theory. They compared those two methods when simulating the focusing waves and the cylinder.

In the present studies, CFD method based on Navier-Stokes equations is used to solve high nonlinear free surface focused
wave problems and wave—structure interaction problems. With high performance computers, this numerical method is more popular in shipbuilding and ocean engineering fields. Considering the fluid viscosity, the results of CFD method are closer to physical experimental results. Currently, this method is gradually being recognized by engineering designers. Plenty of numerical simulations and validation works have been done by researchers throughout the world. This calculation method can be divided into Euler method and Lagrange method. The former method use meshes to calculate the velocity, pressure, and other parameters in the global flow field. The free surface capture methods include VOF and Level set methods. Through calculating the water and air fraction in each mesh, VOF is able to show the free surface information. Focusing on the problems of extreme waves, Westphalen et al. (2012) adopted commercial CFD packages STAR-CCM+ and Ansys CFX 11, using a finite volume approach and a control-volume finite element method to do numerical calculations. The results showed that CFD tools are powerful for offshore structure design, and able to solve high nonlinear interaction problems. Chen et al. (2014) applied open source code OpenFOAM to assess its performance when solving the nonlinear wave—structure interactions. The results showed OpenFOAM could model this problem accurately, capture up to fourth order harmonic and depict the whole field information. Another OpenFOAM application case was made by Hu, Greaves, and Raby (2016). The focused waves were generated using new wave boundary condition. The work in this article was systematic and logical. Again, the reliability and accuracy of OpenFOAM was proved. Level set is another method to depict fluid free surface. The open source CFD code REEF3D is commonly used to solve various wave hydrodynamics and wave—structure interaction problems in ocean and offshore engineering based on level set method. Kamath et al. (2016) conducted and evaluated a series of numerical simulations on plunging breaking wave forces that impacted on the vertical cylinder using REEF3D. Bihs et al. (2017) simulated the interaction between focused waves and vertical cylinder, together with the analysis of the breaking focused waves using REEF3D. In addition, a flexible Lagrangian technique of CFD, smooth particle hydrodynamics (SPH), has been used to simulate various wave—structure interaction problems. Nonlinear wave profiles and dynamics are studied using SPH method by researchers (Omidvar, 2010; Lind et al., 2016). With regard to the discretization scheme, finite element method (FEM) has also been adopted in some studies; Hildebrandt and Srinam (2014) used FNPT-FEM to simulate the focused wave interaction with a cylinder. The numerical results were verified, and the features of pressures on the cylinder surface and the vortex shedding around the cylinder were discussed. It shows that SPH method is also a reliable method for wave—structure interaction problems. In addition to the above method, a fully nonlinear potential flow solver combined with CFD solver was adopted by Paulsen et al. (2014) to make the calculation more efficient. Four different complex cases were conducted. The good comparison with experimental results showed that this method is feasible.

The objective of this paper is to do numerical simulations of focused waves with three wave steepnesses and three incident wave angles ($0^\circ$, $10^\circ$, $20^\circ$). The pressure on the surface of a fixed FPSO-shaped model and wave elevation around the model are calculated. All the numerical simulations are carried out by the in-house CFD code naoe-FOAM-SJTU. Our in-house solver has developed a wave maker module, which can generate irregular waves like the focused wave. First, the values of wave height in different positions of the empty wave tank are obtained through computations and compared with CCP-WSI experimental results. After that, the focused wave interaction with FPSO model is simulated, and the scattered waves around the hull are analyzed. The runup phenomenon around the FPSO hull is showed, and the pressure data corresponding to six cases are given. The nonlinearity of the wave—wave interaction, wave elevation phenomenon, and wave load on the structure characteristics are discussed.

### NUMERICAL MODEL

The numerical simulation of two-phase flow in this paper adopts our in-house solver naoe-FOAM-SJTU (Shen et al., 2014), which is based on the default solver interDymFoam in OpenFOAM. For wave—structure interaction problems of ocean engineering and hydrodynamics of ship motion, modules of wave generation/damping and six-degree-of-freedom (6DOF) and others are developed and integrated into this solver. As the Reynolds number is relatively small in wave generation simulation, the laminar model is selected, which means the turbulence model is not considered when solving the Navier-Stokes equations. The relevant mathematical formula details used in this solver can be seen as follows.

#### Governing Equations

The fluid here is considered as unsteady, incompressible with viscosity. First, the Navier-Stokes equations are integrated and calculated over the whole space and time domain. The N-S governing equations are

$$
\nabla \cdot \mathbf{U} = 0
$$

$$
\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla (\rho \mathbf{U} \cdot \mathbf{U}) = -\nabla P_d - \rho \mathbf{g} \cdot \mathbf{x} + \nabla (\mu \nabla \mathbf{U}) + \mathbf{f}_d
$$

where $\rho$ is the density of the water, which is 1,000 kg/m$^3$ in this paper; $\mathbf{g}$ and $\mu$ denote the gravity acceleration vector and the dynamic viscosity of fluid, respectively; $\mathbf{U}$ is the velocity of the fluid while $U_x$ is the velocity of grid nodes; $P_d = P - \rho \mathbf{g} \cdot \mathbf{x}$ is dynamic pressure of the fluid flow field. $f_d$ here represents the source item. The solution is discretized into cells and time steps. The pressure—velocity coupling is solved by PIMPLE algorithm with an iterative procedure.

#### Free Surface Capture

In the present work, the volume of fluid (VOF) method is applied to capture the interface by tracking the water and air fraction in each cell (Hirt and Nichols, 1981). If the volume fraction value is $\alpha$, the state of each cell is as follows:

$$
\alpha(x, t) = \begin{cases} 
\alpha = 1 & \text{water} \\
0 < \alpha < 1 & \text{air} \\
\alpha = 0 & \text{free surface}
\end{cases}
$$

Usually, the contour with the cell volume fraction $\alpha = 0.5$ is extracted to represent the free surface. The advantages, such as good mass conservation, computational efficiency, and easy implementation, have made the VOF method one of the most popular methods (Cao and Wan, 2015).

#### Wave Generation and Sponge Layer

Before the calculation of the pressure on the structure, the part of wave generation is of vital importance, since it will affect the
where \( \eta \) is the elevation of the free surface, \( N \) is the total number of the wave components, \( A_j \) is the amplitude of the wave component \( j \), whose angular frequency, wave number, and phase is \( \omega_j, k_j \) and \( \varepsilon_j \) respectively. To ensure the amplitude of each wave component focus at a specified time \( T_f \) and location \( X_f \), phase \( \varepsilon_j \) will be set as the following equation:

\[
e_j = k_jX_f - \omega_jT_f
\]

Same with the physical wave tank, waves are also absorbed at the end of the tank in numerical wave tank to reduce the wave reflection from outlet boundary. The wave absorbing method is added in the naoe-FOAM-SJTU solver. Sponge layer is applied by adding an artificial viscous term to the source term of the momentum equation. The term is expressed as

\[
f_s = -\mu_s U
\]

where \( \mu_s \) is the artificial viscosity set by the following equation:

\[
\mu_s(x) = \begin{cases} 
\alpha_s \left( \frac{x - x_0}{L_s} \right)^2, & x > x_0 \\
0, & x \leq x_0
\end{cases}
\]

where \( \alpha_s \) is damping strength coefficient for the sponge layer. \( L_s \) is the length of the sponge layer, and \( x_0 \) is its beginning position. It can be understood more clearly through Fig. 1. The figure shows the arrangement of the wave generation in numerical computational domain. It gives the numerical velocity inlet and outlet with setup of sponge layer, as well as the focused wave point.

**CASE DESCRIPTION AND NUMERICAL DOMAIN**

In this paper, a fixed FPSO simplified model is subjected to six focused waves with different wave steepness (\( kA = 0.13 \), 0.18, and 0.21) and the different incident angle (\( \alpha = 0^\circ \), 10°, and 20°). Forces are calculated and compared to assess the influence caused by the factor of wave steepness.

**Physical Model and Experimental Configuration**

The physical model chosen was the same as that used in the experiment done in the Ocean Basin at the University of Plymouth’s COAST Laboratory; the structure (M3) has vertical sides and each end is semi-circular with the same radius (0.15 m). The full height of the structure is 0.303 m and the draft is 0.153 m, as shown in Fig. 2. Similar to the model used in experiments (Mai et al., 2016), Fig. 2 shows the physical model in numerical simulation. Table 1 illustrates the wave parameters for both the wave fields test case and fixed FPSO-shaped body case. Each wave was created using linear superposition of 244 wave fronts with frequencies evenly spaced between 0.101563 Hz and 2 Hz and a theoretical focus location, \( x_0 \), 13.886 m from the wave inlet boundary. The amplitudes of the frequency components were derived by applying the NewWave theory to a JONSWAP spectrum with the parameters in Table 1 where Alpha is the angle of propagation relative to the centerline of the basin and Phi is the phase of the components at the focus location.

The wave gauges were positioned differently in cases with and without the model to make the wave gauge displacement more clear. The setup of wave gauges are from Hu et al. (2016). For cases 21BT, 22BT, and 23BT, wave gauges 7, 11, 12, 15, 16, and 17 will be analyzed. In order to analyze the wave—structure interaction in detail, only wave gauges 15, 16, 17, 24, and 7 will be considered. Meanwhile, time series of pressure in 1, 2, 3, 4, 6, and 8 will be analyzed. The wave parameters for each of the test cases are shown in Table 1.

According to the physical experiment, a computational domain is built as the model of numerical wave tank (NWT). The sketch of computational domain is demonstrated in Fig. 3. The length, width, and depth of the NWT are 23 m, 4 m, and 2.93 m, respectively. The FPSO model is set at the focused position, and the distance from the bow and the inlet boundary is 13.886 m. To prevent the reflection of the waves at the end of the numerical wave tank, a 3-meter length sponge zone is set near the outlet boundary to reduce wave amplitude.

To ensure the steady propagation and lower damping of focusing waves, in free-surface mesh refinement layer, the number of the grid is more than 40 in one focused wave height and more than 80 in one characteristic wavelength. Usually, as the reflection

![Fig. 1 A diagram of the position of sponge layer in computational domain](image)

![Fig. 2 Geometry of FPSO-like body](image)

Table 1 Wave parameters for each of the test cases

<table>
<thead>
<tr>
<th>ID</th>
<th>( A ) (m)</th>
<th>( T_p ) (s)</th>
<th>( H ) (m)</th>
<th>( H_s ) (m)</th>
<th>( kA )</th>
<th>Alpha (rad)</th>
<th>Phi (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11BT1</td>
<td>0.06914</td>
<td>1.456</td>
<td>2.93</td>
<td>0.077</td>
<td>0.13</td>
<td>0</td>
<td>( \pi )</td>
</tr>
<tr>
<td>12BT1</td>
<td>0.09128</td>
<td>1.456</td>
<td>2.93</td>
<td>0.103</td>
<td>0.18</td>
<td>0</td>
<td>( \pi )</td>
</tr>
<tr>
<td>13BT1</td>
<td>0.09363</td>
<td>1.362</td>
<td>2.93</td>
<td>0.103</td>
<td>0.21</td>
<td>0</td>
<td>( \pi )</td>
</tr>
<tr>
<td>21BT1</td>
<td>0.08930</td>
<td>1.456</td>
<td>2.93</td>
<td>0.103</td>
<td>0.17</td>
<td>0</td>
<td>( \pi )</td>
</tr>
<tr>
<td>22BT1</td>
<td>0.08930</td>
<td>1.456</td>
<td>2.93</td>
<td>0.103</td>
<td>0.17</td>
<td>0.174533</td>
<td>( \pi )</td>
</tr>
<tr>
<td>23BT1</td>
<td>0.08930</td>
<td>1.456</td>
<td>2.93</td>
<td>0.103</td>
<td>0.17</td>
<td>0.349066</td>
<td>( \pi )</td>
</tr>
</tbody>
</table>
Fig. 3 The numerical wave tank computational domain

effect of the structure, the wave flow field is more complex around the FPSO hull; hence, the mesh near the FPSO is also refined.

Convergence Verification

It is well known that mesh quality is of vital importance in CFD numerical simulations. A well-designed mesh can improve both the accuracy and efficiency of the simulation. Therefore, a mesh convergence verification is carried out by comparing the results of three mesh densities. The mesh quality is divided into three levels, which are coarse, intermediate, and fine meshes. The cell numbers of each level are 76 w, 249 w, and 691 w, respectively. Because the proper time step has not been found, a temporary selection of time step here is 0.01 s. And the amplitude of the focused wave used here is 0.08 m.

Fig. 4 Demonstrations of mesh

Considering the accuracy and efficiency of the calculation, intermediate mesh is selected, and its detail is shown in Fig. 4. It should be observed from Fig. 6 that the focused wave amplitude is far lower than the expected height, no matter how fine the mesh is. This is because the time step 0.01 s selected here is too large, causing wave damping to happen during the wave propagation process. So, the time step convergence verification is conducted afterwards. Several time steps are selected, including $\Delta t = 0.001$ s, 0.0005 s, and 0.0003 s. With the time step decrease, the simulation time becomes longer. The corresponding results can be seen in Fig. 6.

The amplitude parameter of the focused wave used in these time step convergence verification cases is 0.09128 m, the same as the physical experiment configuration. Through the comparison between CFD results and experimental results, it can be seen that the time step of 0.0005 s is the most suitable value to be adopted in following work among three cases. Compared with the experimental results, the wave crest at the focused position agrees with the experimental results better than the wave trough. The wave profile after the focused time matches the target results very well both in wave height and period, while the wave amplitude before the focused time is lower than that of experimental results. One possible reason is the difference of wave generation methods between numerical simulation in this paper and the physical experiment. This result in the focused wave profile cannot match the experimental results perfectly.

RESULTS AND DISCUSSION

In this section, simulations of focused waves with different incident steepness in empty NWT module are presented and verified with experimental results. After that, the FPSO benchmark model is set into the computational domain. Numerical simulations of wave interaction with FPSO hull are given. The global and local evolution of the free surface are also presented and analyzed.

Wave Elevation Validation of Focused Waves in Empty NWT

To validate our in-house hydrodynamics solver, cases with the same parameters of the experiment are simulated. Numerical wave elevation results are demonstrated in Figs. 7–12.

From Figs. 7–12, it can be observed that the wave elevation time-history lines agree well with the experimental results in general, and they are in better agreement with each other at the time after focused time. However, with the increasing of the wave steepness, nonlinear phenomenon is more apparent. Wave–wave interaction happens during the wave propagation process, which will shift the focused time and position deviating from the theoretical value. For example, the focused time in 11BT1 and 12BT1 cases are set at 50 s, but there are small offsets in these two cases. Waves recorded at WG16 focused ahead of the theoretical focused
As for the different inlet angles of the wave elevation, when the angle is zero, the highest peak of the wave elevation does not accord well, but with better agreement after the focused time. As the incident wave angle increases, the wave peak agrees better but does not accord well after the focused time. It may be due to the reflection of the numerical wave tank. The reflected wave would affect the incident wave, especially after the focused position. And for wave generation in CFD, especially for long time generation, the viscous effect will reduce the aimed wave height.

Comparing the wave elevation at bow and stern of the FPSO between numerical and experimental results (see WG16 and WG24 in Figs. 7–9), it can be seen that the wave elevation results at WG16 of the two methods agree well. It shows that the generated waves meet the requirements of next simulations to calculate the pressure on the bow of the FPSO model. As for the results of WG24, it can be found that experimental results are slightly larger than numerical results. This maybe because of the wave damping in numerical simulations and the different actual focused positions. We also notice that the experimental wave elevation results of WG24 are larger than that of WG16. This phenomenon may illustrate that the waves actually focus at the place after theoretical focused position. The influence of wave angles on empty tank is considered, shown in Figs. 10–12. When WG7 is placed beside the center of the wave tank, the difference is obvious. The wave elevation value and wave phase in wave angle 0° is larger than that of wave angles 10° and 20°. Especially when $\alpha = 20°$, the value reduces sharply at the focused time. However, in other wave gauge positions, the wave phase difference in the focused

Fig. 7 Time series of the surface elevation at (a) WG16, (b) WG18, (c) WG17, (d) WG24, and (e) WG7

Fig. 8 Time series of the surface elevation at (a) WG16, (b) WG18, (c) WG17, (d) WG24, and (e) WG7
Case 3 13BT1 – Wave Elevation Comparison (kA = 0.21)

Fig. 9 Time series of the surface elevation at (a) WG16, (b) WG18, (c) WG17, (d) WG24, and (e) WG7

position is not obvious. While WG7 is far from the centerline, the other wave gauges are set around the centerline. Therefore, it can be seen that in focused time of the empty tank, the wave angle would influence the wave amplitude value but affects the wave phase little.

From overall results and comparison work, our hydrodynamics solver can be proved to be reliable. The wave generated above can be used to simulate the interaction between focused waves and FPSO-like structure.

Wave Interaction Cases Between Focused Waves and FPSO Model

The fixed simplified FPSO model in NWT is set at the same position of the physical wave tank, where the bow of the FPSO is 13.886 m away from the front boundary of the wave tank. The results from the reflection on the bow of the FPSO hull show that the wave profile will be deformed. Before the pressure and wave elevation are analyzed, the validations of pressure and wave ele-

Case 4 21BT1 – Wave Elevation Comparison (α = 0°)

Fig. 10 Time series of the surface elevation at (a) WG7, (b) WG11, (c) WG12, (d) WG15, (e) WG16, and (f) WG17
Fig. 11 Time series of the surface elevation at (a) WG7, (b) WG11, (c) WG12, (d) WG15, (e) WG16, and (f) WG17

Fig. 12 Time series of the surface elevation at (a) WG7, (b) WG11, (c) WG12, (d) WG15, (e) WG16, and (f) WG17

viation around the FPSO body are shown. Figure 13 illustrates the comparison between experimental results and the present work. Specified pressure (pressure sensor 2) and wave elevation (WG16) are compared. The trend of the pressure curves and surface elevation curves are coordinate with the experimental results. However, there exist some discrepancies between the present work and experimental results. The wave field around FPSO is complex, so the existence of discrepancies may be due to many reasons.
Fig. 13 Time series of the (a) pressure at p2; (b) surface elevation at WG16
Numerical Study of Focused Waves Acting on a Fixed FPSO-Shaped Body

The flow field around the FPSO hull near the theoretical focused time is shown as Fig. 14. It can be observed that the wave runup and the interface decline phenomenon happen when the incident wave encounters and passes the FPSO hull. Blocked by the FPSO hull, waves will pass through sides and underneath the hull. As the U magnitude distribution on the field longitudinal section shows, the wave diffraction will generate a fast flow (i.e., vortex) at the corner of the hull. Thus, a large amount of wave energy is consumed during the wave propagation process. Hence, the interface elevation at the stern will be lower than that without FPSO.

From Fig. 15, the results of wave surface elevation at FPSO bow (WG16) and FPSO stern (WG24) are compared with the corresponding results in NWT without FPSO. It can be found that the diffraction enhanced the surface elevation near FPSO bow, about 12.2%, 27.4%, and 26.4% in 11BT1, 12BT1, and 13BT1 cases, respectively. It can also be seen that the surface elevation is suppressed after putting the FPSO into the wave tank. The declined surface elevation is approximately 27.6%, 21.3%, and 21.1% in 11BT1, 12BT1, and 13BT1 cases, respectively.

Meanwhile, during the simulation process, local instantaneous free surface elevation details can be captured and displayed. The wave profile around the structure can be compared with experimental phenomenon. Figure 16a shows a wave type observed in experiments on the interaction between focused wave and vertical cylinder (Sheikh and Swan, 2003). By comparing the experimental and numerical results, as shown in Fig. 16b, it can be observed that the simulated wave profile is quite similar with actual physical phenomenon when the wave trough encounters the structure. This is because the FPSO model used here can be regarded as a lengthened cylinder along the x-axis. This comparison shows that naoe-FOAM-SJTU can display the flow field information quite well.

It can be seen that the influence of wave angle on wave amplitude value is not proportional, both in cases with and without models. In Figs. 10–12, when there is no model inside the wave tank, the wave amplitude value when the wave angle equals 10° is almost the same as that when the angle equals 0°. However, the wave amplitude of wave angle equal to 20° shows much difference. It is smaller than that of 10° and 0° around the focused time but becomes larger after the focused time. That is due to the change of distance between inlet position and focused position under different wave angles. When it comes to the case with the model in it, the wave gauge changes. Due to the existence of the model, the scattered wave amplitude is almost the same in the oblique waves, and the wave phase difference is more obvious. The snapshots of wave runup for three different incident wave angles are shown in Fig. 17. The wave split is symmetrical in wave angle of 0°, while it is asymmetrical in oblique wave conditions.

Comparison of physical and numerical measured pressure at the specific position on the bow of FPSO is shown in Figs. 18–20. Among these sensors, P1-P4, P2-P5, and P3-P6 are at the same height but at different x coordinates, so their results are combined into each figure separately.
The general comparison shows that the pressure measured at P1-P3 is higher than that at P4–P6, especially between P1 and P4 in each case. These three cases have studied the influence of different focused wave characters on wave pressures from two aspects. The first aspect is to compare the effect made by two kinds of focused waves with the same characteristic period and different wave heights (see Fig. 18 and Fig. 19). The second aspect is to compare the effect made by focused waves with the same significant wave height and different characteristic periods (see Fig. 19 and Fig. 20).

Comparison of pressure results of cases 11BT1 and 12BT1 shows that larger wave height and steepness will increase the pressure on the bow of FPSO, especially at 0.05 m above the initial free surface. From these results, we also find that this influence will decline with the increase of the water depth, and the difference between the two pressure results in each figure will be smaller, as well.
Comparison between the results of cases 12BT1 and 13BT1 shows that the measured pressure of focused waves is close to each other, although the wave steepness is different. Compared with case 11BT1, the results are maybe similar because the wave height at the focused position is almost the same and the small difference of wave steepness is less significant compared to the wave height factor. The higher pressure measured in case 5 is probably because of the higher wave elevation at the bow. A slight difference in the pressure curves is the higher pressure of the first crest in case 15 (Fig. 20a) than that in case 14 (Fig. 19a).

Comparison between the pressure probe at the same height in cases 21BT1, 22BT1, and 23BT1 is shown in Figs. 21–23. With the increased wave angle, the second crest of time history of pressure is decreased, especially the pressure above the free surface. Meanwhile, the time of the first crest is delayed with the increased wave angle. The time delayed of the first crest is obvious between 0° angle and 10° angle, but shows less difference between 10° angle and 20° angle. Thus, the oblique wave shows decreasing pressure value and a time delay in focused time.

CONCLUSIONS

This paper applied our in-house solver naoe-FOAM-SJTU to generate focused waves and solved the focused wave loads on a fixed FPSO-shaped body. The physical model is chosen from a benchmark test. First, the wave elevation of empty wave tank is simulated. Three different incident wave angles are considered. The mesh convergence and time step convergence are carried out. The results are compared with the experimental results. The comparison shows that this numerical method is capable for wave—structure interaction problems. Then the model is placed inside the tank, and the scattered wave elevation and pressure on model are calculated. The results show a detailed reference of using the presented CFD solver to study wave and structure interactions and can be discussed and compared with those results by using other CFD solvers in the future.

The pressures on the bow of the FPSO hull for six cases are calculated and measured during the following numerical simulations. The basic rules observed from these results are discussed in the present work, and the result is validated in a CCP-WSI blind test. In addition, more related research can be conducted in subsequent studies, like the offset phenomenon of the focused time and position and the evolution of the breaking focused waves. Moreover, as the theoretic focused time related to the time steps in numerical simulations is too large, each case will run on a HPC cluster for several days. So, the optimization of meshes and numerical scheme can also be studied in the future.

The influence of different incident wave angles on scattered wave elevation and pressure on model are discussed. The incident wave angle would affect the maximum wave crest and wave loading. With the model inside, the split point of wave would change
Fig. 23 Calculated pressure of P1-P4, P2-P8 and P3-P6 (a-c) on the bow of the FPSO along with the incident wave angle; thus, the wave load and wave phase in the same wave probe position and pressure position are different. The discrepancy between the presented work and experimental results are under consideration. Since the mesh and time step convergence has been carried out, the choice of a different numerical discretization scheme is expected to achieve better results.

ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China (51879159, 51490675, 11432009, 51579145), Chang Jiang Scholars Program (T2014099), Innovative Special Project of Numerical Tank of Ministry of Industry and Information Technology of China (2016-23/09), and Lloyd’s Register Foundation of Special Appointment (Eastern Scholar) at Shanghai Institute of Higher Learning (2013022), Innovative Special Project of Academic Leaders Program (17XD1402300), Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institute of Higher Learning (20141101), Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institute of Higher Learning (20151101), Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institute of Higher Learning (20161101), and Lloyd’s Register Foundation of Special Appointment (Eastern Scholar) at Shanghai Institute of Higher Learning (20171101). The authors are most grateful.

REFERENCES


