Focused Wave Loading on a Fixed FPSO using Naval Hydro pack

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ABSTRACT
Validation of the Naval Hydro CFD software pack for focused wave loading on a fixed FPSO is presented in this paper. Naval Hydro is based on Finite Volume CFD software called foam–extend–4.0, and it is specialised for large–scale, two-phase surface flows encountered in naval hydrodynamics. Simulations are performed using SWENSE method (Spectral Wave Explicit Navier–Stokes Equations) for solution decomposition, while implicit relaxation zones are employed for wave initialisation and damping. Numerical results are submitted to a blind comparison with experimental results within the CCP–WSI Blind Test Workshop. Six cases are considered altogether where different incident waves and incident angles are considered. Pressure loads and free surface elevation are considered in this work.

KEY WORDS: Focused Wave Loads; FPSO; Wave Run–up; Naval Hydro Pack; CFD.

INTRODUCTION
Static naval objects such as Floating Production Storage and Offloading (FPSO) vessels are often exposed to severe weather conditions, where the operability, life span, and structural integrity may be endangered. There is an ongoing effort in the scientific community aimed at the development, validation and certification of computational methods for predicting wave–body interaction. Finite Volume (FV) based Computational Fluid Dynamics (CFD) methods comprise one of the largest and most popular groups of computational methods for various problems, including naval hydrodynamics, and are more increasingly subjected to rigorous verification and validation in order to assure and promote their accuracy and applicability in modern marine industry. This paper presents a part of such an undertaking within the CCP–WSI Blind Test Workshop, where numerical results submitted by participants are compared to experimental measurements.

In this work Naval Hydro software pack is used to conduct simulations of focused wave loading on a static FPSO model. Naval Hydro pack is based on open–source, FV based CFD software called foam–extend–4.0, and it is specialised for large–scale, two phase flows with rigid body motion and wave generation. The discontinuities across the interface are taken into account with the Ghost Fluid Method (GFM) Vukčević, Jasak, and Gatin [2017] which imposes the free surface boundary conditions within the FV framework. For efficient wave propagation, SWENSE method Vukčević, Jasak, and Malenica [2016a; 2016b] is employed, which is a solution decomposition approach where the flow field is decomposed into the incident portion arising from the potential wave theory, and diffracted component caused by inherent nonlinearities of Navier–Stokes equations. Surface waves are initialised and damped by using implicit relaxation zones Jasak et al. [2015] which are placed at the inlet and outlet of the computational domain, gradually blending the fully nonlinear CFD solution to the target incident wave field. The wave field is initialised with the NewWave theory Tromans et al. [1991].

Six cases are considered in total, divided in two parts: in Part 1 different focusing wave characteristics are used, with zero incident angle corresponding to head waves conditions. In Part 2, the same wave conditions are used with different incident angles. Pressure and surface elevation signals on several locations are reported. In addition to wave–body interaction simulations, the wave propagation is checked by performing empty–domain computations, where the signal is compared to the incident linear wave elevation signal and to the results of Higher Order Spectrum (HOS) nonlinear wave theory implemented in Naval Hydro Gatin et al. [2017]. Using the data from the empty–domain simulations, the effect of fixed FPSO to the wave field is examined by comparing the two surface elevation data sets.

The paper is organised as follows: in the next section the numerical model is briefly presented, including GFM and SWENSE. Third section describes the test cases considered in the study, with geometry and wave field definitions. Next, the numerical set–up is presented, including computational domain geometry and discretisation details. In the fifth section
results of empty-domain computations are presented with surface elevation comparison including experimental results, followed by wave load results. Finally, discussion and a brief conclusion are given.

NUMERICAL MODEL

This section briefly outlines the numerical methodology used in this work, including GFM and SWENSE. Immiscible, two–phase, incompressible, viscous and turbulent flow model is governed by continuity and Navier-Stokes equations, which have the following form within SWENSE method Vukˇcevi´c, Jasak, and Malenica[2016a]

\[ \nabla u_F = -\nabla u_I, \]

\[ \frac{\partial (u_F)}{\partial t} + \nabla (u_F u_F) - \nabla (v_{eff} \nabla u_F) = -\frac{\partial (u_I)}{\partial t} + \nabla (v_{eff} \nabla u_I) - \frac{1}{\rho} \nabla p_d + \nabla u_I \nabla v_{eff}, \]

where indices \( P \) and \( I \) denote diffracted and incident components of the flow, respectively. The velocity field is denoted with \( U \). \( v_{eff} \) stands for effective kinematic viscosity, \( \rho \) is the fluid density, while \( p_d \) is the dynamic pressure defined as \( p_d = p - \rho g x \). Here, \( p \) is total pressure, \( g \) denotes constant gravitational acceleration, while \( x \) stands for radii vector with respect to the origin of the coordinate system.

The interface is defined by using the Level Set method derived from the Phase Field equation Sun and Beckermann [2007]. Sun and Beckermann [2008] which is more suitable for decomposition than the more popular Volume of Fluid (VOF) method. For more details on interface capturing and implementation of SWENSE method in Naval Hydro pack the reader is directed to Vukˇcevi´c, Jasak, and Malenica [2016a].

In order for the above equations to be valid for both fluids (air and water), the discontinuities of pressure gradient, density and dynamic pressure must be taken into account. In the Naval Hydro pack, GFM is utilised for discretisation of the free surface boundary conditions Vukˇcevi´c, Jasak, and Gatin [2017]. The discontinuities are described by jump conditions, which state:

\[ p_d^+ - p_d^- = -(\rho^+ + \rho^-)g x, \]

\[ \frac{1}{\rho^+} \nabla p_d^+ - \frac{1}{\rho^-} \nabla p_d^- = 0, \]

where superscripts + and - denote values infinitesimally close to the interface on the water and air side, respectively. The above equations stem from the dynamic free surface boundary condition, where the normal stress balance is satisfied exactly, while the tangential stress balance is approximated Vukˇcevi´c, Jasak, and Gatin [2017].

FOCUSED WAVE LOADING ON FPSO

The considered test cases correspond to experimental studies from Mai et al. [2016] which are presented in this section. The geometry of the experimental program is shown in Figure 1 where three different FPSO models are shown. In this study, only the longest model is considered, label Model 3 in Mai et al. [2016]. The dimensions of the wave basin are also indicated on the figure, as well as wave gauges (WG) and their positions. Front and side view of the bow of the vessel is shown in Figure 2 with indicated positions of pressure gauges. Schematic view of the experimental wave tank is shown in Figure 3. The working depth \( h \) is 2.93 m.

As mentioned above, six different cases are considered which are divided in two parts:

1. Part 1: three wave cases with different spectral characteristics, as shown in Table 1
2. Part 2: three wave cases with different incident angles, as shown in Table 2

In Table 1 and Table 2 \( a \) denotes the amplitude of the focused wave, \( T_p \) is the peak period of the JONSWAP spectrum, \( H_s \) is the significant wave height, \( k_a \) denotes wave steepness, \( \alpha \) stands for the incident angle, where zero degrees denotes head waves, and \( \phi \) denotes the phase shift of individual wave components in the NewWave theory.

<table>
<thead>
<tr>
<th>CCP–WSI ID</th>
<th>( \alpha, ^\circ )</th>
<th>( T_p, s )</th>
<th>( H_s,m )</th>
<th>( k_a )</th>
<th>( \alpha, ^\circ )</th>
<th>( \phi, \text{rad} )</th>
</tr>
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<tbody>
<tr>
<td>11BT1</td>
<td>0.069</td>
<td>1.456</td>
<td>0.077</td>
<td>0.13</td>
<td>0</td>
<td>\pi</td>
</tr>
<tr>
<td>12BT1</td>
<td>0.091</td>
<td>1.456</td>
<td>0.103</td>
<td>0.18</td>
<td>0</td>
<td>\pi</td>
</tr>
<tr>
<td>13BT1</td>
<td>0.094</td>
<td>1.362</td>
<td>0.103</td>
<td>0.21</td>
<td>0</td>
<td>\pi</td>
</tr>
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SIMULATION SET-UP

In order to reduce the required computational time, computational domain is significantly reduced with respect to the dimensions of the physical wave tank. In order to avoid the influence of boundaries, implicit relaxation zones are placed next to outlet boundaries Jasak et al. 2015. Figure 4 shows the computational domain with the FPSO model. The relaxation zones are indicated with the red colour at the calm free surface. The blue portion of the free surface is the full CFD part of the domain. The domain is 20.7 m long, 7 m wide, and the depth is set to 2.93 m. The inlet boundary is set to 4.5 m in front of the FPSO, while the outlet is set 15 m behind the stern. In the experimental wave tank the bottom has variable depth, however given the depth of the wave tank and spectral wave characteristics the influence of the bottom on the wave field can be neglected. Hence, constant depth is set in the numerical domain, with depth that corresponds to the shallower part of the wave tank.

Three different computational grids are used in this work, one for each incident angle case with characteristics shown in Table 3. Grids are of hybrid type, containing structured and unstructured regions, where structured hexahedral cells prevail. In order to keep the direction of wave propagation parallel with the grid direction, grids for cases 22BT1 and 23BT1 are generated by rotating the FPSO model and fitting the computational mesh to the rotated model. Figure 5 shows the top view of the grid in the horizontal plane on the calm free surface. The finest grid level stretches from the FPSO model to the inlet boundary in order to allow the waves to propagate in uniform grid resolution until they reach the FPSO model. Cell size in the finest region corresponds to $\Delta x = 0.01 \text{ m}$, $\Delta y = 0.02 \text{ m}$ and $\Delta z = 0.005 \text{ m}$. Figure 6, Figure 7 and Figure 8 show discretised FPSO model for grids 1, 2 and 3, respectively. It can be seen that grids are very similar except for the orientation of the model.

Time-step is controlled in all simulations in order to maintain the Courant–Friedrich–Lewy (Co) number below 1. This results in time-steps ranging between 0.005 and 0.015 seconds. Second order backward scheme is used for time marching, and upwind biased scheme with second order differer correction is used for convection. All other operators and interpolations are performed using linear second order schemes. Conjugate Gradient linear solver is used for the pressure, momentum and free surface transport equations, with absolute tolerance set to $1E-7$.

Table 2 Wave parameters for test cases in Part 2

<table>
<thead>
<tr>
<th>CCP–WSI ID</th>
<th>$a$, m</th>
<th>$T_p$, s</th>
<th>$H_s$, m</th>
<th>$k a$</th>
<th>$\alpha$, $\circ$</th>
<th>$\phi$, rad</th>
</tr>
</thead>
<tbody>
<tr>
<td>21BT1</td>
<td>0.089</td>
<td>1.456</td>
<td>0.103</td>
<td>0.17</td>
<td>0</td>
<td>$\pi$</td>
</tr>
<tr>
<td>22BT1</td>
<td>0.089</td>
<td>1.456</td>
<td>0.103</td>
<td>0.17</td>
<td>10</td>
<td>$\pi$</td>
</tr>
<tr>
<td>23BT1</td>
<td>0.089</td>
<td>1.456</td>
<td>0.103</td>
<td>0.17</td>
<td>20</td>
<td>$\pi$</td>
</tr>
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Table 3 Computational grid characteristics

<table>
<thead>
<tr>
<th>Grid ID</th>
<th>CCP–WSI ID</th>
<th>No. cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11BT1, 12BT1, 13BT1, 21BT1</td>
<td>4 134 460</td>
</tr>
<tr>
<td>2</td>
<td>22BT1</td>
<td>4 138 516</td>
</tr>
<tr>
<td>3</td>
<td>23BT1</td>
<td>4 138 521</td>
</tr>
</tbody>
</table>
WAVE PROPAGATION TESTS

Before moving on to wave loading simulations, wave propagation is checked in order to ensure valid incident wave group. Grids without the FPSO model is generated which corresponds exactly to grids 1, 2 and 3. Equivalent numerical settings are used described in the previous section.

The focused wave is generated by superimposing 244 linear wave components equidistantly spaced between 0.1 and 2 Hz. A Collaborative Computational Project in Wave Structure Interaction n.d. Focusing point is set at the bow of the FPSO, at time $T = 10$ s. Free surface elevation is measured in time on locations indicated in Figure 1 corresponding to WG 16, 17 and 24. The measured surface elevation signal is compared to linear evolution and experimental results. The shorter domain which is used in CFD in front of the FPSO with respect to the experiment may cause a difference in the level of nonlinearity of the wave field at the focusing location since there is less time for nonlinear wave-to-wave interaction and wave modulation to develop. In order to assess the influence which different domain length may have on the wave field, and ultimately on wave loads, surface elevation signal from CFD is compared to fully nonlinear HOS method Gatin et al. 2017 which is based on the potential flow model. In HOS simulations, equivalent amount of time and space to the experiment is given for development of nonlinearities in the wave field.

For the sake of brevity, only the comparison for WG 16 will be shown here, which is located at the bow of the model. Figure 9 shows the surface elevation comparison for case 11BT1, where EFD stands for experimental results. The four signals correspond well, where the HOS signal shows higher wave crests surrounding the focused wave through. At the focused wave through CFD signal is more similar to HOS than to the linear solution, unlike the remained of the signal. Figure 10 shows signal comparison for case 12BT1, where similar behaviour is observed at the wave through. However, at the wave crest preceding the focusing wave through, CFD and HOS correspond better with respect to the linear solution indicating stronger nonlinearities in the wave field. This is expected since 12BT1 wave case is steeper than 11BT1. For case 13BT1 this behaviour is even more pronounced, as shown in Figure 11 since this is the steepest wave case. Cases 21BT1, 22BT1 and 23BT1 have the same spectral properties, giving equivalent wave fields. Hence, one graph is given for these three cases on Figure 12. Similar behaviour to case 12BT1 is exhibited, since the wave steepness is similar as well. All surface elevation signals correspond very well to experimental measurements.

Overall the surface elevation signals show reasonable correspondence between linear, CFD, HOS and experimental results, with some differences which should be kept in mind. Nonetheless, acceptably accurate wave loads should be obtained using these numerical settings.

WAVE LOADS RESULTS

In order to examine the effects of wave-body interaction, the surface elevation is compared for simulations with and without the FPSO model. Pressure signals are also reported, where only 1 to 6 pressure gauges are reported for cases 11BT1, 12BT1 and 13BT1 since the flow is symmetric. For case 21BT1 all pressure gauges (1 to 9) are reported in order to facilitate the comparison with 22BT1 and 23BT1 cases.

Figure 13 shows the top view of the wave field in the most severe case 13BT1, at the time of focusing. Figure 14 and Figure 15 show cases 22BT1 and 23BT1 where the difference in the incident angle can be observed.

The comparison of surface elevation signals at WG 16, 17 and 24 for case 11BT1 is given in Figure 16 where the incident elevation from the empty domain simulations is compared to the diffracted wave field.
in the presence of the FPSO model. For the two gauges in front of the bow, wave amplitudes are larger with respect to the incident wave field. As expected, at wave gauge behind the stern (WG 24) the amplitudes are smaller due to wave energy dissipation. Very similar behaviour is observed on Figure 17 and Figure 18 for cases 12BT1 and 13BT1, respectively. Since case 21BT1 is also a head wave condition, similar results to Part 1 cases are observed on Figure 19. For the oblique case 22BT1 shown in Figure 20, diffraction wave shows larger differences with respect to head wave cases. This is especially true for surface elevation gauge 17. Surprisingly, for larger incident angle (23BT1) the incident and diffraction wave fields show little difference for gauge 17, as shown in Figure 21.

As mentioned above, relative pressure is measured at the bow of the model, on positions indicated on Figure 22, Figure 23 and Figure 24 show relative pressure signals for cases 11BT1, 12BT1 and 13BT1, respectively. Gauges at the same vertical positions are grouped together on individual graphs for easier comparison. As expected, pressure is higher on the centreline with respect to gauges positioned at 45° with respect to the centreline. On Figure 25, Figure 26 and Figure 27 pressure signals for cases 21BT1, 22BT1 and 23BT1 are presented, respectively. For case 21BT1 gauges positioned at symmetric positions with respect to the centreline show identical pressure signals, which is expected since the incident angle is 0° for this case. For case 22BT1 shown on Figure 26, pressure measured on gauges P7, P8 and P9 is higher than pressure measured at the corresponding gauges on the opposite side (P4, P5 and P6) due to their position on the windward side. For case 23BT1 this effect is more pronounced, where the gauges on the windward side show very similar pressure values to gauges positioned at the centreline. However, no significant increase in maximum pressure peak is observed for different heading angles. Differences are smaller than 20 Pa.

Fig. 13 Free surface elevation at the time of focusing for case 13BT1.

CONCLUSION
Wave loading of a simplified FPSO model is investigated in this work using numerical simulations. Naval Hydro software pack based on open-source software foam–extend–4.0 is used, which employs advanced numerical methods for simulating large-scale, incompressible and viscous two-phase flow. The study is performed for the CCP–WSI Blind Test Workshop A Collaborative Computational Project in Wave Structure Interaction [n.d.] where the numerical results of various participants will be compared to experimental values.
Irregular wave group defined with the NewWave theory is used for wave generation. Six different wave cases are examined, where four have zero incident angle, while two cases have 10 and 20 degrees wave incident angle with respect to the central plane of the FPSO model. Accuracy of wave propagation in the present CFD model is checked by performing simulations without the FPSO model and comparing the free surface elevation to the linear solution, nonlinear solution based on potential flow model, and experimental results. The comparison showed that small differences exist between the surface elevation measured in CFD
Comparison of surface elevation signals between the simulations with and without the FPSO model showed reasonable trends, where the diffraction increased the elevation at the bow and lowered it at the stern of the vessel. Pressure measured at the bow at six locations for symmetrical cases and nine for asymmetrical is also presented, showing that no significant increase in pressure is caused by 10 and 20 degrees incident angle.

The study produced physical and consistent results, while the accuracy is yet to be determined in the scope of the CCP–WSI Blind Workshop by comparing all the presented results to experimental measurements.

REFERENCES

A Collaborative Computational Project in Wave Structure Interaction. https://www.ccp-wsi.ac.uk/blind_test_series_1focused_wave


Fig. 27 Relative pressure signals for case 23BT1.

