Freak Wave-Induced Ship Motion with Sloshing Tanks Based on a HOS-CFD Coupling Method

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INTRODUCTION

Nowadays, the study of wave-structure interaction becomes a hot issue. In real sea states, offshore structures would suffer a very hostile environment such as freak waves. The freak wave has the feature of significant high wave amplitude and short time duration, thus it brings wave breaking on structures and caused damage. Therefore, the investigation on freak wave and structure interaction is required. In general, as focused wave can be well simulated with large wave height in transient time at specified time and space, studies often adopted focused waves.

The first measurement of focused wave was New Year wave which happened at the Draupner platform in the North Sea off the coast of Norway (Adcock, T.A.A and Taylor, P.H., 2009; Adcock, T.A.A et al, 2011). Some experimental studies on focused wave structure interactions were also carried out (Li, J. et al, 2012; 2014) on studying the focused wave run-up and forces on structures. Many researchers discussed the freak wave interacted with structures in a numerical way. Newman, J.N. and Lee, C.H (2002) overviewed two boundary-element method to measure the wave forces. Although potential theory was an accurate and efficient computational method to simulate wave-structure interaction, it had limitations on simulating complex wave phenomenon. Therefore, the studies of freak wave and structure interaction often employed CFD method. Westphalen, J. et al (2014) applied four CFD methods to simulate a wave energy device in extreme waves. Hu, Z.Z. et al (2016) applied Open source CFD tool OpenFOAM to do the simulation of focused wave passing through a fixed cylinder. Zhuang, Y. and Wan, D.C (2019) simulated a focused wave interacted with a fixed FPSO in naoe-FOAM-SJTU. CFD method can give ability in solving all flow regimes in hydrodynamics, especially for overturning flow and breaking waves. However, the cost of CFD cannot be ignored. Generating focused wave needs long space and long time to be focused, the time consuming and numerical dissipation of CFD is enormous. Therefore, we need to extend our method to seek for better solutions.

In the present work, we combine our in-house CFD solver naoe-FOAM-SJTU with a pseudo-spectral method High-Order-Spectral method (HOS) to simulate a multi-directional focused wave interacted with LNG ships. HOS method (Dommernuth, D.G. and Yue, D.K.P, 1987) elevates potential velocity on free surface and communicates mode space and physical domain using Fast Fourier Transform. Therefore, HOS method can generate nonlinear wave in a fast and efficient way. As we mention before, we desire to study the focusing time spot and focusing space, thus the source cost of time and wave elevation before focusing time and space can be ignored. Therefore, the wave generation is implemented by HOS, and wave-structure interaction is simulated in CFD method.

The new combined solver is discussed in detail and validation is shown. A model-scaled focused wave is generated by an open source HOS software named HOS-Ocean (Ducrozet, G. et al, 2016). A ship coupled with two LNG tanks is considered in the focused wave to figure out the nonlinear ship motion. Zero filling ratio and 20% filling ratio are both included to study the coupling effects in focused waves.

METHODOLOGY

Governing Equation

The incompressible Navier-Stocks equations are adopted in this paper to investigate the viscous flow. Using dynamic deformation mesh, the governing equations are:

\[ \nabla \cdot \mathbf{U} = 0 \]  
\[ \rho \left( \frac{\partial \mathbf{U}}{\partial t} + \mathbf{U} \cdot \nabla (\mathbf{U} - \mathbf{U}_0) \right) = -\nabla p + \mathbf{g} \times \mathbf{\omega} + \mu \nabla^2 \mathbf{U} + f_v + f_s \]

Where \( \mathbf{U} \) is velocity field, \( \mathbf{U}_0 \) is velocity of grid nodes; \( \rho \) is density; \( \mathbf{g} \) is gravity; \( \mathbf{f}_v \) is dynamic pressure; \( \mathbf{f}_s \) is the surface tension term in two phases model.

The solution of momentum and continuity equations is implemented by using the pressure-implicit split operator (PISO) algorithm (Issa, R.I. 1986). PISO algorithm applies mass conservation into pressure equation, thus when pressure equation converges, continuity error decreases. This method uses a predictor-corrector on solving pressure-velocity coupling, and utilizes a collocated grid method (Rhie, C.M. and Chow, W.L., 1983).

VOF Method

The Volume of fluid (VOF) method with bounded compression techniques is applied to control numerical diffusion and capture the two-
phase interface efficiently. The VOF transport equation is described below:

\[
\frac{\partial \alpha}{\partial t} + \nabla \cdot (\mathbf{U} - \mathbf{U}_g) \alpha = 0 \quad (3)
\]

Where \( \alpha \) is volume of fraction, indicating the relative proportion of fluid in each cell and its value is always between zero and one:

\[
\begin{align*}
\alpha &= 0 & \text{air} \\
\alpha &= 1 & \text{water} \\
0 < \alpha < 1 & \text{interface}
\end{align*}
\]

### High Order Spectral Method

HOS (High Order Spectral Method) is a pseudo-spectral method which can solve fully nonlinear wave in an accurate and efficient way. The formulation is based on the free surface velocity potential. Following Zakharov (1968), the surface potential can be defined as:

\[
\phi(x,t) = \phi(x, \eta(x,t), t)
\]

Therefore, the dynamic and kinematic boundary condition of surface potential in free surface are:

\[
\eta_x + \nabla \cdot \phi_x \phi_x - (1 + \eta \phi_x \eta \phi_x) \phi_x(x, \eta, t) = 0 \quad (6)
\]

\[
\phi_{xx} + \frac{\eta}{2} \phi_x \phi_x - \frac{1}{2} (1 + \eta \phi_x \eta \phi_x) \phi_{zz}^2(x, \eta, t) = -Pa \quad (7)
\]

where \( \phi_x \) is the surface potential. Expanding \( \phi \) in a perturbation series and then further expand each order of \( \phi \) evaluated on free surface in a Taylor series:

\[
\phi(x,t) = \sum_{m=1}^{M} \sum_{k=0}^{\frac{M}{m}-1} \frac{c^k}{k!} \phi^{(m)}(x,0,t) \quad (8)
\]

With the initial velocity potential and surface elevation is given, the unknown \( \phi \) can be solved according to equation (8). With the help of Fast Fourier Transform (FFT), the information can be rapidly transported between mode space and physical space. HOS method can convergence fast due to the existence of exponential profile.

### Combination with HOS and CFD

The HOS method is a potential theory which requires less need for time steps and mesh size. However, time step and mesh size is essential for CFD method, and the required time step or mesh size may be much smaller than those in HOS method. To combine those two theories, the mismatch of time steps and mesh size should be solved. The direct way to build the communication between HOS and CFD is applying interpolation schemes. The interpolation method we used is based on a HOS wrapper program called Grid2Grid (Choi, Y.M., 2017). Grid2Grid reconstructed the HOS grid from result mode files through inverse FFT. It has to be mentioned that the information from HOS is absent in z coordinate. Grid2Grid also built the information on z coordinate, which matches the CFD domain. Spline module is employed to do the interpolation.

Despite the difference in time step and mesh size, there still exists domain setup difference between HOS and CFD. As shown in Fig. 1, in CFD domain, ship is set on original zero point while in HOS domain it set the corner of its domain on original zero point. The ship is set on zero point due to the 6DOF module, it calculates forces and moments of the structure according to earth coordinate, which is the zero point. Therefore, in order to match the information from HOS to CFD, a communication zone is built to receive wave field information from HOS. The position of communication zone can be defined to capture the wave fields we need, as shown in Fig.1, it can be displaced in arbitrary position. The position of the communication zone can be defined manually, we choose two parameters (x, y) to confirm the position of communication zone. It has to be mentioned that the calculation in CFD domain is not moved. Communication zone receives wave signal from HOS field, and matches the wave fields into CFD domain.

Fig.2 shows the HOS mesh and CFD mesh. The HOS grids come from the reconstruction in Grid2Grid, each grid point stands for volume mesh grid and contains wave fields’ parameters.

Fig.1. The information communication of the combined solver in naoe-FOAM-SJTU

Fig. 2. The HOS mesh and CFD mesh

Fig.3 illustrates the calculation process in combined solver. First of all, the HOS calculation is done and the results file is obtained. Secondly, the HOS grids are handled through Grid2Grid and interpolate into relaxation zone. After that, the wave field is constructed and applied as wave signal into CFD zone. Some modules in naoe-FOAM-SJTU such as 6DOF and mooring system are employed to finish the calculation.
Fig. 3. The calculation process of the combined solver in niae-FOAM-SJTU

Wave Generation and Damping

The wave generation is based on the results of HOS. We mention the combination and information communication between HOS and CFD; however, the communication should base on the interface. Therefore we construct the interface which provides communicate grids through waves2Foam (Jacobsen, N.G. et al, 2012). The waves2Foam applies relaxation zone scheme to receive the signal from HOS and propagates the signal into CFD zone. The relaxation zone scheme is illustrated as:

$$\Phi = \alpha \Phi_{\text{computed}} + (1-\alpha)\Phi_{\text{target}}$$

where $\Phi_{\text{target}}$ is the parameters such as velocity potential and wave elevation in HOS, $\Phi_{\text{computed}}$ is the original parameters in CFD, $\Phi$ is the final parameters in wave propagation, $\alpha$ is weighting factor. The value of weighting factor is from 0 to 1; the variation of the weighting factor is shown in Fig. 4. In the meantime, the implementation of relaxation zone can avoid wave reflection, therefore it can be a good wave damping function as well.

NUMERICAL SIMULATION

Numerical Setup

The numerical model chooses a simplified LNG FPSO, which is a physical model in experiments carried out by Nam, B.W et al (2009). The details of the numerical model such as ship parameters and tanks arrangement can be found in Zhuang, Y. and Wan, D.C (2016, 2017, 2018, 2019). The length of the ship model is 2.85m and the draft is 0.13m. The ship contains two LNG tanks with different length. The two tanks are arranged asymmetrically in the inner ship. The natural frequency of 20% filling ratio in roll motion is 0.9597Hz (Zhuang, Y. and Wan, D.C, 2019).

Fig. 5 shows two kinds of filling ratio in tanks, they are 0% filling ratio which is empty tanks and 20% filling ratio, respectively. This paper chooses the same filling ratio in fore and aft tank.

Fig. 4 The relaxation zone in inlet and outlet

The selected CFD computational domain is described as $-6.41m < x < 12.1m$, $-9.26m < y < 9.26m$, $-1.85m < z < 1.85m$, shown in Fig. 6 (a). In order to receive information from HOS domain, the incident relaxation zone is set in front of the ship. And in case of wave reflection, the outlet relaxation zone is set at the end of the CFD computational domain. The communication zone is set as $x=33.3m$, $y=33.9m$ (the description of x and y is according to Fig. 1), which makes the focusing position in front of the ship. The displacement from communication zone to HOS domain is shown in Fig. 6 (b).

Fig. 5 Geometry of the ship and demonstration of filling ratio.

(a) ship with empty tanks (b) ship with two 20% filling tanks

Fig. 6 The setup of computational domain

(a) The setup of computational domain in CFD zone
(b) The setup of HOS and CFD zone

Fig. 7 The setup of computational domain

The meshes are generated by snappyHexMesh, an auto mesh generation utility provided by OpenFOAM. The mesh generations are shown in Fig. 7. To capture the wave around the ship and flow inside the tank, free surface and tanks are refined. The mesh generation around the ship is 30 cell grids per ship length, 10 cell grids per ship width and around 30 cell grids per tank width. The total cell number of case 1 is around 7.2M.
Fig. 8 shows the original wave field which is generated by HOS method. In order to test the focusing wave field transportation into CFD zone, three mesh generation are included. The total number of grids in empty wave tank are 3.33M, 4.01M and 5.46M respectively. The time step of these three cases are the same, $\Delta t = 0.002t$. The results of 3.33M and 4.01M is almost the same in wave elevation, the result of 5.46M is closer to HOS result, shown in Fig.9. As it needs to be mentioned, there are two methods to initialize the wave field, one is mapping all the wave field at the specific time point to the whole CFD zone, which is illustrated in case of 3.33M and 4.01M. The other is initializing the wave field in zero wave elevation and let wave propagate from wave inlet, which is illustrated in 5.46M. Thus the time history of 5.46M has discrepancy at the beginning curve. The final mesh grid number is chosen to be 5.46M.

**Freak Wave**

The verification of this coupled method can be found in Zhuang et al (2018). In this paper, a freak wave is adopted. The open source software HOS-Ocean is applied to do the simulation. The wave field is 70m×70m, and the period of the focused wave is $T=1.2048s$, with $H_s = 0.01m$. The generated wave field is shown in Fig. 8. The focusing point is at ($x = 33.9m$, $y = 33.9m$), and the focusing time is $T_p = 49.09s$. According to the approximation solution of dispersive equation by Eckarck (1952), the wave length can be estimated as:

$$\lambda = \frac{\mu_0}{\sqrt{\tanh \mu_0}}$$

where $\mu = 2\pi h / \lambda$, $\lambda$ is wave length and $h$ is wave depth. $\mu_0 = (2\pi)^2 h / (gT^2)$, $T$ is the wave period. With the known water depth $h=2m$, we can obtain the approximate wave length which is 2.278m.
Results

The mesh convergence around the ship can be found in Zhuang, Y. and Wan, D.C (2019). The comparison of heave, roll and pitch motion in different filling ratios are shown in Fig. 11. The time coordinate is set as the simulation time of CFD zone, not the realistic wave propagation time. According to previous studies of ship coupling with two sloshing tanks, the existence of free surface in tanks influence little in heave motions in regular waves. It seems that the sloshing tanks also affects little in heave motion in freak wave. However, the roll motion in different filling ratios is obviously different. The 20% filling condition decreases the value of roll motion to some extent. Before the ship encounters with the focusing point and time of the wave, the phase of roll motion in 0% and 20% is almost the same. After the crest of the focusing wave passes through the ship, the sloshing in tanks reduces the frequency of the roll motion. The existence of the sloshing fluid in tanks also contains the roll motion value of the ship. The roll motion of zero filling ratio ship decreases rapidly along with the wave elevation, while the roll motion of 20% filling ratio ship decreases a little in a few period due to the sloshing flow in tanks. The pitch motion of different filling ratios is also presented. The difference in pitch motion between two filling-ratio ships is not obvious, which means the sloshing fluid doesn’t affect the fore or aft bulkhead of the tank, or the influence in two tanks balances each other. It has to be mention that the period in heave, roll and pitch motion is larger than that of empty tank wave propagation. This may due to the break before the highest wave crest encounters with the ship.

Fig.11 Time history of ship motion in different filling ratios

(a) Heave motion
(b) Roll motion
(c) Pitch motion

Fig.12 illustrates the snapshots of wave field of two different filling ratios. The choice of time-point is the highest value of heave motion (T = 7.65s) and roll motion (T = 7.4s). It can be seen that the wave breaks when it reaches the ship, as we mentioned before. Roll motion reaches the largest value before heave motion reaches the largest value. When 20% filling ratio ship reaches the largest roll degree, the sloshing in tanks are very gentle, while when the ship reaches the largest heave motion, the sloshing fluid climbs on the right bulkhead of the tank.

(a) 0 filling ratio in T=7.4s           (b) 0 filling ratio in T=7.65s
(c) 20% filling ratio in T=7.4s       (d) 20% filling ratio in T=7.65s

Fig. 12 Snapshots of wave fields in 0% and 20% filling ratios

In order to give a further research on the coupling effects under the freak wave, the snapshots of wave field and sloshing tanks are shown in Fig. 13. The duration of the time is chosen from T=7.2s to T=7.95s, which includes the largest and smallest value of roll and heave motion. When the focusing wave starts to encounter with the ship, there is a wave crest in tanks. After the ship reaches the largest roll degree, the wave crest in tanks starts to climb the bulkhead of the tank. Before ship reaches the largest value of heave motion, the fluid in tanks climbs the highest position in tank, almost reaches the slope of the top tank. After the sloshing fluid climbs on the bulkhead, the wave crest in tanks breaks and overturns to form a new wave crest. When T = 7.85s, the wave field in outer space is gentle and the ship starts to roll in opposite way, the fluid...
in tanks forms a shape of ‘Ω’, the highest crest in the middle of the tank and the lowest trough in the two sides of the tank. When \( T = 7.95 \text{s} \), the roll motion of the ship almost reaches the trough of the motion curve, the energy of the wave crest in tanks passes to the pressure on bulkhead and forms a wave trough in the left bulkhead of the tanks.

(a) \( T = 7.25 \text{s} \)
(b) \( T = 7.45 \text{s} \)
(c) \( T = 7.60 \text{s} \)
(d) \( T = 7.75 \text{s} \)
(e) \( T = 7.85 \text{s} \)
(f) \( T = 7.95 \text{s} \)

Fig. 13: The coupling effects in 20% filling condition

Fig. 14 shows the sloshing fluid in aft (left) and fore (right) tank at some specific time-point. The sloshing fluid in fore and aft tank shows little different in these time points, which illustrates the obsolete coupling effect in pitch motion is due to the wave excitation. The diffraction of focusing wave crest spreads along the length of the ship, thus gives the balance forces along the ship length. The pitch motion is gentle and moved around zero. The excitation of wave on pitch motion gives the same sloshing phenomena in two tanks. However, due to the nonlinearity of the freak waves, the little discrepancy is also observed in \( T = 7.85 \text{s} \). When the wave crest in tank passes through to the middle of the tank in aft tank, the fluid which climbs on the bulkhead still exists in fore tank. The sloshing in tanks gives local pressure on tanks, after integration along the bulkhead on ship, the discrepancies is not obvious in ship motion.

(a) Sloshing in aft (left) and fore (right) tank at \( T = 7.6 \text{s} \)

Fig. 14: Snapshots of sloshing details in aft and fore tanks

CONCLUSIONS

This paper applies potential-viscous method which combined HOS method with CFD method using our in-house solver naoe-FOAM-SJTU. A three-dimensional directional focusing wave is generated and a FPSO with two sloshing tanks is simulated under such freak wave condition. Two different filling ratios are discussed. Firstly, the HOS method and coupled method is introduced. A freak wave is generated by HOS method, and then the freak wave is tested and simulated in CFD zone. The well agreement indicates the coupling method has the ability to simulate directional 3D focusing waves.

The ship motion in freak wave and the coupling effects are discussed in this paper. Similar to that in regular wave, ship in freak wave shows little coupling effects in heave motion, but the coupling effects is quite obvious in roll motion. The 20% filling ratio in aft and fore tank decreases the roll motion and enlarge the frequency of roll motion after encountering with the focusing wave. The sloshing in tanks is violent and shows little different in aft and fore tank. The focusing wave breaks before it encounters with the ship, which is shown in snapshots of wave fields and time history of ship motion.

This paper gives an attempt on simulating ships coupled with two sloshing tanks in freak waves. The new coupled method can do this simulation well. However, as the freak wave is generated without support of experiments, and with large amount value of grid number, the verification and accuracy needs further studies.

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