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Numerical simulations of FPSO with sloshing tanks in a random freak waves

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Abstract: This paper presents a potential-viscous coupled method to simulate a floating production storage and offloading (FPSO) with two liquefied natural gas (LNG) sloshing tanks in a random freak wave. The potential theory uses high-order-spectral (HOS) method. The random wave is generated by HOS for 2 000 s, and a freak wave is observed around 1 830 s. The FPSO LNG model was firstly verified in regular waves using HOS-computational fluid dynamics (CFD) coupled method and validated the HOS-CFD coupled method can solve the ship motion coupled with sloshing tanks accurately. The FPSO with LNG tanks are then simulated in the freak wave, showed the coupling effects when the freak wave passes. With the existence of the sloshing tanks, the amplitude of the roll motion decreases and the period of roll motion changed. Wave breaking phenomenon can be observed when the wave crest of the freak wave encounters with the ship.

Key words: Ship motion with sloshing tank, high-order-spectral-computational fluid dynamics (HOS-CFD) method, naoe-FOAM-SJTU solver, freak waves

Introduction

In the real sea states, the offshore structures would suffer complex and extreme wave conditions, such as freak wave condition. These freak waves occur randomly and needs long-time evolution. The freak wave appears in a short time and forms an extreme large wave crest and trough. The freak wave is hard to capture and simulate, while the wave component of the freak wave is more complicated, which made the motion responses of the structures more difficult to predict. In ocean engineering, some offshore structures themselves had complex hydrodynamic characteristics, for example, floating production storage and offloading (FPSO) with sloshing tanks. With the existence of free surface in tanks, the ship motion will excite the fluid in tanks begin to slosh, and the sloshing tanks will influence the ship motion in return. This kind of influence happens simultaneously, therefore, the FPSO with sloshing tanks in freak waves is worth studying.

In the early numerical simulations, the researchers applied potential theory to solve coupling effects of the sloshing tanks and ship motion. Most of these studies solved the coupling effects separately, the ship motion acted as the excitation of the tank, and the force generated by the fluid in the tank acted as additional force on the ship[1-2]. Newman[3] simplified this problem, he applied WAMIT to simulate both ship motion and sloshing tanks simultaneously. With the development of computational science, computational fluid dynamics (CFD) method became popular. The CFD method had the advantage of solving violent sloshing fluid and non-rectangular shape tanks, some researchers applied CFD method to solve sloshing tanks and used potential theory to solve ship motion[4-6]. Igbadumhe and Fürth[7] had reviewed the numerical methods for analyzing ship motion coupled with sloshing tanks. However, such methods cannot solve breaking waves outside the ship. In order to study the hydrodynamics around the ship, a field method named RANS-RANS (Reynolds averaged Navier-Stokes) method was applied to solve this problem[8]. Zhuang et al.[9] applied CFD method solving both ship motion and sloshing tanks simultaneously to achieve the fully coupled ship motion with sloshing tanks. Therefore, the fully

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coupled sloshing method by CFD was applied in this paper.

In order to simulate the freak wave, a potential-viscous theory was applied. The freak wave was generated by high-order-spectral (HOS) method which is a model of high efficiency and accuracy[10-11]. The HOS-CFD coupled method can transform the wave information which was generated by HOS into CFD method[12-13].

This paper applied the coupled method of HOS and CFD in our in-house solver naoe-FOAM-SJTU[14] to simulate FPSO with sloshing tanks in freak waves. First of all, the freak wave was generated by HOS-NWT[15], and be transferred into CFD zone. A FPSO model with two LNG tanks was chosen and was validated in regular waves. Meanwhile, the coupling effects were considered. The motion responses of FPSO with two sloshing tanks in the freak wave is discussed. Besides, the coupling effects of ship motion and sloshing tanks are analyzed. The wave field around the ship and the sloshing phenomenon are discovered.

1. Numerical method

This section introduces the numerical method used in this paper. The HOS method and CFD method as well as the combination between these two methods are introduced. Meanwhile, the way the ship motion and sloshing tanks are solved simultaneously are also illustrated.

1.1 *HOS-CFD coupled method*

The HOS-CFD coupled method is one-way coupling method, applying domain decomposition coupled method. The viscous method uses our in-house solver naoe-FOAM-SJTU.

naoe-FOAM-SJTU[14] is an in-house solver based on the open source software OpenFOAM, equipped with six DOF module, overset grids and some turbulence models. The governing equations are:

$$\nabla \cdot \boldsymbol{U} = 0 \tag{1}$$

$$\frac{\partial \rho \boldsymbol{U}}{\partial t} + \nabla \cdot [\rho(\boldsymbol{U} - \boldsymbol{U}_g)\boldsymbol{U}] = -\nabla p_d - \boldsymbol{g} \cdot \boldsymbol{x} \nabla \rho \tag{2}$$

where $\boldsymbol{U}$ is velocity field, $\boldsymbol{U}_g$ is velocity of grid nodes and p_d is dynamic pressure.

The in-house solver naoe-FOAM-SJTU applied volume of fluid (VOF) to capture the free surface. The numerical model in this paper is chosen to be RANS model, as zhuang et al.[9] have been studied that laminar model and RANS model did not change the ship motion response in naoe-FOAM-SJTU, while laminar model overestimated the sloshing phenomenon in tanks.

The potential method is based on high order spectral (HOS) scheme. The partial differential equation on dynamic and kinematic free surface boundary condition shown below[10]:

$$\eta_t + \nabla_x \phi^s \cdot \nabla_x \eta - (1 + \nabla_x \eta \cdot \nabla_x \eta)\phi_z(\boldsymbol{x}, \eta, t) = 0 \tag{3}$$

$$\phi_t^s + \eta + \frac{1}{2}\nabla_x \phi^s \cdot \nabla_x \phi^s - \frac{1}{2}(1 + \nabla_x \eta \cdot \nabla_x \eta)\phi_z^2(\boldsymbol{x}, \eta, t) = -Pa \tag{4}$$

where ϕ^s is the surface potential velocity. Writing ϕ in a perturbation series and expanding each order of ϕ evaluated on free surface in a Taylor series, the surface potential velocity is

$$\phi^s(\boldsymbol{x}, t) = \sum_{m=1}^{M} \sum_{k=0}^{M-m} \frac{\eta^k}{k!} \frac{\partial^k}{\partial z^k} \phi^{(m)}(\boldsymbol{x}, 0, t) \tag{5}$$

with the initial conditions known for the simulation, Eq. (5) can be solved for unknow ϕ.

Due to Eqs. (3), (4) we can get the unknown ϕ with the given times. The results of HOS can be combined into CFD zone using the relaxation scheme[16].

$$\phi = \alpha_R \phi_{\text{computed}} + (1 - \alpha_R)\phi_{\text{target}} \tag{6}$$

The relaxation weight α_R is exponential weight. The exponential weight has the following form[16].

$$\alpha_R = 1 - \frac{\exp \sigma^p - 1}{\exp 1 - 1} \tag{7}$$

The exponent p is set to 3.5 as default. σ is a local coordinate, the value is from 0 to 1.

The whole calculation process of combined HOS-CFD method can be illustrated as:

(1) Applying HOS-NWT[15] to do the wave generation, and store information on modes.

(2) Looking for desired time duration and wave field.

(3) At the time of CFD simulation, corresponding to the time in HOS wave field.

(4) Mapping the relaxation zone to the HOS wave field, and propagate wave information into CFD zone.

(5) Solving Navier-Stokes equation in CFD zone.

(6) Before the end time, back to (3).

Figure 1 shows the calculation process of the combined solver of naoe-FOAM-SJTU. The coupled method needs to transfer the HOS modes from frequency domain to time domain, and needs to refine the HOS mesh to map with that in CFD zone. The HOS information are handled with the help of Grid2Grid[17].

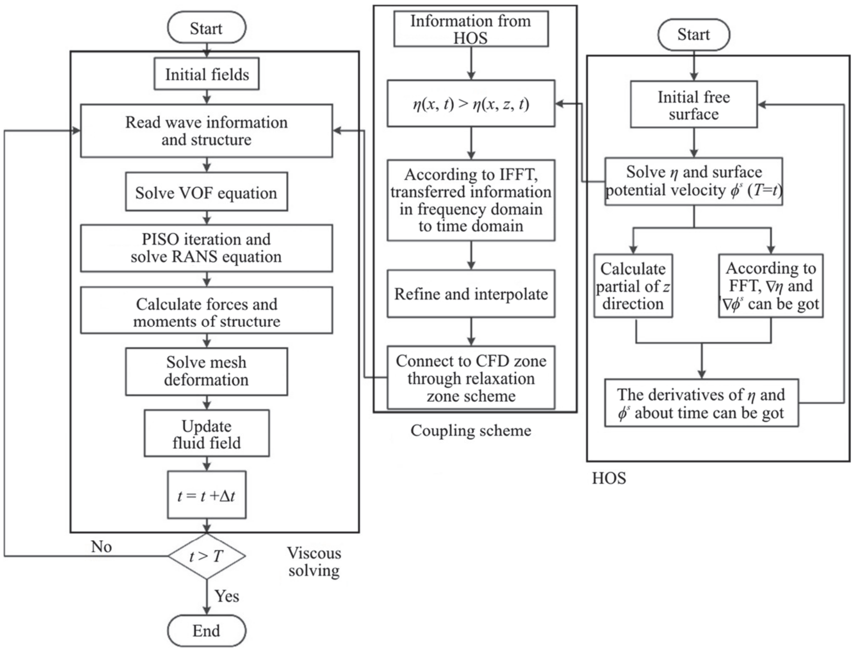


Fig. 1 The calculation process of the combined solver in naoe-FOAM-SJTU

1.2 *Ship motion and sloshing tanks fully coupled model*

The sloshing tanks and the ship motion are solved in a fully coupled model. This fully coupled model unified interior free surface and exterior free surface, thus the sloshing tanks and ship motion can be simulated simultaneously. The way to achieve the coupling model is to generate a tunnel on the top of the tank, thus the pressure and velocity in tanks can be connected with wave fields. The details can be found in previous works[9, 18].

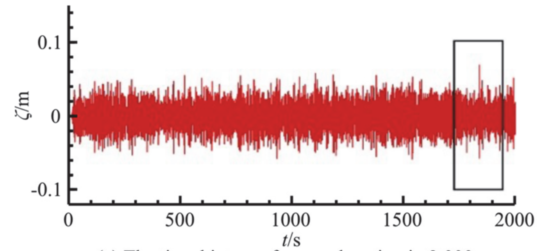
2. Numerical study

2.1 *Numerical study of a random freak wave*

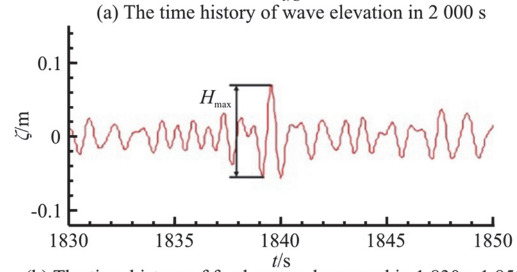
The definition of the freak wave is not unified up till now, therefore we choose a common definition of the freak wave, that the wave height is more than twice of the significant wave height $(H_{\max} > 2H_s)$ [19-20].

The wave field is 50 m×30 m, the spectrum peak period $T = 1.2048\ \mathrm{s}$, the significant wave height $H_s = 0.05\ \mathrm{m}$, the wave spectrum is chosen to be JONSWAP. In this paper, we applied HOS-NWT to simulate 2 000 s to find the freak wave. A wave probe is set with a distance of 11.928 m from wave maker.

The time history of wave elevation of this wave probe is shown in Fig. 2(a) in which ζ represents for the wave elevation. After the simulation time of 1 800 s, a peak wave height is observed. With a close sight of the peak wave height, as shown in Fig. 2(b) we can find that the maximum wave height $H_{\max} = 0.12\ \mathrm{m}$, is more than twice of the significant wave height. Therefore, the freak wave is found. We choose this time duration to do the simulation.



(a) The time history of wave elevation in 2 000 s



(b) The time history of freak waves happened in 1 830 s-1 850 s

Fig. 2 (Color online) The time history of wave elevation in HOS-NWT

After we got the results of the freak wave in HOS, the coupled method is applied to generate the freak wave in CFD method. The computational viscous domain is set as $-2.85\ \mathrm{m} < x < 5.70\ \mathrm{m}$, $-2.275\ \mathrm{m} < y < 4.275\ \mathrm{m}$ and $-2.85\ \mathrm{m} < z < 2.85\ \mathrm{m}$. The relaxation zone for wave damping is set to be 0.7 m. The mesh around free surface is refined twice to capture the wave, and the total mesh grids is 1.86×10^8. The CFD domain is set in the distance of $x = 11.928\ \mathrm{m}$,

$y = 15$ m from original point of HOS domain, and the simulation time starts at 1 830 s. The result of the coupled method is shown in Fig. 3. Comparing with the original wave elevation from HOS-NWT, the coupled method can generate the freak wave in viscous zone accurately.

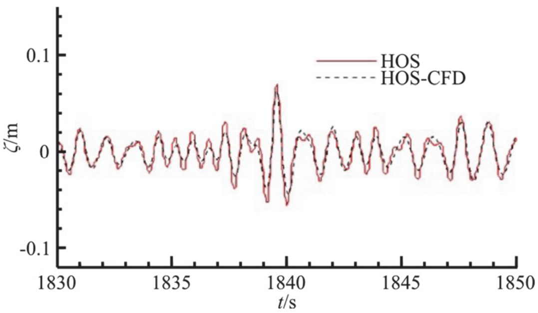


Fig. 3 (Color online) The comparison of wave elevation between HOS and HOS-CFD coupled method

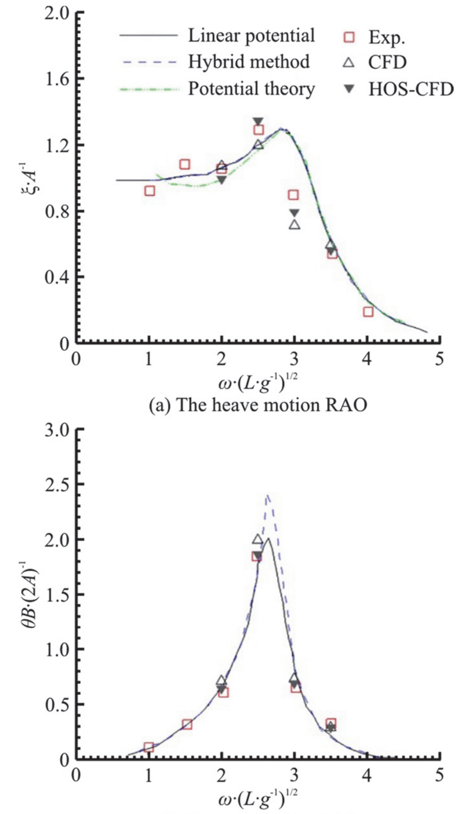
2.2 *The verification of ship with sloshing tanks*

Before we do the simulation of FPSO in the freak wave, the numerical model of FPSO with two sloshing tanks needs to be verified. The verification of this numerical model has been done in previous works with CFD method[9, 18], thus in this paper, only the verification with HOS-CFD coupled method is carried out. The LNG FPSO model is chosen from the experiments which are made by Nam et al.[21], the computational setup can be found in previous work[9, 18]. Two kinds of filling ratios are chosen to be simulated, with 20%-20% (filling ratio in fore-aft tank) filling condition and 0%-0% filling condition.

The comparison of different numerical results is shown in Figs. 4, 5. The experimental data comes from the model test[21]. Meanwhile, they also investigated this problem in potential theory. Gou et al.[22] simulated this model in linear potential theory. Jiang et al.[5] applied hybrid method to do the simulation. The hybrid method solved ship motion in potential theory and the sloshing tanks in CFD method. The previous works in CFD method are also presented to do the comparison, remarked as white triangle.

The heave and roll motion RAO are analyzed. The heave motion RAO is defined as ξ / A, which ξ represents the maximum heave motion. The roll motion RAO is analyzed with $\theta B / 2A$, which θ is the maximum roll degree, B is the beam of the ship and A is wave amplitude. It can be seen that the results of HOS-CFD agree well with the experimental results, shows the accuracy of the numerical methods and the numerical model.

Comparing the roll motion RAO between the zero filling ratio and 20% filling ratio, it can be seen that the natural frequency of the ship motion has been changed due to the existence of the sloshing tanks. The natural frequency of ship motion decreases due to the sloshing tanks, and shows a second peak around the non-dimensional frequency of 3.25. The value of roll motion of the ship with sloshing tanks is larger than that of zero-filling ratio ship in their separate natural frequency, while around the natural frequency of zero filling ship, the roll motion of ship with sloshing tanks decreases. In general, the existence of sloshing tanks with 20%-20% filling ratio affects the ship motion apparently in regular waves. This kind of influence is known as coupling effect.



(a) The heave motion RAO

(b) The roll motion RAO

Fig. 4 (Color online) RAOs in beam wave condition with 0%-0% filling condition

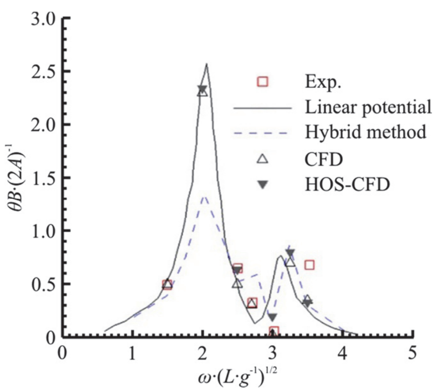


Fig. 5 (Color online) Roll motion RAO in beam wave condition with 20%-20% filling ratio

2.3 *The analysis of motion response in freak wave*

Figure 6 shows the setup of the computational domain of viscous zone. The FPSO liquefied national gas (LNG) is set in the distance of 2.85 m from inlet boundary, and the setup of the computational domain is the same as that of freak wave. Figure 7 shows the mesh generation around the FPSO LNG, the mesh around the ship and inside the tanks is refined to capture the fluid. The total mesh grids are 3.01×10^{8}.

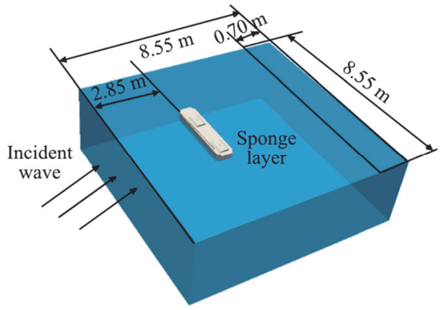
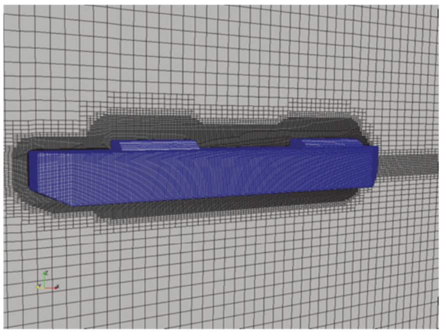
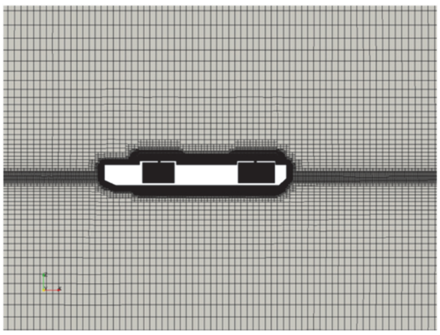


Fig. 6 (Color online) The setup of computational domain



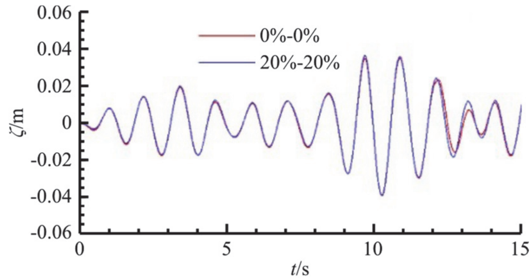
(a) The mesh generation around ship



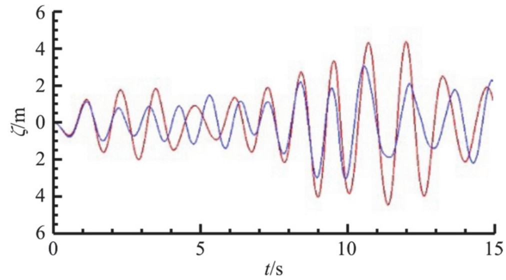
(b) The mesh generation in tanks

Fig. 7 (Color online) Computational mesh for FPSO LNG

Figure 8 shows the comparison of RAOs between empty FPSO and 20% filling ratio FPSO. The horizontal coordinate-axis represents the simulation time of viscous zone, not the propagation time of the freak wave. It can be seen that the trend of heave motion shows little difference between regular waves and that in the freak wave. The heave motion of zero filling ratio FPSO and 20% filling ratio FPSO is almost the same. However, the roll motion of FPSO with two different filling ratios shows large difference. With the sloshing tanks, the roll motion of FPSO is smaller than that of empty-tank FPSO. The existence of the sloshing tanks decreases the roll motion of the ship.



(a) The time history of heave motion



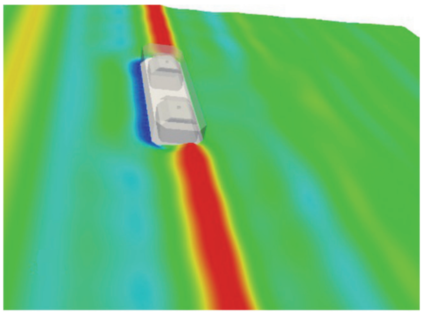
(b) The time history of roll motion

Fig. 8 (Color online) The comparison between RAOs in 0%-0% filling condition and 20%-20% filling condition

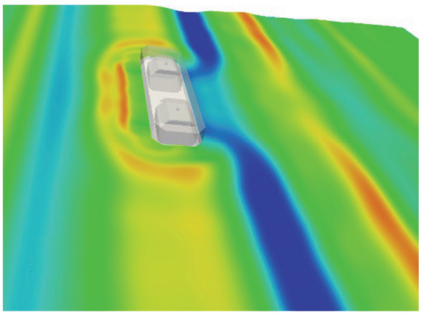
The occurrence time of the freak wave is around 1 840 s, which in CFD time is around 10 s. However, both the FPSO with empty tanks (0%-0%) and sloshing tanks (20%-20%) reach the maximum roll motion after 10 s. The ships reach the maximum heave motion is around the time which freak wave occurs. As for FPSO with 20% filling ratio tanks, the roll motion is still large after encountering the wave peak of the freak wave, while the roll motion of the 0% filling ratio ship decreases rapidly, shows the same trend with the wave elevation of the freak wave. Therefore, it can be seen that the freak wave gives a large excitation on the ship. When the ship encounters with the freak wave, the ship generates a large restoring moment which excites a large roll motion on the next period, and the sloshing tanks restrain this kind of excitation.

2.4 *The coupling effects of sloshing tanks and ship*

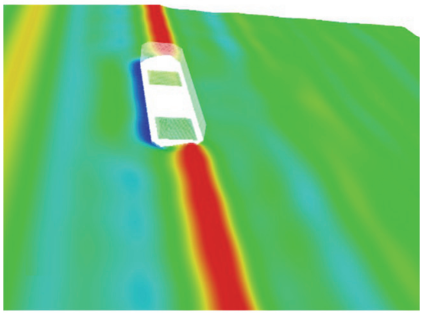
Figure 9 shows the wave field around the FPSO with two kinds of filling conditions. Two time-spots are chosen to be analyzed. The one is around 10.6 s, when the maximum roll motion occurs. The other is 9.65 s, which is the maximum heave motion occurs. It can be seen that heave motion reaches the peak value earlier than that of roll motion. When the FPSO encounters with wave crest of the freak wave, the fluid in tanks is very gentle, and the radiation wave can be found. When the FPSO reaches the position of maximum roll motion, the radiation wave around ship bow and stern is violent, and the fluid inside the tank forms a small wave peak in the middle of the tank.



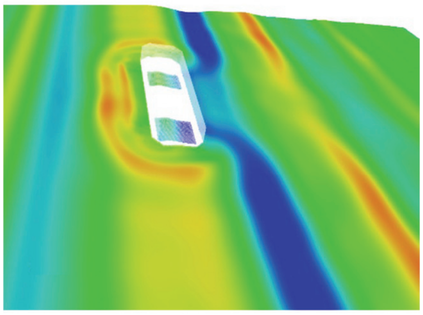
(a) $t = 9.65$ s of 0% filling ratio



(b) $t = 10.60$ s of 0% filling ratio



(c) $t = 9.65$ s of 20% filling ratio



(d) $t = 10.60$ s of 20% filling ratio

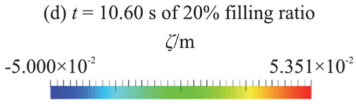
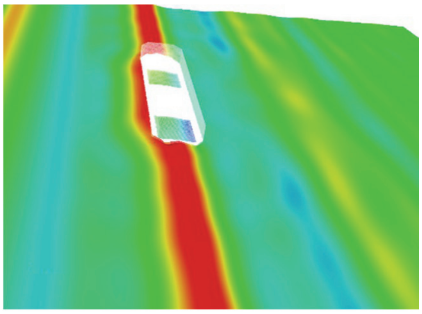
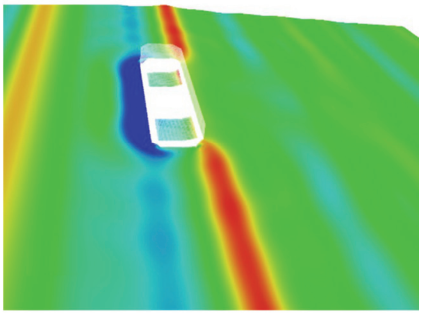


Fig. 9 (Color online) Snapshots of wave fields in 0%-0% and 20%-20% filling ratios

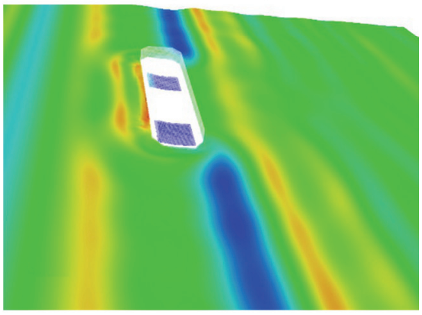
In order to study the coupling effects in the freak wave, Fig. 10 shows the wave fields around the ship and the fluid inside the tanks. The time duration starts from $t = 9.5$ s and ends up with $t = 11.0$ s. When the wave crest encounters the FPSO, the fluid in tanks shows a small runup on the left bulkhead of the tank. After the FPSO reaches the position of maximum



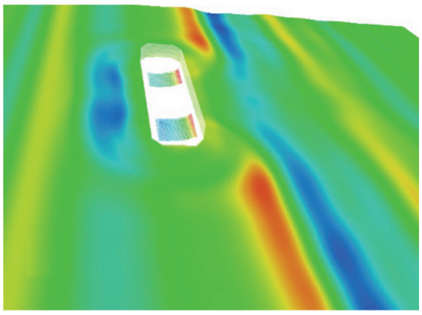
(a) $t = 9.5$ s



(b) $t = 9.8$ s



(c) $t = 10.3$ s



(d) $t = 11.0$ s

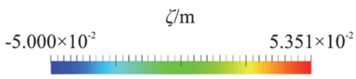


Fig. 10 (Color online) The coupling effects in 20%-20% filling condition

heave motion, the wave peak inside the tank reaches the right side of the tank, and climbs up on the bulkhead. Before the ship reaches the position of the maximum roll motion, the wave trough of the freak wave encounters the FPSO, the fluid inside the tank is gentle but the fluid around the ship shows the break phenomenon. When the time $t = 11.0\ \mathrm{s}$, the wave crest and trough both passes through the FPSO, the fluid inside the tank climbs on the right bulkhead of the tank.

It can be seen that wave crest of the freak wave excites the motion of FPSO, which excites the fluid inside the tank begins to slosh along the direction of the roll motion. The natural frequency of the sloshing tank and the ship are different, thus the fluid in tanks gives contrary moment to the ship. This kind of moment not only decreases the value of the roll motion, but also changes the motion period.

3. Conclusions

This paper applied a potential-viscous combined solver HOS-CFD to simulate the coupling effects of ship motion and sloshing tanks. The ship motion and sloshing tanks were solved in a fully coupled CFD method. The FPSO with two LNG tanks were chosen, and two kinds of filling ratios in tanks were considered to figure out the coupling effects. This numerical model was verified in regular waves, showing the HOS-CFD coupled method had the ability to simulate FPSO with sloshing tanks accurately. The coupling effects of the sloshing tanks on ship motion were also found.

A random freak wave was simulated in HOS method and made as an input into viscous zone to do the fully coupled simulation. It can be found that under the freak wave, the existence of sloshing tanks not only decreased roll motion, but also changed the frequency of the roll motion. FPSO with 20% filling ratios showed a lower roll motion when the freak wave passed by. When the FPSO encountered with the freak wave, the one with empty tanks showed large motion response to the freak wave, even when the wave crest passed. The one with sloshing tanks showed restrains on roll motion, after wave crest passed, the amplitude of roll motion decreased rapidly. Meanwhile, the wave breaking was–observed around the FPSO when the freak wave contacted the ship.

In this paper, the observation of the freak wave is due to a long-time simulation. As the probability of the occurrence of the freak wave is small, the simulation time has to be long enough to find out the freak wave. Therefore, researchers began to find new methods to generate freak waves, such as generating focused waves or changing the wave phases to make freak waves. HOS method has the advantage to simulate freak waves, with the help of combination with the CFD method, the new coupled method can be implemented under more freak-wave conditions.

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