The Eleven Asian Computational Fluid Dynamics Conference (ACFD11)
September 16-20, 2016, Dalian, China

Numerical study on coupling effect of LNG tank sloshing and ship motion in waves

Yuan ZHUANG, Chonghong YIN, Decheng WAN*
State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean and Civil Engineering,
Shanghai Jiao Tong University, Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration,
Shanghai 200240, China
** Corresponding author: dcwan@sjtu.edu.cn*

Abstract

In this paper, numerical simulations of ship motion coupled with LNG tank sloshing in waves are considered. The fully coupled problems are performed by our own unsteady RANS solver, naoe-FOAM-SJTU, which is developed based on the open source toll libraries of OpenFOAM. The internal tank sloshing and external wave flow are solved simultaneously. The considered models are LNG FPSO with two tanks. Three degrees of freedom is released in the regular beam waves. The ship motion responses of LNG FPSO are carried out to compare with existing experimental data to validate this solver. Next, different wave condition is chosen to figure out the wave amplitude effect on coupled motion. The sloshing tanks observed in this paper can reduce the roll motion in waves, especially low filling ratio tanks, and large wave amplitude discussed in this paper also reduce the roll motion.

Keyword: *LNG sloshing, Coupled motion, waves, naoeFOAM-SJTU solver*

1. Introduction

With the development of LNG and FPSO, the sloshing tanks which affect the ship motion is still worth discussing. The ship motion excited by external waves influences tank sloshing and the sloshing liquid in tanks affect ship motion in return. The coupling effects depend on external waves and tank filling conditions, and strong coupling effect may cause impulsive pressure and even structure damage in tanks. Therefore, it's essential to take a numerical study on the coupling effects. Computational Fluid Dynamics (CFD) plays a vital role in numerical simulation, especially in solving the nonlinear surface and turbulent flow. Therefore, it's an effective way to simulate the coupling effect in CFD method.

Several studies have been done for the coupled motion response of ship motion and tank sloshing. Nam, et al[1] implemented both numerical and experimental methods for LNG FPSO model with two tanks. The impulse-response-function (IRF) was used to simulate ship motion and finite-difference method was adopted to solve nonlinear tank sloshing. In recent decades, many studies used viscous flow theory in order to solve the nonlinearity of the tank sloshing. Li, et al[2] applied both potential flow theory and viscous flow theory under OpenFOAM. Jiang, et al[3]also used OpenFOAM to simulate the coupling effect, and applied VOF to capture the interface. The paper still considered ship response in IRF method. Shen and Wan[4] achieved fully coupled of ship motion and tank sloshing by using unsteady RANS in-house solver, naoe-FOAM-SJTU.

The object of this paper is to simulate the coupling effects of ship motion and inner tank sloshing by CFD method. The internal sloshing tank and external sea waves are treated as an entire computational region and both are solved by Reynolds-Average Navier-Stocks (RANS) model simultaneously. Volume of fluid (VOF) is used to capture both the liquid in tanks and wave surface outside. The computations are performed by our in house solver naoeFOAM-SJTU, which developed based on the open source tool packages, OpenFOAM. The dynamic deformation mesh module is implemented to capture ship motion, and with the solver contains 6-degree-of –freedom motion module, wave generation and damping module, it is possible to simulate ship motion in waves coupled with sloshing tanks.

To validate the current CFD method, a LNG FPSO with two tanks is chosen as model ship. Five different filling conditions are selected in beam waves. The simulation results are compared with those in experiments to prove the ability of our solver. Ship motion with sloshing tanks in large wave amplitude is investigated to observe the effects of wave amplitude.

2. Methodology

The incompressible Reynolds-Averaged Navier-Stocks equations are adopted in this paper to investigate the viscous flow. The solution of momentum and continuity equations is implemented by using the pressure-implicit spit operator (PISO) algorithm. A k-ω SST model is selected for turbulence closure[6].

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:

$$\frac{\partial \alpha}{\partial t}+\nabla\cdot\left[\left(\boldsymbol{U}-\boldsymbol{U}_g\right)\alpha\right]+\nabla\cdot\left[\boldsymbol{U}_r(1-\alpha)\alpha\right]=0 \tag{1}$$

Where $\boldsymbol{U}_g$ is velocity of grid nodes and α is volume of fraction, indicating the relative proportion of fluid in each cell and its value is always between zero and one:

$$\begin{cases}\alpha=0 & \text{air}\\ \alpha=1 & \text{water}\\ 0<\alpha<1 & \text{interface}\end{cases} \tag{2}$$

3. Geometry and Conditions

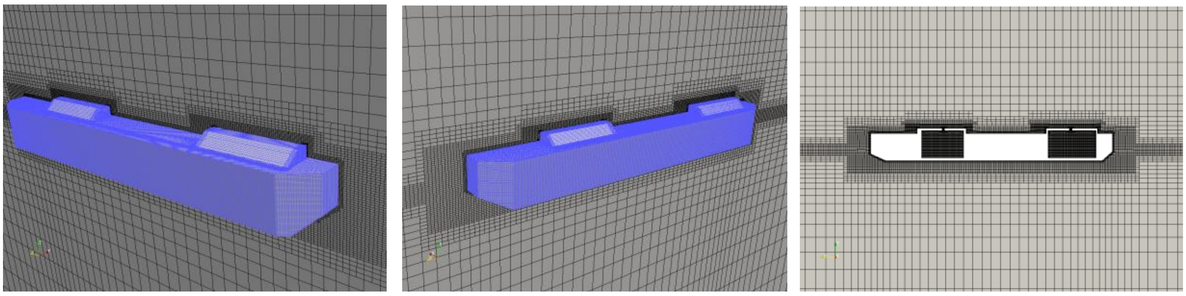
To validate the current method, a LNG FPSO model with two prismatic tanks is considered. The main particulars of LNG FPSO are shown in Table 1. Compared with experiments which have been done by Nam, B. W. et al[1], this paper selects LNG FPSO which is 1/100 scale of 284m length. The length, breadth and height of the fore tank and the aft tank are 49.68m, 46.92m, 32.23m and 56.62m, 46.92m, 32.23m respectively. The distance from the bottom of tank to the keel line is 3.3m.

The current method simulates five different filling conditions of inner tanks. To compare with experiment data, the filling ratios carried out as the same with those in experiments: 0%-0% (fore tank-aft tank), 20%-20%, 30%-30%, 57.5%-43.3% and 82.6%-23.5%. The daft at each condition were kept the same, as well as longitudinal moment inertia. Considering the large-amplitude motion of LNG FPSO, the length of regular wave is chosen as 2.865m, 1.005 times length of the ship. Same to the experiment, the wave height is fixed to 0.025m, and encounter frequency is 4.6382.

The selected domain is described as $-1.0L_{pp}<x<2.0L_{pp}$, $-1.5L_{pp}<y<1.5L_{pp}$, $-1.0L_{pp}<z<1.0L_{pp}$. The meshes are generated by snappyHexMesh, an auto mesh generation utility provided by OpenFOAM. The total cell numbers are around 2.1M, and the LNG tanks require 0.5M cells. The mesh details are shown in Fig. 1. Fig.1(c) shows two small tunnels connected the LNG tanks to the external region, which can keep the pressure inside the tanks same to the external region, and simplify the computations.

Table 1 Main particular of LNG FPSO

Main particulars		Full Scale	Model
Scale factor	—	1	1/100
Length between perpendiculars	L_{PP} (m)	285	2.85
Maximum beam of waterline	B_{WL} (m)	63	0.63
Draft	T (m)	13	0.13
Displacement	Δ (m^3)	220017.6	220.0176
Natural period of roll	T_{ϕ} (s)	13	1.3
Vertical Center of Gravity (from keel)	KG (m)	16.5	0.165
Radius of gyration	K_{xx}	19.45	0.1945
	K_{yy}	71.25	0.7125



(a) bow (b) stern (c) ship hull with tanks

Fig.1 Demonstrations of meshes

4. Results

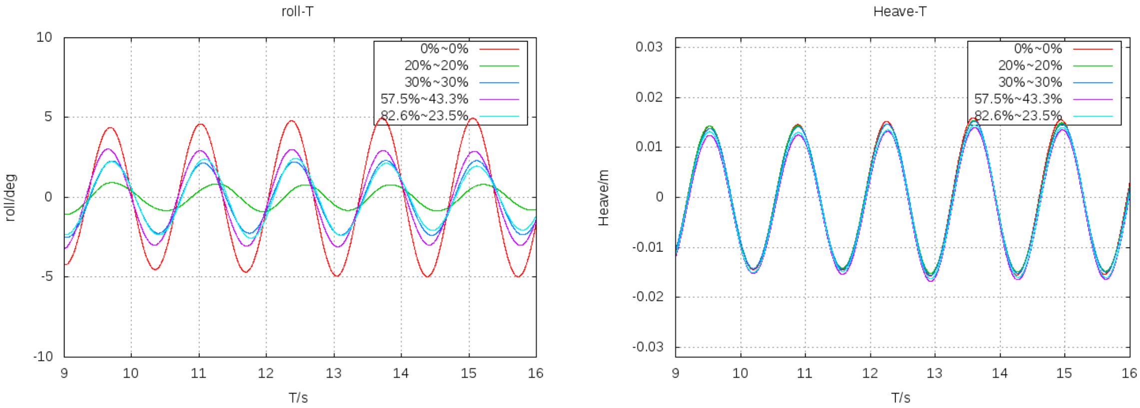
4.1 Validation

The ship motion was restricted to three degree-of-freedom, heave, pitch and roll. The normalized motion amplitude and natural frequency were considered to compare with experimental data. The normalized roll motion is given as:$R_1 = \theta B/2A$,[3] which θ is maximum degree of roll motion, B is beam of ship and A is wave amplitude; The normalized heave motion is given as: $H_1 = \xi/A$, which ξ is the maximum value of heave motion; and normalized natural frequency is given as:$T = \omega(L/g)(1/2)$, which ω is natural frequency of water, L represents length of ship. This paper uses T=2.5 when the wave length is close to ship length.

Table 2 shows the comparison of roll motion and heave motion between current computation and experiments in beam waves. Five different filling conditions were considered, and the results fairly agree with those in experiments.

Table 2 Comparison of ship motion between CFD and experiments

No	Filling ratio	EFD($\boldsymbol{R_1}$)	CFD($\boldsymbol{R_1}$)	EFD($\boldsymbol{H_1}$)	CFD($\boldsymbol{H_1}$)
1	0%~0%	1.85	2.00(8%)	1.25	1.28(2.4%)
2	20%~20%	0.60	0.50(-16%)	-	1.22
3	30%~30%	1.25	1.10(-12%)	-	1.21
4	57.5%~43.3%	1.30	1.28(-1.5%)	-	1.10
5	82.6%~23.5%	1.20	1.10(-8.3%)	-	1.04



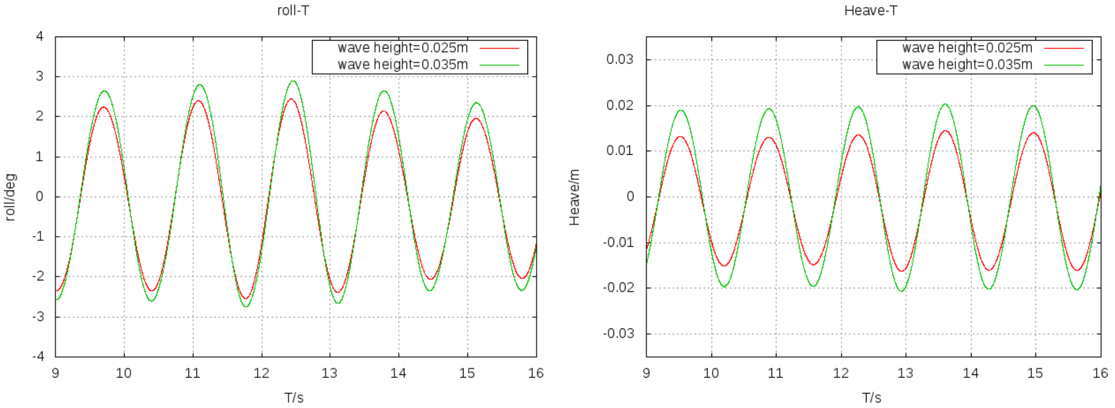
(a) roll motion (b) heave motion

Fig2. Time history of heave and roll motion with different filling ratios

Time histories of heave and roll motion are shown in Fig.2. It indicates that the ship exhibits sinusoidal motion beam waves. In beam wave condition, the coupling effects of ship motion and tank sloshing are not obvious in heave motion, shown in Fig.2(a), but quite significant in roll motion, shown in Fig.2(b). The four partially filling conditions of sloshing tanks all reduce the roll amplitude of ship motion, and especially for low-filling condition, like 20%~20%, the decrease in amplitude of roll motion is evident and thus shows great coupling effect. For the water in tanks is shallow, the sloshing in tanks is more violent and influence ship motion more.

4.2 Effects of Wave Amplitude

To observe the effects of wave amplitude, one more wave condition is chosen. The wave height is fixed to 0.035m and the wave length stays the same. The 82.6%-23.5% filling condition is considered to observe the effect. Fig. 3 shows the time history of heave and roll motion which compared to small wave amplitude. It is observed in Fig.3 that large wave amplitude induce large motion for 82.6%-23.5% filling ratio. Considering normalized roll motion R_1, larger wave amplitude condition is smaller than that of small wave amplitude, shows the nonlinear growth of sloshing-induced moments to wave amplitudes.[3]



(a) roll motion (b) heave motion

Fig3. Time history of heave and roll motion in different wave conditions

5. Conclusions

In this paper, the ship motion fully coupled with internal sloshing tanks in waves is presented. The computational simulations are performed by our in-house solver naoe-FOAM-SJTU. The internal tank sloshing and external wave excitation are computed simultaneously by solving RANS equations. Two phase interface is captured by VOF method. To validate the current method, LNG FPSO is chosen to compare with existing measurements data. Four different filling conditions are considered both in the head and beam wave. The results show fairly agreement with those in experiments. At the meantime, the coupling effects are investigated. With the wave length equal to 1.005 times ship length, the sloshing has remarkable effect on roll motion in the beam wave condition. The comparison between four different filling ratios with non-filling ratio indicates that all these four kinds of filling conditions reduce the roll amplitude of ship motions, especially the low filling ratios, like 20% filled tanks. To further study the ship motion coupled with sloshing tanks, a large wave amplitude wave condition is chosen. The 82.6%-23.5% filling ratio shows small normalized roll motion due to sloshing tanks. However, this paper only investigates one filling condition in large wave condition, more filling conditions in different wave amplitudes are needed to be studied.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (51379125, 51490675, 11432009, 51579145, 11272120), Chang Jiang Scholars Program (T2014099), Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning (2013022), and Innovative Special Project of Numerical Tank of Ministry of Industry and Information Technology of China (2016-23/09), to which the authors are most grateful.

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