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Coupled analysis of integrated dynamic responses of side-by-side offloading FLNG system

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ABSTRACT

Integrated dynamic responses of FLNG system in side-by-side offloading operation are investigated numerically and experimentally in this paper. A numerical code is developed based on potential flow theory to predict the interactions between connected vessels' motions and liquid sloshing in the time domain. The impulsive response function (IRF) method is adopted in the resolution for 6 DOF vessels' motions, nonlinear sloshing in liquid tanks is solved using boundary element method (BEM), and connection system including hawsers and fenders is numerically modeled as linear response system. A series of model tests are conducted to validate the feasibility of the numerical code. Hydrodynamic interaction between the vessels and shielding effects under different wave directions are analyzed; sloshing effects on the vessels' motions and on the loads of connection system are investigated; the sensitivities of the vessels' motions and loads to connection system stiffness are discussed. It is found that the vessels' motions are significantly affected by the hydrodynamic interactions between vessels and sensitive to wave directions for shielding effects. The radiation forces of the adjacent vessel tend to amplify vessel's motions and LNG carrier is more likely to be affected by FLNG's radiation forces for their difference in displacement. In addition, compared with solid loading condition, liquid loading vessel tends to have decreased natural roll frequency and have increased sway motions in the frequency region that higher than the natural sloshing frequency. The two sloshing responses peaks appear in the natural roll frequencies and natural sloshing frequencies, which are respectively mainly excited by vessels' roll and sway motions. Besides, in low fill conditions, the sloshing loads contribute to larger sway motions in low fill conditions for the natural sloshing frequencies are closer to the main response frequency region of vessels. Sloshing nonlinearity gets obvious in the conditions with low fill conditions and large wave amplitude, while the motion responses of vessels have slight nonlinearity with the increases of sloshing nonlinearity when no violent sloshing with wave break is excited. Furthermore, small stiffness of the connection system has slight influences on the vessels' motions, and resonant motions can be excited when the natural frequency of the connection system located in the wave frequency region.

1. Introduction

The development of floating liquefied natural gas (FLNG) system that can produce, process and store liquefied natural gas (LNG) offshore has been stimulated by the increasing demand of natural gas. One challenge for the operation of FLNG system is LNG offloading to an LNG carrier. Considering the efficiency and the limitation of flexible pipeline in transferring LNG under extremely low temperature, side-by-side configuration is more economically attractive than tandem configuration in offloading operation. In the hydrodynamic perspective, the side-by-side arrangement of a FLNG system involves interactions between multiple bodies, sloshing in liquid tanks and resonance in the narrow gap between vessels. Besides, the connection system adopted to restrict the relative motions between vessels also plays a crucial role, and attentions should also be paid to the loads on the connection system.

Hydrodynamic interactions among floating bodies in proximity exist in many applications in ocean engineering and have received many

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researchers' attentions. Kodan (1984) analyzed two parallel floating structures using strip theory. Inoue and Islam (1999) calculated motions of multiple floating offshore structures with consideration of the effects of connectors and mooring lines in the frequency domain. Buchner et al. (2001) developed a numerical model to predict the hydrodynamic responses of paralleled moored vessels in the time domain, where hydrodynamic coefficients were prepared in the frequency domain. Newman (2001) presented numerical and analytical results in the research of multiple floating bodies, first and second order interaction effects were considered. Choi and Hong (2002) and Hong et al. (2005) applied high order boundary element method (HOBEM) to simulate side-by-side vessels in the time domain. To research the coupling mechanism of two adjacent vessels, Koo and Kim (2005) compared three different numerical methods in combining motion equations. Zhu et al. (2008) developed a numerical program to simulate hydrodynamic interactions of three-dimensional multiple floating structures in the time domain based on potential flow theory, the governing equations were solved in time domain directly rather than using IRF. Pessoa et al. (2015) conduced numerical and experimental research on two floating structures connected with mooring lines and fenders. First order relative motions and loads on connection system were investigated. Zhao et al. (2012) carried out numerical simulation of FLNG system in parallel arrangement with time-domain analysis code SIMO. Xu et al. (2015) studied coupled motions of three barges in side-by-side arrangement; a numerical program was developed and validated by test results. Based on relative motions between vessels, loads on connection system were obtained by assuming the connection system reacts quasi-statically (Hong et al., 2005; Zhao et al., 2014; Pessoa et al., 2015).

For floating vessels in proximity, resonance in the gap between vessels is also a complicated phenomenon and is of practical importance. Molin (2001) derived analytical solution of resonance in moon pools. Sun et al. (2010) studied the first and second order resonant properties between barges in parallel. The results of model tests showed that resonant frequencies would shift depending on whether the barges were fixed or floating. Zhao et al. (2017) experimentally investigated the resonant sloshing responses in the gap between two fixed barges. In the calculation of hydrodynamic coefficients in the frequency domain, potential flow theory tends to over-predict resonant responses in the gap and generates inaccurate hydrodynamic coefficients for no viscosity was accounted. Huijsmans et al. (2001) applied a rigid lid in the gap to suppress the unrealistic prediction. Chen (2005) modified the free surface condition between vessels by introducing an artificial damping term to suppress resonant fluid in the gap. This method had been used in sloshing problems to account for energy dissipation (Faltinsen, 1978). Lu et al. (2011) and Yao and Dong (2015) also applied a dissipating parameter to study the wave elevation in the gap, and sensitivities to the parameter value were discussed. It was found that the artificial damping term can suppress unrealistic resonant sloshing effectively, but the selection of proper value still needs much effort.

Moreover, sloshing in the liquid tanks in FLNG system makes vessels' motion responses much different from solid loading condition. To date, many methods have been adopted in the predication of sloshing in liquid loading vessel. Lee et al. (2007) and Nam et al. (2009) calculated sloshing in a liquid tank through a Navier-Stokes solver, and coupled the sloshing loads with the ship motion solved by linear potential flow. Jiang et al. (2015) used the open source computational fluid dynamics (CFD) code OpenFOAM to investigate the couplings in liquid loading vessels in the time domain and found impact loads due to violent sloshing had less effect on ship's global motion responses. CFD methods solving Navier-Stokes equations tend to have low efficiency in dealing with FLNG system with large liquid tanks and various fill conditions. Malenica et al. (2003) considered dynamic coupling of liquid loading vessel in the frequency domain, and linear potential theory was adopted in the solving both sloshing and vessel's seakeeping properties. Rognebakke and Faltinsen (2003) applied a multimodal method to simulate coupled ship motion and nonlinear liquid sloshing in a tank; experiments were conducted to validate the numerical program. Newman (2005) proposed that unless coupling ship motions and sloshing loads in the time domain, the liquid tank could be regarded as an extension of the exterior wet surface. Thus, no iteration between internal sloshing loads and external wave loads was needed, but it would result in larger size of matrix equation. Mitra et al. (2012) studied coupling between three dimensional sloshing and ship motion in different sea conditions, sloshing in tank was simulated based on potential flow and good agreements with experimental results were achieved. Research conducted by Zhao et al. (2015) proved potential flow with an artificial damping model can give accurate and highly efficient simulation of sloshing in the time domain.

Although multi-body floating system and liquid sloshing in vessels have been widely investigated, these two parts were mostly considered separately. The fully coupled analysis of liquid loading FLNG system in side-by-side configuration was rarely conducted. This study aims to develop an accurate and efficient numerical code to predict the dynamic responses of side-by-side arranged FLNG system. The coupling between sloshing in liquid tanks and vessels' motions are solved in the time domain, and hydrodynamic interactions between the vessels as well as motion responses under the restriction of connection system are investigated. A series of experimental tests are conducted to validate the numerical code. The research results reveal hydrodynamic interactions are sensitive to wave direction and small motions are excited when the vessel is located in the lee side. Sloshing loads will change the natural roll frequencies of vessels and lead to increased sway motions in the frequency region higher than that of natural sloshing frequency.

2. Mathematical formulation

In this study, an FLNG system with parallelly arranged FLNG vessel and LNG carrier is considered, and each vessel has two liquid tanks. In the numerical model, coordinate systems are defined as shown in Fig. 1. The global coordinate system $O-XYZ$ is earth-fixed with Z axis pointing upward. Vessel-fixed coordinate systems $O_1-X_1Y_1Z_1$ and $O_2-X_2Y_2Z_2$ are respectively located in the gravity center of FLNG and LNG carrier, with OX and OY pointing to the bow and portside of the vessels. The FLNG-fixed coordinate system vessel $O_1-X_1Y_1Z_1$ coincides with the earth-fixed coordinate $O-XYZ$ initially. The four tank-fixed coordinate systems $o-xyz$ are located in the free surface center initially and parallel with the vessel-fixed coordinate system.

2.1. Vessels in side-by-side configuration

Vessel motions in waves are regarded as linear system that response linearly to wave excitation. In the time domain calculation, impulsive response function method based on frequency-domain results is used in dealing with radiation forces, and solution of vessel motions in the frequency domain is required.

The linear incident wave potential can be written in a general form as:

$$\phi_I(x, y, z, t) = \frac{\zeta_a g}{\omega} e^{kz} \sin[k(x\cos\beta + y\sin\beta) - \omega t - \sigma] \tag{1}$$

where ζ_a, ω, k, β, σ are the wave amplitude, frequency, wave number, heading angle and phase shift, respectively. The potential in the flow field can be regarded as the superposition of incident wave potential, radiation potentials and diffraction potential:

$$\phi = \phi_I + \phi_{Ri}^F + \phi_{Ri}^L + \phi_D \tag{2}$$

where ϕ_I is the incident wave potential, ϕ_{Ri}^F and ϕ_{Ri}^L are respectively the radiation potential corresponding to the 6° motions of FLNG and LNG carrier; ϕ_D is the diffraction potential. In the flow field, the potential ϕ satisfies the Laplace equation: