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Coupling analysis between vessel motion and internal nonlinear sloshing for FLNG applications

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HIGHLIGHTS

- A numerical code is developed to investigate the coupling in liquid loading vessel.
- Model tests are conducted to validate the code and provide perceptual results.
- Coupling mechanism and characteristics in different motion modes are presented.
- Sloshing nonlinearity and its effects on coupling results are discussed.
- Sensitivities of coupling effects to fill levels and wave directions are analyzed.

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ABSTRACT

The coupling interaction between vessel motions and internal tank sloshing is of vital importance for Floating Liquefied Natural Gas (FLNG) system design and operation due to the exposure to diverse sea states at any filling level. A numerical code based on potential flow is developed in this study to investigate the coupling interaction between 6 degrees of freedom (DOF) vessel motions and internal nonlinear sloshing. The impulsive response function (IRF) method is adopted in the resolution for the 6 DOF vessel motions, and internal liquid sloshing is numerically solved with the boundary element method (BEM). The coupling interaction between vessel motions and internal sloshing is calculated in the time domain through an iteration strategy. For the purpose of validating the code and enabling a perceptual understanding of these coupling effects, experimental tests of a vessel with two rectangular tanks are conducted. The proposed code is also validated by previous numerical and experimental results. In addition, the coupling interaction characteristics of internal liquid sloshing and vessel motions are studied, and the sensitivities of coupling effects to filling levels and wave directions are also analyzed. Decreased natural roll motion frequency and response amplitude are excited in the liquid loading condition more than in the solid loading condition; sway motion has a decreased response in the natural sloshing frequency and a response peak in the frequency region that is higher than the natural sloshing frequency; heave motion is not sensitive to sloshing loads. Phase shift analysis reveals that phase shifts between the wave and the sloshing loads change rapidly near the natural roll frequency and natural sloshing frequency. Furthermore, the natural sloshing frequency varies with changes in the filling level, and the coupling effects become obvious when the natural sloshing frequency is close to main response frequency region of the

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vessel. Moreover, coupling effects under head wave conditions have similar properties to those under beam sea conditions, but the sensitivity of pitch motion to sloshing is much lower than that of roll motion.

1. Introduction

As a promising facility in exploiting offshore natural gas fields in deep water, an FLNG system equipped with liquefaction plants and LNG storage tanks has attractive advantages in developing remote and scattered natural gas fields. However, sloshing in the LNG tanks will significantly affect the motion of the FLNG vessel. FLNG vessel has large ranges of filling levels during the production process. Particularly in the offloading operation, the filling level can change greatly within a relatively short period. Thus, the demand for accurate and efficient tools to predict the coupling responses of liquid loading FLNG vessels has been increasing in the literature.

The coupling of vessel motions and internal sloshing has been analyzed in using various methods. Malenica et al. (2003) and Newman (2005) conducted coupling analysis in the frequency domain, where both vessel motions and liquid tank sloshing are linearized. Zhao et al., (2011) and Hu et al. (2016) both used numerical models to analyze internal sloshing loads on FLNG vessel in the frequency domain, and experimental results were presented for comparison (Hu et al., 2016). The linearized vessel motion model has been proven to be efficient, and calculation in the time domain can be performed based on frequency-domain results using the IRF method (Cummins, 1962; Ogilvie, 1964). Nevertheless, because the sloshing nonlinearity can affect the accuracy of the coupling responses prediction, more researches have been conducted in the time domain and nonlinear sloshing has been taken into consideration. Because the computational fluid dynamics (CFD) method can address the complicated internal sloshing problem, many studies have used a combined linear vessel motion model and CFD solver to simulate the coupling between vessel motions and liquid sloshing. Kim et al. (2007), Lee et al. (2007) and Nam et al. (2009) adopted the SOLA scheme (Kim, 2001) to simulate sloshing in liquid tanks for the analysis of a liquid loading vessel. Nam et al. (2009) compared the numerical simulation results with experimental results of a ship equipped with two liquid tanks. Li et al. (2012) and Jiang et al. (2015) used OpenFOAM to investigate sloshing and coupling with linear vessel motions in the time domain. Jiang et al. (2015) found that impact loads may be important for structural safety but have little effect on the global responses of a ship. Cercos-Pita et al. (2016) considered nonlinear vessel motions and sloshing using SHIXDOF (nonlinear ship motion simulation program with six degrees of freedom) and a CFD approach based on a fully nonlinear SPH solver.

Although CFD solvers perform well in liquid sloshing prediction, they tend to consume large computational resources and have poor efficiency in dealing with an FLNG system with varying filling conditions during the offloading operations. Comparatively, numerical analysis based on potential theory has advantages in computing time. Rognebakke and Faltinsen (2003) studied partially filled rectangular tanks in waves numerically and experimentally. Nonlinear sloshing in tanks was solved with a multimodal approach proposed by Faltinsen and Timokha (2001). Mitra et al. (2012) simulated nonlinear sloshing based on potential flow, and nonlinear vessel motion was simulated using a hybrid marine control system, and responses in complex sea conditions were analyzed. Huang et al. (2012) and Zhao et al. (2014) assumed sloshing in a liquid tank as perfect flow and investigated the coupling of liquid loading in a rectangular tank both numerically and experimentally. Artificial damping was introduced in their numerical simulation to account for viscous damping effects in sloshing. In terms of sloshing effects on vessel motion responses, potential flow can give good results with high efficiency.

Experimental tests can provide a more reliable and perceptual understanding of coupling responses in a liquid loading vessel. Experimental research conducted by Rognebakke and Faltinsen (2003), Huang et al. (2012) and Zhao et al. (2014) simplified the liquid tank into two dimensions. Coupling with vessel's roll motion was not considered (Rognebakke and Faltinsen, 2003; Zhao et al., 2014). Nam et al. (2009) carried out experimental tests of a vessel with two tanks in 3D, and ship motions were restricted to heave, roll and pitch. Coupling among 6 DOFs was not considered, which might also be of high importance for the coupling interaction results.

The objective of the study is to develop an accurate and efficient numerical model to address the coupling interaction of internal liquid sloshing and 6-DOF vessel motion with high efficiency. An impulsive response function is used in predicting vessel motions in the time domain, and sloshing liquid is solved based on potential flow theory. For the safe operation of equipment on the topside, strict regulations on the motions of FLNG vessel are required, and sloshing in LNG tanks must not be violent (Zhao, 2013). Moreover, the main concern of coupling analysis is the effects of sloshing on the global motion responses of a vessel, which are slightly affected by the impact of sloshing loads (Jiang et al., 2015). Therefore, the potential flow theory is applicable in this study. Experimental tests are also conducted to validate the proposed numerical model. Based on numerical and experimental results, the coupling mechanism and sensitivities to filling levels and wave directions are studied. The sloshing effects on a vessel's motions are closely related to the phase shift between the sloshing and vessel's motions, and coupling properties differ for different motion modes. The filling level will change the sloshing natural frequency, and different coupling results can be induced.