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Estimation of gap resonance relevant to side-by-side offloading

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ABSTRACT

Side-by-side offloading is becoming a more and more important offshore operation, where one vessel is moored alongside another one, forming a narrow gap between them. Using different types of incident waves, i.e. white noise waves, transient wave groups and regular waves, we investigated both the transient and steady-state resonant responses of the fluid in narrow gaps at model scale. The nonlinearity and uncertainties in obtaining the response amplitude operators (RAOs) of resonant fluid motions in narrow gaps are addressed. It appears that transient wave group testing is a promising approach for the investigation of gap resonance problem, because it avoids unwanted wave reflection induced by the limitation in the size of wave basins. To predict the gap resonant RAOs numerically, artificial damping is introduced into three different potential flow solvers to damp the otherwise over-estimated free surface motions in narrow gaps. The predicted RAOs, which are based on the potential flow solvers with the addition of calibrated damping, then show satisfactory agreement with the experimental data for a series of narrow gaps. This result confirms the reliability of the potential flow solvers in predicting gap resonant response (at model scale) for narrow gap widths that are relevant to engineering practice.

1. Introduction

Floating liquefied natural gas (FLNG) facilities are a new type of offshore structure. These are being developed as a game changer in offshore hydrocarbon development to unlock stranded gas reserves (Zhao et al., 2011). One of the key challenges is the product offloading operation, which may proceed with vessels in a side-by-side configuration. Reliable offloading is essential for successful FLNG implementation. In the side-by-side scenarios, one of the floating bodies is moored alongside the other one, forming a gap that is very narrow relative to the principal dimensions of the FLNG and carrier. The fluid inside the narrow gap may experience significant resonant response when excited at particular wave frequencies. The practical importance of the gap resonance is unclear at the moment, due to the difficulties in predicting the magnitude of the gap resonance. This leads on to difficulties in accurate prediction of the second order forces when conducting the waterline integral part of that force calculation.

Investigations into the steady-state response of the gap resonance phenomenon have been done both in 2D, e.g. Faltinsen et al., 2007 & Lu et al., 2011 and 3D, e.g. Pauw et al., 2007, Molin et al., 2009 & Dinoi et al., 2014. While many research efforts into the gap resonant response have been undertaken, the majority concentrated on analysis of the maximum gap resonant amplitude at steady state in regular waves. However, real ocean waves are never regular and reaching steady state is not straightforward in tank experiments due to the long time for the gap resonance to build up to its maximum amplitude, by which time reflected waves from the edges of the tank may affect the experiments. Actually, the time required for the gap resonance to build up to steady state is also a challenge for time domain simulations, as demonstrated by Watai et al. (2015). This is associated with the main characteristic of the gap resonance as a very low damped phenomenon. To overcome the challenges of achieving a steady state response, there is interest in the behaviour of the fluid in the gap in transient wave groups, as considered by Eatock Taylor et al. (2008) who numerically simulated the gap resonant response under focused wave groups based on linear potential flow theory.

The frequencies and mode shapes of the gap resonances can be well predicted using the approach given by Molin et al. (2002), whose solution is an extension of that for the moon-pool problem (Molin, 2001). A

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comprehensive numerical study of the frequencies, mode shapes and response amplitudes for the gap resonances in between two fixed boxes was made by Sun et al. (2010) using potential flow theory.

It is well-known that potential flow theory predicts significantly larger responses than are observed in physical experiments, e.g. Faltinsen et al., 2007 & Pauw et al., 2007. Much work suggests that the viscosity is the main source of the discrepancy between linear potential flow theory and experimental data (Molin et al., 2009; Kristiansen and Faltinsen, 2012). Feng and Bai (2015) carried out fully nonlinear numerical simulations without including viscosity and reported that nonlinearity may induce slight shifts in the resonant frequency (similar to the well-known resonant frequency shift observed for a nonlinear spring), though with rather limited effect on the amplitude. Many methods have been proposed to improve the level of agreement between potential flow calculations and physical model test results. For instance, Huijsmans et al. (2001) suppressed vertical motion in the gap completely by introducing a rigid lid, Newman (2001) split the gap motion into generalized modes, allowing different damping rates for each motion, and Chen (2005) introduced a dissipative damping term in the free surface condition. By introducing an additional damping term, all methods seem to be able to achieve good agreement with experimental data, but the selection of the additional damping coefficient is generally empirical. A robust method of estimating this damping is of significant importance for practical applications, because it would allow for estimates of gap resonance efficiently using the linear potential flow theory.

The majority of the existing studies focused on the resonant response of the fluid in gaps which were not sufficiently narrow to be representative of practical FLNG offloading operations. For instance, Fournier et al. (2006) investigated the gap resonance surface elevations based on gap widths of 20 m and 30 m at full scale. However, a typical side-by-side offloading may have a mean gap width of 4 m between vessels exceeding 200 m in length. Thus, there is an emerging need to investigate the characteristics of the resonant response of the fluid in such narrow gaps. As mentioned above, gap resonant performance under transient wave group excitations is also of interest, which avoids the challenge of achieving a steady state response both in numerical simulations and experiments.

In light of this, we carried out an extensive set of experiments to investigate the gap resonant response under excitations of regular waves, white noise waves and focused transient wave groups (the so-called NewWave, Zhao et al., 2017). The response amplitude operators (RAO) of the gap resonance are obtained from the three different types of wave excitation. These RAOs are then used to validate the numerical predictions using three different potential flow solvers, i.e. WADAM, HydroSTAR and WAVELOAD-FD; each uses a different method to introduce artificial damping in the narrow gaps.

2. Experimental set-up

Model tests were carried out in the Deepwater Wave Basin at Shanghai Jiao Tong University, China at the scale of 1:60. To focus on the gap resonance and simplify the study, we selected two identical rectangular boxes to represent a side-by-side moored two-body system at model scale. Each model is 3.333 m long, 0.425 m high, 0.767 m wide and the gap width is set as 0.033 m, 0.066 m and 0.132 m, respectively. At full scale, it represents a vessel of 200 m long, 25.5 m high and 46 m wide and the gap width is 2 m, 4 m and 8 m, respectively. It should be noted that the geometry of the vessel models in this study has been simplified, so are not directly applicable to any engineering project. However, the results here should provide a database for the validation of numerical models and the simplicity of the geometry allows a fundamental understanding of gap resonance to be developed. At the same time, this study will demonstrate the advantage of using transient focused wave groups for gap resonance which is a very slightly damped phenomenon.

During the model tests, the two identical boxes were fixed to a gantry which provided enough stiffness to hold them rigidly in place. The experimental set-up is illustrated in Fig. 1. As shown in Fig. 1, the vessel models have round corners at both bilges, each with a radius of 0.083 m running along the full length. The two boxes are fixed together and immersed to a draft of 0.185 m alongside each other. A more detailed description of the experimental set-up was reported in a previous study (Zhao et al., 2017).

Prior to the experiments, all the waves including white noise waves, regular waves and transient focused wave groups were calibrated. As the latter two types of wave test results will be discussed in detail in the following sections, we just provide the calibrated spectra of the white noise waves here in Fig. 2. Two white noise wave records were generated in the wave basin, one with the significant wave height of 42 mm and the other 84 mm. It should be noted in Fig. 2 that the larger white noise wave has a narrower spectral bandwidth than the smaller one. This is because it is very hard to achieve the high wave energy distribution at high frequency. The white noise waves were generated for 25 min (which after removing an incident transient phase corresponded to 23.24 min at model scale is equivalent to ~ 3 h at full scale). The white noise waves may not be realistic of ocean wave spectra, but they are an efficient way to obtain the RAOs, and the broad bandwidth of the spectrum is able to trigger several gap resonant modes in the same test.

3. Artificial damping to potential flow solvers

Within the scope of potential flow theory, the velocity potential Φ must satisfy both the Laplace equation and a series of boundary conditions. To avoid repeating the basic theory, which can be found in many textbooks on hydrodynamics, we focus on the discussion of the linearized free surface boundary conditions, where viscous damping effects are commonly introduced in industry standard potential flow solvers.

The kinematic free surface condition requires that the fluid particles should remain on the free surface. The linearized form of this boundary condition is given by

$$\eta_t = \Phi_z, \tag{1}$$

where η refers to the water surface.

The linearized dynamic free surface condition from the Bernoulli equation is given by:

$$\Phi_t = -\frac{1}{\rho}(p + \rho g \eta) + C(t), \tag{2}$$

where, p is the pressure acting on the free surface and the "constant" term $C(t)$ is independent of the space coordinates but may depend on time. The pressure term has been used in the study of oscillating water column

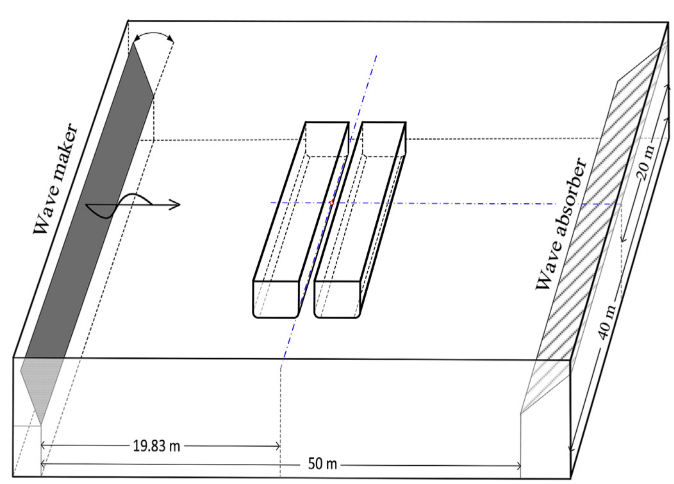

Fig. 1. Experimental set-up in the wave basin. The gantry where the models were fixed are not shown here.