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Numerical simulation of wave resonance in the narrow gap between two non-identical boxes

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A B S T R A C T

Wave resonance in the narrow gap between two side-by-side non-identical boxes is investigated by employing a two-dimensional numerical wave flume based on the OpenFOAM® package. The focus of this study is to examine the influence of the energy transformation and the energy dissipation on the hydrodynamic behavior of wave response around resonant conditions. Numerical simulations show that the unrealistic wave resonant responses in the narrow gap by the linear potential flow model are due to not only the energy dissipation induced by the fluid rotational motion, but also the energy transformation associated with the free surface. With the increase of incident wave amplitude, relatively more energy is reflected, leading to the decrease of wave resonant response and energy dissipation in the narrow gap at the resonant frequency. When slightly away from the resonant frequency, the energy dissipation becomes the dominant factor for the decrease of wave response in the narrow gap with increasing the incident wave amplitude. As for the influence of gap configuration, on one hand, energy dissipation has the dominant effect for the typical case of small upstream and large downstream box drafts. On the other hand, the reflected energy is more important for the typical large upstream and small downstream box drafts. More resonant fluid exists in the gap with the increase of gap breadth, leading to the decrease of reflection coefficient and the increase of transmission coefficient.

1. Introduction

In recent years, as the offshore oil and gas explorations and operations have moved towards deeper waters and harsher environments, Floating Production Storage and Offloading (FPSO) and Floating Liquefied Natural Gas (FLNG) production systems become more attractive. These structures are maintained stationary by a spread or turret mooring system, and a Liquefied Natural Gas (LNG) ship or shuttle tanker periodically approaches them for loading gas or oil according to a close proximity in side-by-side arrangement. For this loading operation, one of the key technical challenges is the fluid resonance in the narrow gap between them under the wave action.

Wave resonance in the narrow gap between two bodies in a close proximity has been studied extensively. Early examinations were focused on the theoretical study of eigenfrequency and eigenfunction of the resonant modes, based on the linearized potential flow theory. An analytical solution was derived in Molin (2001) for the barges with infinite length and beam in the infinite water depth, where the formula for the resonant frequencies of piston- and sloshing modes were obtained via solving an eigenvalue equation. Molin et al. (2002) further extended the work to the gap resonance in an open-ended narrow gap. Furthermore, Faltinsen et al. (2007) proposed an analytical method based on the domain decomposition approach, in which the piston-like mode in a two-dimensional moonpool between two heaving rectangular floating hulls in the finite water depth was discussed. Besides the analytical solutions, numerical simulations in the framework of potential flow theory have also been adopted to investigate the resonant modes, for example in Sun et al. (2010) where the free surface piston- and sloshing-modal resonant behavior around two adjacent barges was investigated by using the second-order potential flow analysis in the frequency domain.

According to extensive comparisons, it has been demonstrated that

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the potential flow model is capable of predicting the resonant frequencies and capturing the resonant modes. However, the potential flow model was reported to over-predict the resonant amplitudes. Focused on this problem, Saitoh et al. (2006) conducted a set of experimental investigations in a wave flume, and suggested that the resonant amplitudes are dependent on the body draft and gap breadth. This conclusion is consistent with the analytical and experimental results of Molin (2001). Iwata et al. (2007) extended this work to the three-body problem, indicating that the number of boxes also has the significant effect on resonant phenomena. At the same time, with the fast development of computing technology and numerical technique, Computational Fluid Dynamics (CFD) simulation has also been taken as an alternative method in recent years. Lu et al. (2011a,b) investigated the variations of resonant amplitudes by a three-step high-order upwind Taylor-Galerkin Finite Element Method (FEM). In Moradi et al. (2016) the effect of water depth on resonant behavior of the fluid trapped between two side-by-side bodies was studied. Numerical results found that the potential flow model not only over-predicts the resonant wave amplitude, but also gives an incorrect variation tendency of the resonant wave amplitude with water depth.

In order to reduce the computational cost of fully CFD simulations, the coupling model based on the domain decompositions method has been also established. Elie et al. (2013) adopted the approach of Spectral Wave Explicit Navier-Stokes Equations (SWENSE), which is a combination of the linear potential flow model in the frequency domain and the viscous fluid model with RANS turbulent equations, to simulate the gap resonance between side-by-side barges. In addition, in the numerical simulation of Fredriksen et al. (2014), as well as the early work in Kristiansen and Faltinsen (2012), the coupling models based on the domain decomposition were adopted, in which the laminar Navier-Stokes equations were applied in the lower region of the gap, while the potential flow model was used in the upper region of the gap and the outer region. This in fact acquiesces that the fluid rotational motion is important around the gap bottom, while the potential model may be enough for the free surface simulation. Generally, acceptable results of resonant amplitude can be obtained in various experimental tests and CFD simulations, however, the mechanical essence behind the hydrodynamic behavior of the resonant phenomena is still an interesting field. On one hand, it is an important academic problem on the topic of wave and multi-body interactions, which is one type of so-called ‘trapped structures’ in a broad sense. On the other hand, an essential understanding about the major factor on the over-prediction by potential flow models can help to develop an approximated method for the convenient use in industry.

It seems to be speculated that the over-predictions of wave resonance come from the ignorance of the inherent fluid viscosity in potential flow models. Based on this hypothesis, attempts to introduce some damping artificially in the linear potential flow model has been suggested. Newman (2004) modelled a damping term as the body force on the free surface between side-by-side vessels, and Chen (2004) introduced a damping force term into the free surface boundary conditions, which was explained as energy dissipation. The efficiency of the linear dissipative term was presented by Jean-Robert et al. (2006) with comparisons to the commercial software WAMIT® and HydroStar®, as well as measured data. These modified potential flow models are able to suppress unrealistic values, but still cannot capture the actual physical sense. A CFD simulation by Lu et al. (2010) suggested that the wave amplitude in the narrow gap is closely relevant to the vertical velocity along the gap bottom. Examinations of flow pattern indicated that the most violent rotational flow field happens in the vicinity of the gap entrance, where the significant vortex shedding and attached vortex structure can be observed. Faltinsen and Timokha (2015) accounted for the vortex-induced damping by quantifying a pressure discharge condition in the gap opening. The calculations can be supported by their earlier experimental and numerical data in Faltinsen et al. (2007). Lu and Chen (2012) quantitatively calculated the energy dissipation rate for the fluid resonance in the narrow gap induced by waves based on the Navier-Stokes flow solutions. It suggested that the flow separation and vortex motion play the most important role in energy dissipation for a wall bounded region. The majority of energy dissipation happens around the gap entrance, not on the free surface in the narrow gap. Similar findings were also obtained by Kristiansen and Faltinsen (2010) for the piston-mode wave resonance in the gap formed by a ship model arranged in front of a vertical wall. However, due to the existence of vortices square term in the expression of energy dissipation rate, it is not easy to compute the energy dissipation directly, and a clear relationship between energy dissipation and resonant amplitude or other parameters is not currently available.

In addition to the energy dissipation by the fluid viscosity, the process of energy transformation due to the large-amplitude free surface motion may also play an important role on wave resonances in the narrow gap. A fully nonlinear potential flow model was adopted by Feng and Bai (2015) for the wave resonance between two barges, in which the lateral piston mode and longitudinal sloshing mode were successfully captured. In their study, although the free surface nonlinearity was found to play a minor role in suppressing the over-predicted resonance response, nonlinear analysis illustrated the gap resonance to be equivalent to a stiff spring in a nonlinear mass-spring system: the resonant frequency slightly shifts to higher values as incident wave steepness increases. This is an important process of energy transformation due to the large-amplitude piston-like free surface oscillation. Ananthakrishnan (2015) investigated the effect of viscosity and nonlinearity on the forces and waves generated by a floating twin hulls under heave oscillations. Numerical results showed that the nonlinear effect on the wave forces is significant at all frequencies for the large amplitude oscillation relative to the hull draft. Besides, the influence of interaction between the energy transformation in the free surface motion and the energy dissipation in the fluid rotational motion can be speculated during the process of wave resonance. It might be important for understanding the essential hydrodynamic behavior of the fluid resonance in the narrow gap.

The motivation of this study is to investigate the influence of energy transformation and energy dissipation on the hydrodynamic behavior of wave responses around the resonant frequency. In the previous studies, all floating objects were modelled as the identical bodies, whereas in reality the objects may have different sizes, such as the most typical loading or offloading operations of the side-by-side arrangement between FPSO and LNG vessels. Therefore, the system with two non-identical boxes is taken as the background of this study, as the non-identical nature of the system may affect both the resonant frequency and amplitude in the narrow gap compared to the identical box systems. Besides the wave amplitude in the narrow gap, the reflection and transmission coefficients are also attributed to the process of energy transformation. Moreover, the quadratic sum of the reflection and transmission coefficients, $\mathbb{E} = K_r^2 + K_t^2$, defined as energy coefficient, is adopted for examining the energy dissipation. Under the framework of linear potential flow theory, the principle of energy conservation ensures the energy coefficient keeps at $\mathbb{E} = 1$. The value of $\mathbb{E}$ by the present viscous flow model can give us a new view on the energy dissipation due to the influence of fluid viscosity. In sum, an integral comprehensive understanding on the mechanical essence of the gap resonance is expected from the perspective of energy transformation and energy dissipation in the current study.

In Sections 2, 3 and 4, the numerical wave flume used in this work is presented, setup and validated against available experimental and numerical data, respectively. The numerical results and discussions are presented in Section 5 to show the effect of energy transformation and energy dissipation on wave responses around the resonant frequency, including the comparisons of results between the linear potential flow model and the present CFD model, and the influence of gap configuration and incident wave amplitude. Finally, conclusions are drawn in Section 6.