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Numerical investigation of wave forces on two side-by-side non-identical boxes in close proximity under wave actions

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ABSTRACT

Wave forces on two side-by-side non-identical boxes in close proximity under wave actions are investigated by employing a numerical wave flume based on the OpenFOAM® package. The similarity and discrepancy of hydrodynamic behavior between the wave response in the narrow gap and the wave forces on the boxes are the focus of the present study. Around resonant frequencies, the large-amplitude piston-type free surface oscillation in the narrow gap can lead to the peak values in the horizontal and vertical wave forces on the downstream box, and the horizontal wave forces on the upstream box. However, only a rapid decrease with the incident wave frequencies can be observed for the vertical wave forces on the upstream box. The resonant frequencies of the wave forces on two boxes are also different with those of wave response in the narrow gap. With the increase of incident wave amplitude, the resonant frequencies and normalized amplitudes of wave forces on downstream box tend to be smaller, which is similar with that of wave response in the narrow gap. However, the normalized wave forces on the upstream box around resonant frequencies do not always decrease with the increase of incident wave amplitude. On the whole, the hydrodynamic behavior of wave forces has some similar characteristics with that of wave response in the narrow gap. However, evident discrepancy between them can also be observed because the other factors, such as the wave response upstream and downstream the two-box systems, also has the non-negligible contribution to wave forces.

1. Introduction

In the field of offshore and ocean engineering, one of the hydrodynamic issues of crucial importance in the design of Floating Liquid Natural Gas (FLNG) or Floating Production Storage and Off-loading (FPSO) systems is wave induced interactions of a shuttle tanker approaching the FLNG or FPSO. The close proximity of the side-by-side barges is able to generate large-amplitude piston-type free surface oscillations in the narrow gap under wave actions, leading to radical variations of hydrodynamic forces on the barges comparing with that for the same barge in isolation. These extreme waves and resultant hydrodynamic forces would threaten the safety of engineering operations, seriously. An understanding of the mechanisms of hydrodynamics is required in order to achieve the increased safety during loading and off-loading operations.

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Under these circumstances, the topic of gap resonance mentioned above has been receiving increasing attentions nowadays. The large-amplitude piston-like free surface oscillation in the narrow gap in fact shares some similar features with the moonpool resonance problem, for which an analytical solutions was derived by Ref. [15] for the resonant modes and the corresponding modal shapes [4]. proposed a domain decomposition approach for solving the piston-like modal resonance in a two-dimensional moonpool induced by two heaving rectangular hulls [22]. investigated the three-dimensional free surface piston- and sloshing-modal resonant behavior of closely spaced vessels by using the first and second-order wave diffraction analysis in frequency domain, where the lateral and longitudinal modal resonance in waves from any directions were discussed. A fully nonlinear potential flow model was adopted by Ref. [5] for the wave resonance between the side-by-side barges. Numerical simulations suggested that the resonant frequency slightly shifts to higher values as incident wave steepness increases, equivalent to a stiff spring in a nonlinear mass-spring system. Extensive comparisons have demonstrated that the potential flow model is capable of predicting the resonant frequencies and capturing the resonant modes, but the resonant amplitudes have been also reported to be over-predicted compared to the laboratory observations. Many methods were developed for suppressing the unrealistic resonant amplitudes based on the introduction of artificial damping appropriately in the potential flow model, such as in Refs. [3,18]; which can be adopted in the commercial software WAMIT® and HydroStar®.

Although the unrealistic values can be suppressed by the modified potential flow models, the actual mechanical essence of the gap resonance in fact still cannot be simulated, correctly. It has been reported by Refs. [13,14] that different artificial damping values have to be adopted for wave amplitudes and wave forces, separately, even if the same structures and incident waves are considered. Physical experimental measurement is an efficient but expensive method for this problem, such as in Refs. [8,19,21] and among others. Another alternative method is the Computational Fluid Dynamics (CFD) simulation based on the Navier-Stokes equations, where the satisfying predictions and the real physical process can be obtained. The influence of viscosity and nonlinearity on the forces and waves generated by a floating twin hulls under heave oscillations was investigated by Ref. [1]. Numerical simulations showed that the nonlinear effect on the wave forces is important for the large amplitude oscillation, while the viscous effect on wave forces is also significant due to flow separation [17]. studied the fluid trapped behavior in the narrow gap affected by water depth. It was suggested that the ratio of water depth to body draft is the key factor that affects the resonant response in shallow depth regime [6]. conducted the experimental and numerical investigation for wave resonance in moonpools with various inlet configurations at low forward speed by heaving excitation. The dependency of piston-mode behavior on forward velocity and heaving amplitude is observed and the flow separation and shed vorticity from the inlets is found to be an important factor. For gap resonance problem, the significant effect of the gap inlet configurations (i.e. sharp and curved corners) on the resonant wave frequency and amplitude can be observed in Ref. [16]. An empirical model was also proposed to predict wave resonance frequency for different curvatures of the gap inlet [23]. considered the resonant fluid response in the narrow gap between two identical fixed rectangular boxes under the excitation of NewWave-type transient wave groups according to the laboratory observations. The higher-order harmonic components were separated and the nonlinear wave-wave and wave-structure interactions were investigated for the transient wave groups action.

The above-mentioned research efforts are mainly for the identical floating objects, whereas the objects usually have different sizes in reality, such as the most typical loading or offloading operations of the side-by-side arrangement between FPSO and LNG vessels [11]. investigated the gap resonance problem caused by the non-identical two-box system, in which the wave amplitude in the narrow gap, the reflection, transformation and energy-loss coefficients are considered. Numerical simulations suggested that the non-identical nature of the system can not only affect the resonant frequency and amplitude in the narrow gap, but also has the significant effect on the process of energy transformation and energy dissipation compared to the identical box systems. An integral comprehensive understanding on the mechanical essence of the gap resonance can be understood from the perspective of energy transformation and energy dissipation. However, another important aspect, the wave forces on the bodies, are not considered in their work. Since the mechanical essence of the energy transformation and energy dissipation show the close dependence on the configurations of those non-identical two-box system, it is expected that the significant effect of the non-identical nature on the wave forces would be observed, which is also the major motivation of this study.

This paper is based on a direct extension of the numerical method presented by Ref. [11] for wave response in the narrow gap problem. In this study, the wave forces on two-box system with various box drafts are investigated in a viscous numerical wave flume based on the OpenFOAM® package, in which the Naiver-Stokes equations are employed for the governing equations of incompressible two-phase flows. Although the wave forces on two boxes might share some similarities with the hydrodynamic features of wave response in the gap presented in Ref. [11]; some differences in hydrodynamic characteristics between them are expected, and will be highlighted in the present study. The Volume of Fluid (VOF) method [7], documented by Ref. [2]; is adopted to capture the free surface motion, especially the large-amplitude piton-like free surface oscillation in the narrow gap. The relaxation zones by Ref. [9] are equipped to generate the incident wave and eliminate the transmission wave at the inlet and outlet boundaries, respectively, in which the internal wave reflections can also be avoided in this method. More detailed information of the formulations and numerical schemes described above have been given in the previous paper [11]. About the basic numerical implementations of CFD simulations in OpenFOAM®, the readers may refer to [10] and [20]. The classical linear potential flow model is also adopted in this study for the purpose of comparison. The main motivation of the work is the numerical analysis of the behaviors of wave forces on the boxes under various influencing factors, especially when the gap resonance happens, by which some dynamic mechanisms of gap resonance can be revealed.

The rest of the present paper is organized as follows: the geometry of numerical simulations adopted in this work is setup and validated against available experimental and numerical data in Section 2 and 3, respectively. The numerical results and discussions are presented in Section 4 to analyse the effect of wave parameters and body configurations on the wave forces of two boxes, especially around resonant frequencies. Numerical investigations include the comparisons of wave forces between the linear potential