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Wave resonances in a narrow gap between two barges using fully nonlinear numerical simulation

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ABSTRACT

The traditional potential flow theory to describe fully nonlinear waves is reformulated by separating the contributions from incident and scattered waves, in order to improve the computational efficiency. The nonlinear incoming wave is specified explicitly and the modified nonlinear free surface boundary conditions for the scattered wave are expressed in the full Lagrangian description. At each time step only the scattered wave is solved using a mixed Eulerian–Lagrangian scheme by a higher-order boundary element method. The accuracy of the newly developed model is illustrated by comparisons with existing experimental and numerical data in the case of wave diffraction around an array of circular cylinders. Wave resonances in the gap between two side-by-side barges in beam seas, as in Molin et al. [1], are simulated with the barges subjected to regular waves. To clearly understand the gap resonant responses, long time simulations are performed to achieve final steady states, and the resonant mode shapes of the gap surface are presented. The gap free surface RAOs (Response Amplitude Operators) in the case of mild waves are found to agree well with linear calculations. The nonlinear effects on the resonant response due to the free surface conditions are then investigated. The first resonant frequency is found to shift but the peak value is not changed much with increasing incoming wave steepness, which is known as stiff/soft spring behavior of a nonlinear system. Through the investigation of barges with different drafts, the stiff and soft spring behaviors are identified.

1. Introduction

In the last decade, with the development of offshore technology and increasing consumption of oil and gas, more side-by-side operations have been adopted in the marine industry. These operations could be, for instance, liquid cargo offloading from a LNG-Carrier to a FSRU in close proximity. In practice, successful execution of such operations requires numerous considerations including, for example, environmental conditions, vessel arrangements, mooring systems, operation procedures and so on. Among others, the resonant phenomenon associated with the waves in a narrow gap between two side-by-side hulls may be a problem. When gap resonance occurs, high wave motions in the gap could be excited and hence large drift forces may act on the vessels. Utilizing the linear wave theory, Molin [2] derived the formula for estimating the frequencies of resonant modes in a moonpool via solving an eigenvalue problem, which was extended to gap resonances by a modification into an open-ended moonpool in Molin et al. [3]. Later on the resonant behavior of fluid in the gap has attracted much attention especially at the first mode or piston mode, where wave amplifications are more significant than at others.

In a broad sense, the side-by-side barges configuration is one type of so-called 'trapping structure'. The eigenvalue problem associated with trapping structures is not new, and pioneering work based on linear wave theory has provided analytical solutions for the trapping or resonant frequencies. For instance, Linton and Evans [4] presented the near-trapping phenomenon around an array of circular cylinders. Porter and Evans [5] solved wave scattering by vertical barriers, and McIver [6] investigated general torus-like structures. Due to the complex geometry of wave resonances in the gap between two three-dimensional side-by-side vessels, recently the problem has been mainly simulated by numerical models based on linear wave theory. Earlier, Newman and Sclavounos [7] modeled two close rectangular barges by a panel method and reported unusually high wave elevations in the narrow gap as well as large hydrodynamic forces. Koo and Kim [8] investigated the hydrodynamic interactions and coupling effects of a moored FPSO-LNG system with hydrodynamic coefficients obtained from the panel program WAMIT. Sun et al. [9] utilized the 3D program DIFFRACT to simulate two adjacent barges and suggested that both first- and second-order resonances associated with the gap may exist.

However, applications of linear potential flow models are reported to potentially over-predict the wave responses, namely

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RAOs (Response Amplitude Operators) of the free surface elevations in the gap at the frequency of the piston mode. Consequently the mean drift forces on the hulls and ship motions could vary much from the predictions. In order to suppress the unrealistic wave elevations produced from linear models, several methods have been developed. Huijsmans et al. [10] applied a rigid lid on the free surface between side-by-side moored vessels. Subsequently Buchner et al. [11] numerically and experimentally investigated the floating LNG system based on the ‘lid method’ and partially justified the approach of a damping lid in applications. While this ‘lid method’ is able to suppress unrealistic values, it does not however make physical sense. Newman [12] also modeled a damping lid on the gap surface and used a generalized mode technique to compute the lid motions. Meanwhile, Chen [13] introduced a damping force term into the free surface boundary conditions, which was explained as energy dissipation. The efficiency of the linear dissipation term was then presented by Fournier et al. [14] with comparisons to the linear programs WAMIT and HYDROSTAR, as well as experimental data. Thereafter, Pauw et al. [15] utilized a similar technique to predict the wave response within the gap of side-by-side moored vessels, at the resonant frequencies of piston and sloshing modes obtained by the approximated formulations of Molin [2]. Pauw et al. [15], however, demonstrated that there is no a priori method of determining the coefficient of the damping term unless calibrated by experimental tests.

Recently the piston mode of water column motion in the gap was investigated by Kristiansen and Faltinsen [16], who adopted a 2D numerical wave tank model and captured viscous effects by means of a vortex tracking method. Meanwhile, Lu et al. [17] employed a viscous fluid model to study the 2D wave interactions with closely floating boxes. It was reported that in the 2D case gap elevation calculated by linear potential theory could become unreasonably high (over four times higher than model tests) if the gap is sufficiently narrow. Two-dimensional models, however, are somewhat limited in capturing real 3D characteristics of the fluid in the gap, especially in representing higher-resonant modes. Comparisons between 3D linear simulation and experimental tests in Molin et al. [1] show that indeed, linear models tend to over-predict the resonant wave response (about 40% larger at peaks), yet linear results of gap free surface RAOs in 3D models may not be as unrealistic as in 2D simulations.

A straightforward explanation for the discrepancy is that the gap surface elevations in linear theory are over-predicted due to the neglect of fluid viscosity in the potential flow model, i.e. vortex shedding and flow separation at sharp edges and corners. On the other hand, it is known that within the framework of potential flow theory the free surface boundary conditions are nonlinear, which are simplified in the linear approximation. Therefore, both wave nonlinearity and fluid viscosity may contribute to the discrepancy between linear results and measurements. Some research work has been done to throw light on the influence of viscous effects and nonlinear effects of the free surface. The vortex-shedding effects were evaluated in Faltinsen et al. [18] by a discrete-vortex method for a simple case, i.e. a 2D moonpool formed by two rectangular hulls undergoing heave motions. Comparisons with experiments demonstrated that the agreement of resonant frequencies is reasonable for small forcing amplitudes, while the discrepancy increases for larger excitations and a wider moonpool. Adding vortex-shedding effects in those cases does not suppress the discrepancy. The reason might be the relatively small forcing amplitudes used in their experiments and the quadratic velocity dependence of the vortex-induced forces, as explained by Faltinsen et al. [18]. It is of interest that higher harmonics in time histories of wave elevations were captured in their measurements, which highlighted possible effects of free surface nonlinearities. In Kristiansen and Faltinsen’s [19] vortex tracking analysis, it was found that flow separation mainly accounts for the discrepancy of the gap surface amplification between linear results and measurements, and nonlinear free surface boundary conditions are of minor importance. However, it should be noted that the propagating waves in their model tests are of relatively low wave steepness, kA approximately from 0.3% to 1.0% (k is wave number and A wave amplitude). Therefore, nonlinear free surface effects may not be significant in their cases.

In a recent study of Kristiansen and Faltinsen [20], they utilized a domain-decomposition approach, which combines potential flow theory and CFD, to analyze the 2D gap resonance problem. They again concluded that flow separation at barge/ship bilges explains the discrepancy of peak resonant response between linear potential flow model and experiments. In the three-dimensional, experimental and numerical investigation in Molin et al. [1], barges with both rounded and square bilges were simulated and experimental results suggested that the discrepancy is mostly due to the flow separation at the barge bilges.

Not much work, however, has been published closely investigating the nonlinear effects of free surface on the gap resonance. This is one of our major interests here in modeling the gap resonance, where the gap surface behaves as a mass–spring system (e.g. in its piston mode). Theoretical analysis of similar nonlinear mass–spring systems can be found in Vinje [21] for a narrow moonpool and Miles [22] for a circular well, as well as more details in Faltinsen and Timokha [23] for sloshing. In order to assess the nonlinear effects of the free surface in three-dimensional situations, the same two barges with square bilges considered as in Molin et al. [1] are modeled in this study, with wave steepness varying from 0.34% to 6.7%. Calculations with a small frequency step near the piston mode resonant frequency are performed, with sufficiently long time simulations in order to achieve steady state. Careful plots of gap peak response near the resonance show that the resonant frequency slightly shifts to higher values as wave steepness increases, while the peak responses are not significantly reduced. This stiff spring behavior is also observed in the drift forces. With the change of barge draft, the stiff spring behavior will turn to a soft spring behavior when the barge draft over length ratio is sufficiently large.

The aim of this paper is to study the effects of free surface nonlinearity on the wave resonance in a gap between two barges. To achieve this, a fully nonlinear potential flow model capable of running long time simulations efficiently is developed by separating the total wave into a prescribed incoming wave and an unknown scattered wave. The present numerical model is a further extension of the numerical wave tank (NWT) developed by Bai and Eatock Taylor [24,25]. In the present model, the computational domain is circular and a damping zone is placed on the free surface near the tank wall to absorb the outgoing scattered wave such that the tank wall effect can be eliminated. The flow field in the nonlinear incident wave is specified explicitly, thus only the scattered wave needs to be solved. Ferrant et al. [26] applied a similar approach in their nonlinear time-domain model to simulate the wave diffraction around a vertical cylinder, which demonstrated a number of practical advantages in terms of accuracy and computational efficiency. In their model, the separation of the incident wave and the scattered wave is implemented in a semi-Lagrangian formulation of the nonlinear free surface boundary conditions, where the horizontal motions of the free surface points are inhibited and the vertical coordinates become single-valued as $z = \eta(x, y, t)$. This approach could lead to difficulties in simulating moving structures where intersection lines between the fluid and the structures are not horizontally fixed. In this study we present formulations in a fully Lagrangian description of the free surface boundary conditions, which we suggest is more robust for water wave-body interaction problems.