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Numerical investigation of viscous effects on the gap resonance between side-by-side barges

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ABSTRACT

This paper presents a numerical study of the gap resonance between two side-by-side barges by using a multiphase Navier-Stokes equations model. In order to verify the multiphase flow model, it is firstly applied to simulate a two-dimensional gap resonance problem for two fixed boxes under various wave conditions. A comparison of the free surface elevations obtained on successively refined grids confirms the mesh convergence of numerical solutions. The calculated wave elevation response amplitude operators (RAOs) in the gap compare well with the experimental measurements. The multiphase flow model is further extended to calculate a three-dimensional gap resonance problem for two adjacent rectangular barges. The computed free surface RAOs in the gap also agree well with the experimental results. A close examination of the flow velocity and vorticity in the gap region at the piston resonant mode reveals that large amount of vortices are generated by the sharp corners of the two barges and shed downwards, which provide an effective mechanism to dissipate the flow kinematic energy and to reduce the wave elevation in the gap. On the contrary, rounded corners are not able to induce the same level amount of vortices to dampen the gap resonance. The effects of incident wave steepness on the viscous damping associated with the twin-barge system are highlighted.

1. Introduction

As the oil and gas industry is moving towards remote locations and deeper waters, Floating Production Storage and Offloading (FPSO) and Floating Liquefied Natural Gas (FLNG) systems have become economically attractive for offshore field development. Side-by-side offloading from FPSO or FLNG to a shuttle carrier dramatically reduces the cost of building a long pipeline for locations far from any coastal terminal. Technical challenges, however, arise for such multibody floating systems, due to the complexity of multibody hydrodynamics. One of the critical issues might be the wave resonances in the narrow gap between two side-by-side vessels. The gap resonances occur at some particular wave frequencies and are characterized by remarkably amplified wave motions and body responses.

Potential flow models are predominantly used in the industry to study this problem of wave interaction with multiple floating bodies. Theoretical solutions of the resonant modes of fluids trapped between simple bodies were derived by Molin (2001) and Yeung and Seah (2007), in the framework of linear potential flow model. It was reported in Molin (2001) that both the piston and longitudinal sloshing modes of gap resonance can be excited. In the piston mode resonance, the fluid in the gap is pumped up and down as a 'rigid' body with only one peak response along the gap; while the sloshing modes show a near sinusoidal free surface along the gap with several crests and troughs. The pumping or piston mode is found more critical than the longitudinal sloshing modes, in the perspective of fluid motion amplification. The gap resonance discussed in this study refers to the piston mode unless otherwise specified. Linear as well as second-order models have been developed to numerically simulate two adjacent barges or vessels, including Newman and Sclavounos (1988), Kashiwagi et al. (2005), Teigen and Niedzwecki (2006), Lewandowski (2008), Zhu et al. (2008) and Sun et al. (2010). While gap resonant frequencies can be accurately predicted, linear potential models tend to over-estimate the wave responses at the piston mode, according to comparisons with experimental tests.

In attempt to address the discrepancy between the model tests and linear predictions, Feng and Bai (2015), Li and Zhang (2016) developed time-domain fully nonlinear potential flow models to investigate the diffraction and radiation problems for gap resonance respectively. In

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Feng and Bai (2015), it was reported that the free surface nonlinearity does not account for the over-estimation of resonant responses. An experimental study was conducted by Zhao et al. (2017) who excited first and higher harmonic components of the resonant response in NewWaves. The unrealistic prediction is related to the small damping near the resonant frequency in potential flow models. Several approaches have been developed to suppress this unrealistic prediction. Huijsmans et al. (2001) and Buchner et al. (2001) put a rigid lid on the free surface between side-by-side moored vessels. This 'lid method' effectively suppresses the amplified gap free surface, yet holds no physical meaning. Newman (2004) modelled a movable damping lid on the gap free surface and used a generalized modal technique to compute the lid motions. Instead of performing only numerical treatments, Chen (2005) modified the free surface boundary conditions by introducing a damping 'force' term. The damping term acts analogously as energy dissipation that is not taken into account in potential flow models. This method was proven practically effective by Fournier et al. (2006) and Pauw et al. (2007). However, one has to calibrate the unknown dissipation coefficient using measurement data, and there is no a priori theory to determine it. More recently, Watai et al. (2015) and Ganesan and Sen (2016) employed Chen's method in their time-domain model for two side-by-side vessels and again the damping coefficient was calibrated from tests. While predictions of resonant surface elevation in the gap can be improved through calibration, the physical reason of the discrepancy between predictions and experiments might not be addressed in the framework of potential flow.

Viscous flow models based on the Navier-Stokes (N-S) equations have the capabilities of capturing vortex shedding, flow separation and energy dissipation in the bulk of fluid domain, and could provide better understandings of the damping mechanism associated with the piston gap resonance. For prediction of the resonant response, Lu et al. (2010) demonstrated that viscous models provide much improved results than potential flow models in a 2D case of two side-by-side boxes. Similar cases were studied in Moradi et al. (2016) using a N-S solver with a focus on the effect of water depth on dynamics of gap resonance. Based on the understanding of energy dissipation in the 2D gap through viscous models, an energy dissipation model was proposed recently in Chua et al. (2016) through the analysis of energy conservation in a control volume of fluid around the bodies. By comparison between the linear potential flow model with the viscous model, a proper dissipation coefficient in Chen's model can be determined. A link between the energy loss coefficient in the energy dissipation model and the dissipation coefficient in Chen's model was then constructed in Tan et al. (2017). This shows a possible method to determine the dissipation coefficient without the calibration but through an iterative process. To quantify the viscous dissipation upon resonance, Faltinsen and Timokha (2015) presented a pressure discharge model resulting in a modified dynamic free surface condition. By applying a pressure drop coefficient, they achieved good agreements with tests without any priori. Nonetheless, most of the studies are mainly in the 2D framework. Meanwhile, Kristiansen and Faltinsen (2008) employed a vortex-tracking method to study a 2D moonpool formed by two rectangular hulls undergoing heave motions. The vortex tracking analysis revealed that flow separation around the sharp body corners/edges at the gap entrance is the main reason for the discrepancy between potential models and measurements. Their later investigation using a domain-decomposition model in Kristiansen and Faltinsen (2012) confirmed this conclusion. It is worthwhile to mention that the domain-decomposition model combines a potential flow solver in the outer domain and a viscous flow solver in the inner domain. It was demonstrated again that the inner viscous flow model is effective in capturing the viscous damping effect around the floating bodies.

While some understanding of the discrepancy has been created in simple 2D cases of boxes from previous studies, no much light has been thrown on the similar gap resonance associated with a 3D vessels/barges system. It is understood in Feng and Bai (2015) that the discrepancy of peak response between the potential flow model and experimental data in a 3D twin-barge system may not be as high as that in a 2D twin-box system. In this sense, detailed investigations on flow structures (including flow separation and vortex shedding) in the gap resonant fluid around two floating vessels are essential, which will be more helpful for better understanding the damping mechanism in a more realistic situation. More importantly, no work has been published to discuss the effect of incident wave amplitude on the gap resonant responses. This is because RAOs (Response Amplitude Operators) generated from the linear potential flow model are independent of the incident wave amplitude. This independence is mostly true for wave frequencies away from the gap resonance. However, the incident wave amplitude clearly affects the strength of system damping at the gap resonance. Further study on the effect of incident wave amplitude on the gap resonance is needed.

This work attempts to investigate the flow structures around two 3D side-by-side barges upon gap resonances and to shed light on the damping mechanism at the piston mode. The effect of incident wave amplitude on the resonant response is highlighted for barges with both square and rounded bilges. To capture the local flow characteristics near the gap, a viscous flow solver is essential. We build the numerical model based on an open source CFD package OpenFOAM® and implement the model on the massive parallel computing system in the National Supercomputing Center Singapore.

This paper is organized as follows. Section 2 briefly presents the governing equations of a viscous numerical wave tank, the boundary conditions and the techniques for free surface capturing. Numerical implementation of wave generation and absorption is also described. Section 3 validates the numerical model via a simple 2D case of two boxes in a wave flume. Section 4 simulates two 3D side-by-side barges floating in a numerical wave basin. Flow characteristics near the barge bilges at the piston mode gap resonance are demonstrated. Comparisons are made between cases of square and rounded bilges. Effect of incident wave amplitude is further investigated by varying wave steepness. Concluding remarks are drawn in Section 5.

2. Numerical model

The viscous flow model solves the incompressible Navier-Stokes (N-S) equations for a two-phase flow of water and air. A volume of fluid (VOF) technique is incorporated for capturing free surface. The N-S equations are solved by a finite volume method (FVM). The wave tank model is based on the OpenFOAM® multiphase solver 'interFoam'. A wave generation utility 'waves2Foam' presented in Jacobsen et al. (2012) is incorporated to generate propagating incident waves and to dissipate far field reflection waves.

2.1. Governing equations

The continuity equation for incompressible flows reads:

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho \mathbf{u}) = 0,$$

and the Navier-Stokes equations are written as

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla\cdot(\rho \mathbf{u}\mathbf{u}^T) = -\nabla P - (\mathbf{g}\cdot\mathbf{x})\nabla\rho + \nabla\cdot(\mu\nabla\mathbf{u}) + \sigma_t k_\alpha \nabla\alpha, \tag{2}$$

where $\mathbf{u} = (u,v,w)$ is the velocity field in Cartesian coordinates, ρ the fluid density, P the pressure in excess of the hydrostatic part and $\mathbf{g}$ the gravitational acceleration. μ is the dynamic viscosity of the fluid, σ_t the surface tension coefficient and k_α the surface curvature, see Ubbink and Issa (1999). The surface tension coefficient between air and water at 20° is 0.074 kg/s^2. Note that $\rho = \rho(\mathbf{x})$ varies with the volume fraction of water α in the computational cells. The above equations are solved for the two-phase flow simultaneously, and the mixed fluids are tracked using the scalar field α which is 0 for air and 1 for water. Any intermediate value between 0 and 1 represents a mixture of the two fluids. In the VOF