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Analysis of wave resonance in gap between two heaving barges

Yajie Li, Chongwei Zhang*

Department of Mechanical Engineering, University College London, Torrington Place, London WC1E 7JE, UK

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ABSTRACT

A numerical wave tank based on the fully-nonlinear potential-flow theory is built to simulate water wave radiations by floating barges. An approach from the free sloshing model is proposed to predict dominant resonance frequencies of the liquid motion in the gap between two barges. The effectivity of this approach is verified through the 'response amplitude operator' (RAO) analysis. Then, the approach is applied to investigate wave resonances of the gap liquid. In the first series of case studies, two identical barges are considered. Effects of the barge distance and draft on the gap resonance are investigated. It is found that, as the gap distance grows from narrow to wide, the dominant resonance may transfer from the piston type to the sloshing type. As the barge draft decreases, this transfer would emerge earlier. The second series of case studies concern two different barges in a close proximity. It is found that the relative breadth of two barges has minor effects on the resonance frequency, but affects RAOs at resonance evidently. The relative barge draft has a strong effect on resonance frequencies.

1. Introduction

In the field of marine and ocean engineering, there exist many applications where two floating bodies are in a close proximity. Typical examples are multi-hull ships, side-by-side production and transport vessels (e.g. FPSO and shuttle tanker) and pontoon-type 'very large floating structures (VLFS)' used as floating airports. One crucial hydrodynamic issue of this arrangement is the wave resonance in the narrow gap. When the resonance occurs, the free surface in the gap could oscillate violently with a large wave height. The extreme waves and resultant hydrodynamic loads on structures would harm the safety of engineering operations.

The narrow gap resonances may be observed in the radiation problem when structures are forced to oscillate or the diffraction problem when the structures are fixed in incident waves. It is known that the liquid resonance would occur when the excitation frequency of structure oscillations or incident waves is close to certain resonance frequencies of the gap liquid. The resonance frequencies could be determined by the frequency-domain or time-domain approaches.

The frequency-domain solutions are functions of the frequency, from which resonance frequencies could be observed directly. In specific, for the radiation problem, the obtained added mass and damping coefficients have rapid changes near a resonant frequency (particularly, the added mass may have negative values). For the diffraction problem, sharp peaks in the diagram of response amplitude operators (RAOs) in terms of the wave elevations are related to the resonant phenomena. Either analytical or numerical method could be used to obtain the frequency-domain results. For example, Molin (2001) considers the liquid confined by two barges of infinite beam. A quasi-analytical approximation for resonant frequencies and corresponding free-surface modes in the gap is derived. Zhu et al. (2006) focus on the gap effect on the added-mass and damping coefficients of 3D multiple floating structures. The boundary element method (BEM) is useful for the solution. Resonance frequencies of the liquid motion in the gap are observed from the diagram of added-mass and damping coefficients. Faltinsen et al. (2007) study the piston-like steady-state motions of the fluid in a moonpool formed by two barges. They focus on the radiation problem without incident waves and give an analytical solution for the resonance frequencies. Sun et al. (2010) investigate the water wave diffraction by two closely spaced barges using 3D BEM. The barges could be fully fixed or freely floating. The free-surface near-resonant behavior of the first- and second-order is interpreted. The resonance wave frequencies could be read from the diagram of RAOs.

It should be noted that frequency-domain solutions are mainly based on the linear or second-order weakly-nonlinear potential-flow theory. The wave amplitude is assumed to be small, which does not match the wave resonance situation exactly. The time-domain computational fluid dynamics (CFD) method is an alternative option for narrow-gap resonance problems. Typical time-domain studies in recent years are as follows. Lu et al. (2010) study

* Corresponding author.
E-mail address: chongwei.zhang.11@ucl.ac.uk (C. Zhang).

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the fluid resonance in narrow gaps of three identical barges fixed in incident waves. The numerical wave tank with viscous fluid flows is employed. Ning et al. (2015) have investigated the effect of the number of barges on the resonance frequency in narrow gaps. The fluid problem is solved based on the 2D fully-nonlinear potential flow theory. Moradi et al. (2015) adopt OpenFOAM to investigate the effect of corner configurations of two rectangular-type barges on fluid flow resonance in between. Feng and Bai (2015) develop the 3D fully-nonlinear potential flow wave tank to simulate wave resonances in the gap between side-by-side barges. Effects of the free-surface nonlinearity are highlighted. In all above time-domain studies, resonance frequencies of the liquid motion in gaps are obtained through the 'enumeration' method. In the enumeration method, a great number of cases should be simulated at different excitation frequencies of body motions for radiation problems or incident waves for diffraction problems. Then, resonance frequencies are observed from the RAO diagram as in frequency-domain methods. This is a time-consuming work, since every data point in the RAO diagram is essentially defined by a long time history.

In the present study, we would propose an alternative approach to predict dominant resonance frequencies of liquid motions in the gap. Based on the understanding of the liquid sloshing, we know that resonance frequencies of the liquid motion in gaps are intrinsic properties of the liquid itself, regardless of excitation conditions. Thus, dominant resonance frequencies could be reflected in the free sloshing between two barges. To obtain the free sloshing, we firstly oscillate the barges for several periods to give the gap liquid an initial disturbance. Then, we stop oscillating the barges and let the fluid slosh freely in the gap. In this situation, the liquid motion is only driven by the gravity, so that no extra energy is imported into the liquid system. Finally, we abstract the history of wave runups in the gap and perform a fast Fourier transformation (FFT). Dominant frequencies in the spectrum should be resonance frequencies of liquid motions in the gap.

In this paper, the effectivity of the approach to predict resonance frequencies in the gap is verified. This approach is further applied to investigate wave resonances in the gap between two heaving barges. The fluid flow is simulated based on the fully-nonlinear potential-flow theory in the time domain. This paper is structured as follows. Section 2 describes the mathematical model and corresponding numerical procedures. In Section 3, we perform the convergence studies and accuracy verifications of the methodology. In Section 4, we firstly verify the new approach. Then, case studies are performed to investigate the wave resonance between two barges. Effects of the gap width, draft and relative size of two barges on the narrow-gap resonance are discussed. Finally, the conclusions are drawn in Section 5.

2. Mathematical formulation and numerical procedure

Two floating barges in the deep water are considered. The barges on the left- and right-hand side are defined as 'Barge-0' and 'Barge-1', respectively. As shown in Fig. 1, the breadth and initial draft of two barges are denoted by B, B_1, D and D_1. The distance between the inner sides of two barges is L. An earth-fixed Cartesian coordinate system $O-xz$ is defined. The origin O is set at the midpoint of the gap on the undisturbed free surface, the x-axis is pointing upwards and the x-axis is pointing to the right.

2.1. Mathematical formulation

Based on the potential flow theory, the fluid is assumed to be inviscid, incompressible and flow-irrotational. Thus, the velocity potential ϕ in the whole fluid domain Ω satisfies the Laplace's

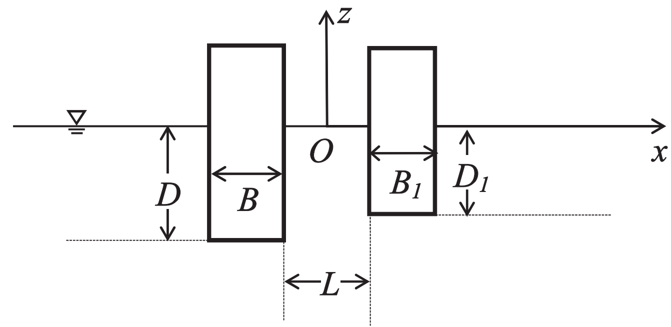

Fig. 1. The sketch of the problem.

equation

$$\nabla^2\phi = \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial z^2} = 0 \tag{1}$$

On body surfaces, due to the impermeable condition, we have

$$\frac{\partial\phi}{\partial n} = \boldsymbol{U}\cdot\boldsymbol{n} \tag{2}$$

where $\partial/\partial n$ denotes the differentiation along the normal direction of the body surface, $\boldsymbol{n}$ is the unit normal vector on the body surface pointing out of the fluid domain, and $\boldsymbol{U}$ denotes the heaving velocity. The kinematic and dynamic conditions on the free surface can be written in the Lagrangian form as

$$\frac{Dx}{Dt} = \frac{\partial\phi}{\partial x};\ \frac{Dz}{Dt} = \frac{\partial\phi}{\partial z} - \nu(x)\cdot z;\ \frac{D\phi}{Dt} = \frac{1}{2}|\nabla\phi|^2 - gz - \nu(x)\cdot\phi \tag{3}$$

where $D/Dt = \partial/\partial t + \nabla\phi\cdot\nabla$ denotes the substantial differentiation following a given fluid particle and g is the gravitational acceleration. Note that an artificial damping zone is applied on the free surface to absorb outgoing waves near the open boundary. The damping effects are represented by terms of $\nu(x)$ in the free-surface boundary conditions. The expression of $\nu(x)$ can be written as (Cointe et al., 1990)

$$\nu(x) = \begin{cases} \alpha\omega\left(\dfrac{|x|-x_0}{\lambda}\right)^2, & x_0 \le |x| \le x_1 = x_0 + \beta\lambda \\ 0, & |x| < x_0 \end{cases} \tag{4}$$

where ω and λ are the characteristic frequency and length of water waves, respectively. We let parameter β denote the damping zone length and α control the strength of the damping. Boundary conditions on the open boundary and seabed are

$$\frac{\partial\phi}{\partial n} = 0 \tag{5}$$

The initial conditions are given as

$$\phi = 0;\ \partial\phi/\partial t = 0 \tag{6}$$

The hydrodynamic force on the body surface can be calculated by integrating the pressure over the instantaneous wetted body surface S

$$\boldsymbol{F} = \int_S p\boldsymbol{n}ds \tag{7}$$

The p is the pressure on the body surface, which can be obtained from the Bernoulli's equation

$$p = -\rho\left(\frac{\partial\phi}{\partial t} + \frac{1}{2}|\nabla\phi|^2 + gz\right) \tag{8}$$

where ρ is the density of the fluid.

Once ϕ and $\partial\phi/\partial n$ are found by solving the boundary value