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Numerical study on fluid resonance of 3-D multi-bodies by a non-reflection numerical wave tank

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ABSTRACT

By introducing mass and momentum source terms into Navier-Stokes equations, a 3-D viscous non-reflection numerical wave tank is developed to investigate the fluid resonance of 3-D multi-bodies with a small gap in waves. The numerical model is first validated by the analytical solutions of the linear monochromatic wave and the experimental data of wave forces on two side-by-side ships in beam waves. Then extensive numerical experiments are conducted to investigate the wave height in the gap, wave forces on multi-bodies, the hydrodynamic differences between the isolated single body and multi-bodies, the influences of 3-D effects, etc. Due to the existence of the small gap, fluid resonance occurs at a special wave frequency, near which large-amplitude wave oscillations and wave forces in sway (i.e., F_y) are observed. The sway forces F_y are highly dependent on the wave height in the gap, while little relationship is observed between the wave forces in other directions (i.e., F_x and F_z) and the wave height in the gap. For this reason, the conventional potential model and inviscid model over-predict the sway forces F_y but works as well as present viscous model in predicting the wave forces F_x and F_z. In addition, the comparison research conducted between the 3-D multi-bodies and the corresponding 2-D multi-bodies in beam waves show that the 3-D effects make the resonant frequency increase but the resonant wave forces decrease.

1. Introduction

In recent years, with the exploitation and utilization of marine resources, multiple floating structures, which include Very Large Floating Structures (VLFS), Liquefied Natural Gas (LNG) carriers moored alongside an offshore terminal, multi-hull ship etc., are widely used in production and construction. Different from the common isolated single structures, there are usually some small gaps within the multi-structures. Due to the existence of small gaps, strong fluid resonance may take place under certain wave frequencies. In this case, wave height in the gap and wave forces on the structures are very large, which will threaten the safety and service performance of the structures. In view of this, it is of tremendous importance to investigate the hydrodynamic resonance of the multiple floating structures and the mechanism of the small gap influence on the resonance.

Many different methods such as physical model experiments, theoretical analysis and numerical simulations have been employed to study the hydrodynamic property of the multi-bodies. For example, for a 2-D diffraction problem of waves acting on a super large floating structure, Miao et al. [1] analytically exploited an asymptotic matching technique to account for the gap influence on the wave forces on the floating blocks. The results showed that sharp peak responses for both vertical and horizontal wave-exciting forces take place around some special frequencies ($k\mathrm{L} = n\pi$), which was later confirmed by the experimental data of Saitoh et al [2]. Thereafter, Saitoh et al. [3] and Iwata et al. [4] conducted some experimental researches on the fluid resonance in gaps of twin boxes and three identical boxes respectively and put forward a theoretical formula to estimate the resonant frequency in the gaps. Although the model test and theoretical methods have some advantages, the demerits of high cost, slow speed and narrow application range limit their applications in practical engineering.

The numerical methods based on the potential flow theory have been the most widely used method for the problem of wave interaction with multiple structures so far. Miao et al. [5] employed a reduced 2-D source distribution method to investigate the hydrodynamic interaction between twin vertical cylinders with small gap. Later, three dimensional frequency-domain and time-domain Green function methods were employed by Zhu et al. [6] and Zhu et al. [7] respectively to solve the similar problem. Their results showed good agreement with each other. However, as the potential flow methods ignore the influence of

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Nomenclature

A_w	Water-plane area of the ship
B_g	Gap width
F_x, F_y, F_z	Wave forces in surge (x direction), sway(y direction) and heave(z direction)
F_y^s	The static component of the wave force in sway(y direction)
g	Gravitational acceleration
h	Water depth
H_{center}	Wave height in gap center
L, B, D,∇	Length, breadth, draft, displacement of the floating body
n_y	The y component of the normal vector.
p	Hydrodynamic pressure
$q(x, z, t)$	Additional mass source term
S_g	The distance between the longitudinal centerlines of wigley hull and rectangular barge
$S(t)$	Instantaneous wetted surface of the floating body
u, v, w	Fluid velocity in x, y and z directions
$\mathbf{V} = (u, v, w)$	Flow velocity vector
x_s, x_e	x coordinates at the start and end points of the spongy layer
α_w	Volume fraction of water
α_c, M	Empirical parameters
β	Wave incident angle
Δx	Horizontal grid size
Δx_s	Width of the mass source region
η	Instantaneous wave elevation
$\mu(x)$	Damping coefficient
υ	Kinematic viscosity of the fluid
υ_w,υ_a	Kinematic viscosity of water, air
ρ	Fluid density
ρ_w, ρ_a	Water density, air density
ϕ_n,γ_n	The nth harmonic amplitude and the corresponding phase
ω, k, λ, T, η_a,H_0	Wave frequency, wave number, wave length, wave period, wave amplitude and wave height
Ω_s	Mass source region

fluid viscosity and vortex, they will over-predict the resonant wave height in the gap and consequently lead to larger wave forces on the floating bodies. Attempts have been made to improve the accuracy of the potential flow method in predicting the resonant responses. Huijsmans et al. [8] used a rigid lid technique to circumvent unrealistic high water velocities on the ship hull. Subsequently Chen [9,10], Pauw et al. [11] and Lu et al. [12,13] proposed a new damping lid method, in which a damping term is added to the free surface condition. Besides, based on the fluid domain decomposition and the expansion of eigenfunctions, Ten et al. [14]developed a semi-analytical method with dissipation and succeeded in predicting the frequency and amplitude of the fluid resonance. While the unrealistic wave response is able to be suppressed by introducing the damping term, a careful tuning is required to select an appropriate value of artificial damping coefficient.

On the other hand, with the development of computer technology, Computational Fluid Dynamics (CFD) method began to be applied to marine engineering. Due to its consideration of fluid viscosity and flow rotation, CFD method can predict the resonant responses more accurately and does not need to introduce the artificial damping term. Recently some researchers applied the CFD method to the problem of wave interaction with multi-bodies. Sauder et al. [15] developed a Navier-Stokes solver based on OpenFOAM to investigated the fluid motions in the gap between a rectangular section and a bottom mounted terminal. This CFD-based solver succeeded in describing properly the fluid resonance in the gap. Lu et al. [16,13] and Chen et al. [17] simplified the 3-D multiple floating structures to 2-D rectangle boxes and investigated the influences of body number, body draft, gap width, etc on the gap resonance by using a 2-D viscous numerical wave tank.

However, due to the complexity and high computational cost of the 3-D model, most of the existing investigations on the wave interaction with multiple floating structures employing the viscous flow method (CFD) are limited to the simplified 2-D model so far. When the floating structures are slender and the wave direction is perpendicular to the gap direction, the simplification may be reasonable. But if each dimension of the structures has the same order of magnitude or the wave direction is parallel to the gap direction, the influences of three-dimensional effects cannot be ignored. So, in this article, a three-dimensional non-reflection numerical wave tank is established by using mass source method first. Then based on the wave tank, hydrodynamic resonant problems of three-dimensional multiple floating structures under the action of water waves in different directions are studied. The numerical results are compared with the potential and inviscid results. Furthermore, in order to investigate the influence of 3-D effects on the fluid resonance, a comparison research is conducted between a 3-D multi-bodies system and the corresponding 2-D multi-bodies system.

2. Numerical model

When numerical methods are employed to investigate the interaction between waves and structures, some problems may be induced. Due to the existence of the structures, the incident wave acting on the floating body will be reflected back to the incident boundary. If no treatment is taken near the incident boundary, wave re-reflection will take place and consequently result in the distortions of the calculated results.

In order to avoid the wave re-reflection, a mass source method accompanied with sponge-layer technique is employed to generate a non-reflection numerical wave tank. The numerical tank is divided into three parts: wave-making region (or mass source region), working region and absorbing regions (Fig. 1). The wave-making region is in the interior of the flow region, where a mass source is introduced to generate a desired wave. Absorbing regions are set at the two opposite ends of the numerical tank so as to prevent the wave reflection and re-reflection from the opening boundaries. Between the wave-making region and absorbing regions is the working region, where the floating structures can be placed to investigate their hydrodynamic property.

Based on the Navier-Stokes equations of the incompressible viscous fluid, Lin and Liu [18] succeeded in establishing a 2-D non-reflection wave tank by introducing a designed mass source function into the continuity equation. In the following, the 2-D model is generalized to the 3-D, and the corresponding 3-D modified N-S equations are:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = q(x, z, t) \tag{1}$$

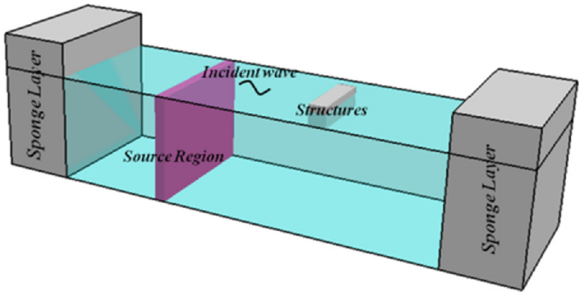

Fig. 1. Sketch of the wave tank generated by the mass source method.