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Numerical investigation on global responses of surface ship subjected to underwater explosion in waves

Y.L. Liu, A.M. Zhang*, Z.L. Tian, S.P. Wang

College of Shipbuilding and Engineering, Harbin Engineering University, Harbin, 150001, China

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ABSTRACT

Transient fluid-structure interaction (FSI) has always been a challenging problem in ship mechanics. Underwater explosion and its highly nonlinear impact on nearby structures are more complicated. In this paper, the global responses of a surface ship subjected to an underwater explosion in waves are numerically investigated considering the nonlinear coupling between the fluid and structure solvers. The fluid field is modeled with the boundary element method (BEM), while the potential decomposition theory is adopted to take the surface waves into account. The global responses of the ship structure are modeled with the mode superposition method. Then a FSI model is established using the mode decomposition method of the acceleration potential to consider the interaction. An underwater explosion experiment is carried out to validate the numerical model, which shows good agreement between the numerical and experimental results. With the presented model, the interactions between a ship and an underwater explosion bubble both in still water and waves are simulated. The dynamics of the ship global responses and the influence of the waves are analyzed which shows noteworthy nonlinearity.

1. Introduction

Shock responses of structure in water subjected to underwater explosion loads have always been the concern of researchers all over the world (Brett et al., 2000; Cole, 1948; Cui et al., 2016; Geers and Hunter, 2002; Hung and Hwangfu, 2010; Klaseboer et al., 2005a; Wang, 2013; Xiao et al., 2017; Zhang et al., 2011b, 2014, 2016, 2017a). The interaction between the fluid and the structure is highly nonlinear especially considering the free surface effect. Global strength is one of the most important aspects in ship strength evaluation. As a typical slender structure, the ship hull can be bended or twisted as a beam subject to the loads distributing uneven along the longitudinal direction of the ship. When the bending moment at the ship hull section exceeds the ultimate moment, longitudinal structural parts will fail and leads to the loose of the global strength. Underwater explosion bubble load is one of the most threatening load that a ship may encounter (Brett and Yiannakopolous, 2008; Chen et al., 2009; Cole, 1948; Hung and Hwangfu, 2010; Klaseboer et al., 2005a; Liu et al., 2014; Wang and Khoo, 2004; Wang et al., 2014; Zhang et al., 2012, 2014, 2016, 2017b). Due to the low frequency feature of the bubble oscillation load which can be close to the frequency of the low order vibration modes of the ship, resonance effects may lead to serious global response of the ship, and threaten its global strength (Chen et al., 2009; Hicks, 1986; Wilkerson, 1985; Xiao et al., 2017; Zhang et al., 2011a, 2014). Many of the traditional researchers used spherical underwater explosion bubble model to predict the whipping response of ships. Steller (1983) studied the damping factors in the whipping responses of the submarine subject to an underwater explosion loading. Hicks (1986) simulated the whipping responses of the surface ship caused by underwater explosion. Kwon and Cunningham (1998) analyzed the difference between several simplification method of the stiffened cylindrical shell subject to underwater explosion. Researches above used the spherical bubble dynamics model ignoring the effects of the its deformation and nonlinear interaction with boundaries. If the explosion was far enough from the ship, the error is negligible. For the surface ship, the effects of the free surface must be considered. Zhang & Zong analyzed the whipping responses of the surface ship subject to the bubble load adopting the spherical bubble model and the linearized free surface condition (Zhang and Zong, 2011; Zhang et al., 2014). As for the nonspherical motion of the underwater explosion bubble nearby the floating structure, Klaseboer et al. (2005b) employed BEM to simulate the underwater explosion bubble dynamics nearby a surface ship. However, the ship is fixed and the free surface is linearized, which ignores the corresponding nonlinear interaction between them. Xiao et al. (2017) investigated the whipping responses of a fluid filled cylindrical shell subjected to underwater explosion using the Doubly Asymptotic Approximation method considering the inner fluid.

When the ship sailing in the sea, it must encounter wave loads

* Corresponding author.
E-mail address: zhangaman@hrbeu.edu.cn (A.M. Zhang).

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which also threats the global strength of the ship. If the surface ship subjects the wave loads and the underwater explosion loads at the same time, the overlaying effect will imperil the ship strength even more seriously. However, the relevant studies are rarely published, and most of the previous researchers studied the 2 nonlinear progresses separately. Liu et al. (2012) adopted BEM and the velocity potential superposition method to investigate the nonlinear interaction between underwater explosion bubble and waves. Xue et al. (2001a, 2001b) investigated the three-dimensional wave-wave and wave-body interaction with the periodic Green's Function. Tanizawa (1995) deduced the acceleration potential method for the nonlinear simulation of 3-Dimensional (3D) body motion in waves, and subsequently Koo. (2003) established the interaction model between floating body and nonlinear waves with 2D potential numerical wave tank.

In this paper, the interactions between an underwater explosion bubble, surface waves and a ship are investigated numerically. The paper is organized as following. Firstly, the theoretical and numerical models of the bubble dynamics and fluid-structure interaction are presented. Secondly, an experiment is carried out to validate the numerical models. Then, the interaction between the bubble and the ship in still water is simulated and analyzed. At last, cases in different waves are studied, and the influences of the waves are discussed.

2. Theoretical and numerical model

2.1. Bubble dynamics based on BEM

As shown in Fig. 1, a Cartesian coordinate system is built up with its origin placed at the midship on the free surface, x axis pointing to the stern of the ship and z axis pointing upward. As for the underwater explosion bubble, the surrounding fluid is used to be assumed inviscid and incompressible because of the high Reynolds number and the low Mach's number for most life time of the bubble (Cole, 1948; Klaseboer et al., 2005a; Liu et al., 2016b). Thus, there exists a velocity potential ϕ which satisfies the Laplace equation

$$\nabla^2\phi = 0. \tag{1}$$

Taking $G = 1/|\mathbf{p} - \mathbf{q}|$ as the Green's function in three-dimensional domain, we can obtain the boundary integral equation

$$c(\mathbf{p})\phi = \int_S \left[-G(\mathbf{p},\mathbf{q})\frac{\partial\phi(\mathbf{q})}{\partial n(\mathbf{q})} + \frac{\partial G(\mathbf{p},\mathbf{q})}{\partial n(\mathbf{q})}\phi(\mathbf{q})\right]\mathrm{d}s, \tag{2}$$

where $\mathbf{p}$ and $\mathbf{q}$ are the field point and the source point respectively, S is the boundary of the fluid domain which consists of the free surface S_f, the bubble surface S_b and the wet surface of structure S_s, $\mathbf{n}$ is the unit normal vector pointing into the fluid, and c is the solid angle watching the fluid domain from point $\mathbf{p}$.

The boundary conditions of the fluid field can be expressed as

$$\frac{\partial\phi}{\partial n} = \mathbf{v}\cdot\mathbf{n}, \tag{3}$$

for the wet surface of the structure, and

$$\frac{\partial\phi}{\partial t} = \frac{P_\infty - P}{\rho_f} - \frac{1}{2}|\nabla\phi|^2 - gz, \tag{4}$$

for the free surface and the bubble surface, where $\mathbf{v}$ is the structural velocity, P_∞ is the hydrostatic pressure at the depth where the vertical coordinate $z = 0$, ρ_f is the density of the fluid, and P is the pressure at the surface. Particularly, P is the atmosphere at the free surface, and defined by the adiabatic gas law at the bubble surface,

$$P = P_0\left(\frac{V_0}{V}\right)^\gamma, \tag{5}$$

where P_0 is the initial pressure of the bubble. V_0 and V are the initial and the current volume of the bubble, respectively. γ is the ratio of specific heats. In this paper, γ is taken as 1.25 for the explosion products (Cole, 1948).

As many previous works have been implemented on the bubble dynamics simulation with BEM, the initial conditions, numerical discretization of Eq. (2) and the time marching scheme are omitted in this paper, and they can be referred to the published articles for detailed Mixed-Eulerian-Lagrangian Method (MEL) implementation (Best, 2002; Klaseboer et al., 2005a; Liu et al., 2016a; Wang et al., 2003; Wu et al., 2017; Zhang and Liu, 2015; Zhang et al., 1998).

2.2. Decomposition theory of velocity potential in waves

In this paper, the third order Stokes wave theory in deep water is adopted to describe the incident waves. The wave amplitude function η_w and the incident potential ϕ_w can be expressed as

$$\eta_w(x,t) = a_w\left\{\cos\theta_w + \frac{1}{2}k_w a_w\cos 2\theta_w + \frac{3}{8}(k_w a_w)^2\cos 3\theta_w\right\} + o((k_w a_w)^4), \tag{6}$$

$$\phi_w(x,z,t) = a_w\frac{\omega_w}{k_w}e^{k_w z}\sin\theta_w + o((k_w a_w)^4), \tag{7}$$

where, a_w is the first order wave amplitude, ω_w is the circular frequency, k_w is the wave number, $\theta_w(x,t) = k_w x - \omega_w t + \varsigma_w$, ς_w is the phase angle, and c_w is the phase velocity which is expressed as

$$c_w = \frac{\omega_w}{k_w} = \left(1 + \frac{1}{2}(k_w a_w)^2\right)\sqrt{\frac{g}{k_w}} + o((k_w a_w)^4). \tag{8}$$

Then the velocity potential of the fluid can be decomposed as

$$\phi = \phi_w + \phi_d, \tag{9}$$

where ϕ_d is the disturbance potential of the ship and the bubble decaying to 0 at infinity. Thus, ϕ_d and its normal derivative satisfies the boundary integral equation. Considering the incident potential ϕ_w is prescribed, we can update ϕ_d with the modified Bernoulli equation

$$\frac{\partial\phi_d}{\partial t} = \frac{P_\infty - P}{\rho_f} - \frac{1}{2}|\nabla\phi|^2 - gz - a_w\frac{\omega_w^2}{k_w}e^{k_w z}\cos\theta_w, \tag{10}$$

where the last term on the right hand represents the effect of the incident potential. Comparing with the nonlinear numerical wave tank

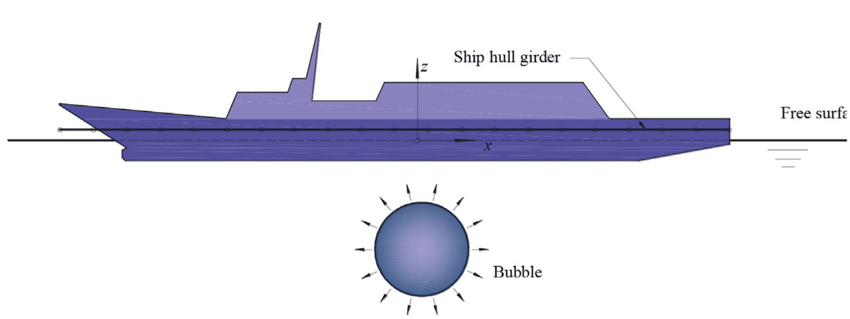

Fig. 1. Sketch of the global response of the ship subject to the bubble load.