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Investigation of bubble dynamics of underwater explosion based on improved compressible numerical model

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ABSTRACT

A bubble jet with velocity of hundred meters per second forms at the final stage of bubble collapse, which makes the compressibility of flow field can't ignore. Based on the spherical bubble model of Geers and Hunter, a compressible numerical model is improved for simulating non-spherical bubble dynamic in this paper. In the present implementation, the compressibility of external liquid and the wave effect of internal gas are considered by the first order external doubly asymptotic approximation and the first order internal doubly asymptotic approximation, respectively. In addition, the volume acceleration model is applied to calculate the initial condition of bubble. After that, the improved compressible numerical model is validated against the underwater explosion experiment data. The numerical result of bubble radius correlates well with the experiment data. Finally, based on the improved compressible numerical model, the influences of wave effect of internal gas and initial condition of bubble on bubble dynamics in free field and gravity field are investigated. The wave effect of internal gas makes bubble radius, radial velocity, translational displacement, jet velocity and remaining total energy decrease. The initial radial velocity, on the one hand, makes bubble radius, radial velocity, translational displacement, jet velocity and remaining total energy increase at the first bubble cycle; on the other hand, intensifies bubble radius, radial velocity, translational displacement, jet velocity and remaining total energy decay.

1. Introduction

Bubble widely exists in ship and ocean engineering field, such as, propeller cavitation bubble, underwater explosion bubble, etc. When a ship's propeller is working in the water with high speed, cavitation bubbles are generated on the surface of it. High speed jets toward to propeller blade formed at the collapse stage of cavitation bubbles will corrode the propeller blade [1,2]. The bubble generated by underwater explosion will damage ship structure, make it form plastic deformation, tear into hole, even break off [3–5]. In addition, bubble is also applied in some other areas. For example, in medicine area, micro cavitation bubbles subjected to shock wave collapse, then form high speed jets along the direction of shock propagation. High speed jets impact stone and make it break into small particles [6,7].

Bubble dynamics in water has been one of the research hotspots for scholars about one century. Bubble dynamics can be divided into two kinds, spherical and non-spherical dynamics. For spherical bubble dynamics, Rayleigh [8] established a spherical bubble motion equation in incompressible, inviscid and irrotational flow field. Plesset [9] proposed the most widely used spherical bubble motion equation through improving the equation of Rayleigh [8], which is Rayleigh-Plesset equation. For non-spherical bubble dynamics, due to the complexity of non-spherical bubble dynamics, numerical simulation is the main research mean. Boundary element method (BEM) is widely used to simulate bubble non-spherical dynamics [10–12]. Besides BEM, volume of fluid (VOF) method [13] and smoothed particle hydrodynamics (SPH) method [14] are also applied to investigate bubble non-spherical dynamics. Lots of scholars have investigated bubble dynamics near different boundaries by BEM. For example, Blake and Gibson [15] and Robinson and Blake [16] simulated the interaction between bubble and free surface. Zhang et al. [17], Brujan et al. [18] and Wang and Khoo [19] simulated the interaction between bubble and rigid wall. Klaseboer and Khoo [20] and Turangan [21] simulated the interaction between bubble and elastic boundary. It's worth mentioning that all of these studies are based on the potential flow theory with compressibility neglected. It leads to the period and maximum radius of bubble be constant. But a large amount of underwater explosion experiments [22,23] show that during bubble pulsation the

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energy of underwater explosion bubble dissipates gradually and the period and maximum radius of underwater explosion bubble decrease constantly. In order to reveal the mechanism of energy dissipation of underwater explosion bubble, the researchers pay more and more attention to the influence of the compressibility of flow field on the bubble dynamics.

For the spherical bubble dynamics in compressible flow field, Keller and Kolodner [24] established a spherical bubble motion equation of compressible flow field based on wave equation and Bernoulli's equation. Through the matched asymptotic expansion method, Prosperetti and Lezzi [25] and Lezzi and Prosperetti [26] also established a spherical bubble motion equation of compressible flow field. But, there are few researches on non-spherical bubble motion in compressible flow field currently. Lee et al. [27] improved incompressible bubble boundary element model through removing a part of bubble potential energy at the final stage of bubble collapse, and investigated the dissipation of bubble energy. On the basis of Prosperetti and Lezzi [25], Wang and Blake [28,29] investigated non-spherical bubble dynamics in compressible flow field through matched asymptotic expansion method and BEM.

In the corresponding author's previous work [30], boundary integral equation of compressible flow field was obtained through matched asymptotic expansion method based on linear wave equation. Associated with the ideal gas state equation, non-spherical bubble dynamics in compressible flow field was investigated. As the research goes deeper, we find that there are some differences between our previous numerical result and underwater explosion experiment data. And we think the differences are mainly caused by the wave effect of internal gas and the initial radial velocity of bubble. For the wave effect of internal gas, Moss et al. [31] proposed a spherical bubble motion equation of incompressible flow field considering the wave effect of internal gas. Geers and Hunter [32] established a spherical bubble motion equation of compressible flow field considering the wave effect of internal gas, which is called the Geers and Hunter model. To the authors' knowledge, the study on the non-spherical bubble motion with the wave effect of internal gas is very rare. In addition, the initial radial velocity of bubble is also seldom considered during the numerical simulations of non-spherical bubble motion. But, In the process of underwater explosion, the shock wave stage provides the initial radial velocity for the bubble phase. Recently, Wang [33] obtained the initial radius and initial velocity of bubble by a backward integration of the Keller equation combined with underwater explosion experiment data.

In the present paper, based on the spherical bubble model of Geers and Hunter [32], a compressible numerical model is improved for simulating non-spherical bubble dynamic. In the present implementation, the compressibility of external liquid and the wave effect of internal gas are considered by the first order external doubly asymptotic approximation [34] and the first order internal doubly asymptotic approximation [35], respectively. The liquid and gas fields are linked at the bubble interface through compatibility of normal velocity and pressure equilibrium. Then, according to the relationship between shock wave pressure and bubble volume acceleration of shock wave phase [36], the initial velocity and initial radius of bubble are calculated combined with the empirical equation of shock wave pressure [22]. On the basis of above, the influences of wave effect of internal gas and initial bubble condition on bubble dynamics in free field and gravity field are investigated. The main contents of this paper include: (1) the improved compressible numerical model, (2) the validity of the improved numerical model, (3) the influence of the wave effect of internal gas on bubble dynamics, (4) the influence of the initial condition on bubble dynamics.

2. Numerical model

2.1. Boundary integral equation

A Cartesian coordinate system *O-XYZ* is used with the origin at the center of bubble and the Z-axis in the vertical direction, opposite to gravity. Nondimensionalization is applied based on the maximum bubble radius R'_m, the liquid pressure at infinity on $z = 0$ plane p'_∞ and the density of the liquid ρ'_l. So length, pressure, time, velocity and velocity potential are normalized to R'_m, p'_∞, $R'_m\sqrt{\rho'_l/p'_\infty}$, $\sqrt{p'_\infty/\rho'_l}$ and $R'_m\sqrt{p'_\infty/\rho'_l}$, respectively. In the present paper, all variables without prime are considered as dimensionless. The maximum bubble radius R'_m can be given by the empirical equation obtained from underwater explosion experimental data [22]:

$$R'_m = 3.38\left(\frac{W'}{H'+10}\right)^{1/3} \quad (1)$$

where W' is the weight of charge, H' is the depth of explosive charge.

For underwater explosion bubbles, the maximum fluid velocity is generally one or two orders of magnitude smaller than the sound speed in fluid, and the bubble wall Mach number is small [33]. So the fluid can be regarded as weakly compressible fluid. The external liquid field is governed by the first order external doubly asymptotic approximation equation [34] at the bubble surface:

$$\frac{\partial\phi_l}{\partial t} + c_l\beta^{-1}\gamma\phi_l = -c_l\dot{u}_l \quad (2)$$

where ϕ_l is the velocity potential of liquid, c_l is the sound speed in the liquid, $\dot{u}_l$ is the normal velocity of the liquid. β and γ are the spatial integral operators defined as:

$$\beta f(p) = \iint_S \frac{f(q)}{|\boldsymbol{r}_{pq}|}dS_q$$
$$\gamma f(p) = \iint_S \frac{\boldsymbol{r}_{pq}\cdot\boldsymbol{n}_q}{|\boldsymbol{r}_{pq}|^3}f(q)dS_q \quad (3)$$

where $\boldsymbol{r}_{pq}$ is the position vector between point p and point q on bubble surface S. $\boldsymbol{n}_q$ is the normal vector of bubble surface with the direction pointing into the liquid here, for the internal gas field mentioned below, the normal vector of bubble surface directs towards the gas. β^{-1} denotes the inverse operator of β. If we define $F(p) = \beta f(p)$, then β^{-1} can be defined as $\beta^{-1}F(p) = f(p)$.

According to the work of Zhang et al. [30], the Bernoulli equation for weakly compressible fluid has the same form as that for incompressible fluid. So, The Bernoulli equation of external liquid field can be written as:

$$\frac{d\phi_l}{dt} = 1 + \frac{1}{2}\left|\dot{\boldsymbol{u}}_l\right|^2 - \delta^2 z - p_l \quad (4)$$

where $\dot{\boldsymbol{u}}_l$ is the velocity vector of liquid, p_l is the pressure of liquid, z is the vertical position of liquid particle, and $\delta = \sqrt{\rho'_l g' R'_m/p'_\infty}$ is the buoyancy parameter, g' is the gravity acceleration.

The internal gas field is governed by the first order internal doubly asymptotic approximation equation [35] at the bubble surface:

$$\frac{\partial\phi_g}{\partial t} + c_g\beta^{-1}\gamma\phi_g = -c_g(\dot{u}_g + c_g L^{-1}\alpha u_g) \quad (5)$$

where ϕ_g is the velocity potential of gas, c_g is the sound speed in the gas, $\dot{u}_g$ the normal velocity of the gas, u_g the normal displacement of the gas. $L = V_g/A$,V_g is the volume of bubble, A is the area of the bubble surface S. α is the averaging operator defined as:

$$\alpha f(p) = \frac{1}{A}\iint_S f(p)dS_p \quad (6)$$