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Analysis of pressure field generated by a collapsing bubble

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ABSTRACT

This paper is concerned with the dynamic pressure induced by a collapsing bubble, based on the potential flow theory coupled with the boundary element method. The pressure is calculated using the Bernoulli equation, where the partial derivative of the potential in time is calculated using the auxiliary function method. The numerical results agree well with experimental results, in terms of bubble shape and pressure fields. There are two root causes of the bubble induced pressure and the dynamic pressure is decomposed into two parts correspondingly. The first part p_g is associated with the imbalanced pressure between the bubble gas and the ambient flow, which measures the contribution of the high pressure gas to the dynamic pressure. The second part p_m is caused by the bubble motion, which helps evaluate the contribution of the jet impact. The variation of p_g has the same pattern with the gas pressure. p_m at the wall center reaches its first peak soon after the jet impact, and then decreases due to the reduction of jet velocity. As the toroidal bubble migrates towards the wall, p_m may rise again. We also investigate the influences of dimensionless parameters on the pressure field induced by a gas/cavitation bubble.

1. Introduction

Bubble dynamics are associated wide applications in industrial systems: cavitation on ship propellers and hydroturbines (Choi et al., 2009; Hsiao and Chahine, 2012), seabed geophysical exploration (Graaf et al., 2014), underwater explosion (Klaseboer et al., 2005; Wang, 2013; Liu et al., 2014), and ultrasonic cleaning (Song et al., 2004; Wijngaarden, 2016; Chahine et al., 2016; Ohl et al., 2006). Analyses of the pressure fields generated by a collapsing bubble are directly associated with the mechanism of erosion, underwater explosion, etc.

Rayleigh (1917) theoretically demonstrated that a local high pressure will be generated during the collapse phase of a spherical symmetrical bubble. The pressure can be very high and consequently leads to an outgoing shock wave (Harrison, 1952). However, the bubble cannot keep spherical when affected by gravity (Zhang et al., 2015a), interacts with a shock wave (Klaseboer et al., 2006), near a free surface (Blake and Gibson, 1981) or near a rigid boundary (Naude and Ellis, 1961). The pressure field surrounding a non-spherical bubble is quite different from a spherical one. The jet formation is the main feature of a non-spherical bubble.

For a bubble collapsing near a rigid wall, there is a high pressure region located behind the jet during collapse (Blake et al., 1986; Best and Kucera, 1992; Zhang et al., 1993; Brujan et al., 2002). After jet impact, another high pressure region is located ahead of the bubble (Best and Kucera, 1992; Best, 1993). Two high local peak pressures were predicted by Blake et al. (1997): The earlier one is associated with jet impact, while the later one coincides with the large internal pressures of the bubble at minimum volume. Philipp and Lauterborn (1998) also observed two individual shock waves during the bubble collapse in some experiments. The first shock wave is generated by the impact of the jet tip onto the opposite bubble wall. The second shock wave emitted when the bubble reaches its minimum volume. Until now, two characteristic effects are believed to be mainly responsible for the destructive action: the high pressure pulse (when bubble reaches its minimum volume) and the high-speed liquid jet impact.

In all, the bubble induced pressure is a combination of the high pressure gas (around minimum volume) and the high-speed fluid motion (jet, splash, rebound, etc.). The correlate mechanisms will offer the reference for the above applications. For example, if the jet impact dominates the erosion process, we should take actions to prevent the jet or change the jet direction (Brujan et al., 2001; Gibson and Blake, 1982; Duncan and Zhang, 1991). If the gas pressure plays an important role in cleaning, we should enhance the compression of the bubble gas. Actually, it is difficult to divide the two effects apart in experiments. However, theoretical or numerical studies could yield a valuable contribution to the clarification of the influences of these two factors on the above applications.

Given this, the dynamic pressure induced by a non-spherical bubble is decomposed into two parts theoretically in present

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study: the first one is caused by the bubble gas pressure and the second one is induced by the bubble motion. Both these two sub-pressures have specific physical meanings, which helps evaluate the gas induced pressure and the jet impact pressure, respectively. For a cavitation bubble with its inner pressure keeps vapor pressure, this pressure decomposition is also implemented and a comparison is made with a gas bubble.

In numerical calculation, boundary element/integral method (BEM/BIM) is used to simulate the bubble motion. BEM was extensively and successfully applied to bubble dynamics, which was validated by a large number of experiments (Tong et al., 1999; Robinson et al., 2001; Dadvand et al., 2011; Wang, 2014; Zhang et al., 2015b; Han et al., 2015). The vortex ring model (Wang et al., 1996; Zhang and Liu, 2015) is adopted to handle the discontinuous velocity potential on a toroidal bubble surface, and a multiple vortex rings model (Zhang et al., 2015b) is used after the splitting of a toroidal bubble. Besides, an auxiliary function method is adopted to calculate the total dynamic pressure and two sub-pressures.

An underwater explosion bubble experiment in literature are used to validate our numerical model, and the experimental and numerical results meet well, in terms of bubble shape evolutions and pressure signals. We also conduct a spark-generated bubble experiment, and the corresponding numerical analysis is made, in which the characteristics of the decomposed pressures are analyzed. At last, the effects of the stand-off parameter, the strength parameter and the ratio of the specific heats for the gas are discussed.

2. Theory and numerical method

2.1. Basic formulas

Consider bubble dynamics in an axisymmetric configuration. A cylindrical coordinate system $O-r\theta z$ is adopted in our model. The origin is placed at the initial bubble center and z axis is pointing towards the opposite direction of the gravity acceleration.

Because of the high velocities and consequent high Reynolds number during the growth and collapse of a bubble, viscosity is found to play a negligible role in the collapse of a cavitation bubbles. For bubbles in a very viscous fluid (more than thousands of time the viscosity of water), the viscosity would slow down the collapse process (Tinguely, 2013; Brujan and Matsumoto, 2014). In the present study, the flow surrounding the bubble is assumed inviscid, incompressible and irrotational. The velocity potential φ satisfies the following boundary integral equation:

$$\lambda(\boldsymbol{r},t)\varphi(\boldsymbol{r},t)=\iint_S\left[\frac{\partial\varphi(\boldsymbol{q},t)}{\partial n}G(\boldsymbol{r},\boldsymbol{q})-\varphi(\boldsymbol{q},t)\frac{\partial}{\partial n}G(\boldsymbol{r},\boldsymbol{q})\right]dS, \tag{2.1}$$

where $\boldsymbol{r}$ is the field point and $\boldsymbol{q}$ is the source point, $\lambda(\boldsymbol{r},t)$ is the solid angle, Sincludes all the boundaries of the flow domain, $\partial/\partial n$ is the normal outward derivative from the boundary. When dealing with a bubble near an infinite rigid wall, the Green function $G(\boldsymbol{r},\boldsymbol{q})$ is taken as

$$G(\boldsymbol{r},\boldsymbol{q})=\frac{1}{|\boldsymbol{r}-\boldsymbol{q}|}+\frac{1}{|\boldsymbol{r}-\boldsymbol{q}'|}, \tag{2.2}$$

where $\boldsymbol{q}'$ is the reflected image of $\boldsymbol{q}$ across the rigid wall.

The kinematic boundary condition and dynamic boundary condition on bubble surface are as follows:

$$\frac{d\boldsymbol{r}}{dt}=\nabla\varphi, \tag{2.3}$$

$$\frac{d\varphi}{dt}=\frac{|\nabla\varphi|^2}{2}+\frac{p_\infty}{\rho}-\frac{p_b}{\rho}-gz, \tag{2.4}$$

where p_b is the bubble gas pressure, p_∞ is the ambient pressure of the liquid at the inception point of the bubble, ρ is the density of the liquid, g is the gravity acceleration.

Assuming that the expansion and contraction of the bubble gas are adiabatic, the gas pressure inside the bubble is expressed as follows:

$$p_b=p_c+p_{ini}(V_{ini}/V)^\kappa, \tag{2.5}$$

where V is the bubble volume, the subscript *ini* denotes initial quantities, κ is the ratio of the specific heats for the gas, p_c is the vapor pressure. Surface tension is neglected in this study for the large Weber number ($We\sim10^4$) during the growth and collapse of a bubble. For bubbles with a radius of the order of micrometer, the effect of surface tension is not negligible anymore (Tinguely, 2013).

Bubble is transformed from a singly-connected into a double-connected form after the jet impact upon the opposite bubble surface, and there exists a velocity potential jump at the impact point. Wang et al. (1996, 2005) introduced a vortex ring inside the toroidal bubble to handle this problem. The vortex ring model has been widely used to simulate the toroidal bubble motion, which is not introduced in detail.

The splitting of a toroidal bubble near a rigid boundary is commonly seen in experiments. In our previous paper (Zhang et al., 2015b), the multiple vortex rings model is established to simulate the interaction between two toroidal bubbles near a rigid boundary. A brief description about this model is made as follows.

Two vortex rings are placed inside the two toroidal bubbles respectively. The velocity potential in the flow is decomposed as follows:

$$\varphi=\varphi_{vr1}+\varphi_{vr2}+\varphi_{vr\_m1}+\varphi_{vr\_m2}+\phi, \tag{2.6}$$

where φ_{vr} is the induced potential by the vortex ring, φ_{vr_m} is the induced potential by the mirror vortex ring (reflection of the vortex ring across the rigid wall), ϕ is the single-valued remnant potential.

The velocity in the flow is also decomposed into five parts:

$$\boldsymbol{u}=\boldsymbol{u}_{vr1}+\boldsymbol{u}_{vr2}+\boldsymbol{u}_{vr\_m1}+\boldsymbol{u}_{vr\_m2}+\nabla\phi, \tag{2.7}$$

where the first four terms are induced velocities by the vortex rings, which can be calculated by the Biot–Savart law. The last part $\nabla\phi$ is induced by remnant potential, which can be calculated using BEM. More details about multiple vortex rings model refers to Zhang et al. (2015b).

Assume the initial bubble has a spherical shape and the velocity on bubble surface is zero. At each time step, the bubble surface and the velocity potential on it are known. We can use these informations to calculate the tangential velocity using finite differential method. The normal velocity is obtained by solving the boundary integral equation. The forward time integrations of Eqs. (2.3)–(2.4) are carried out using the fourth-order Runge–Kutta method.

2.2. Pressure calculation

The pressure distribution p in the flow field can be evaluated using the Bernoulli equation:

$$p=p_\infty-\rho gz-\rho\left(\frac{\partial\varphi}{\partial t}+\frac{|\nabla\varphi|^2}{2}\right). \tag{2.8}$$

Best (1991) and Dawoodian et al. (2015) employed the finite difference approximation to calculate (2.8). However, this method needs several velocity potentials at different time steps, which is not accurate enough. In present study, a more precise approximation is used, which is called the auxiliary function method (Duncan et al., 1996; Wu and Hu, 2004).