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Numerical analysis of the bubble jet impact on a rigid wall

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ABSTRACT

The main characteristic of the bubble dynamics near a rigid wall is the development of a high speed liquid jet, generating highly localized pressure on the wall. In present study, the bubble dynamic behaviors and the pressure impulses are investigated through experimental and numerical methods. In the experiment, the dynamics of a spark-generated bubble near a steel plate are captured by a high-speed camera with up to 650,000 frames per second. Numerical studies are conducted using a boundary integral method with incompressible assumption, and the vortex ring model is introduced to handle the discontinued potential of the toroidal bubble. Meanwhile, the pressure on the rigid wall is calculated by an auxiliary function. Calculated results with two different stand-off parameters show excellent agreement with experimental observations. A double-peaked or multiple-peaked structure occurs in the pressure profile during the collapse and rebounding phase. Generally, the pressure at the wall center reaches the first peak soon after the jet impact, and the second peak is caused by the rapid migration of the bubble toward the wall, and the subsequent peaks may be caused by the splashing effect and the rebounding of the toroidal bubble. At last, both agreements and differences are found in the comparison between the present model and a hybrid incompressible–compressible method in Hsiao et al. (2014). The differences show that the compressibility of the flow is another influence factor of the jet impact. However, the main features of the jet impact could be simulated using the present model.

1. Introduction

Bubble dynamics near a rigid wall has many applications in ocean engineering because of the possible damage threat that can be caused by the impulsive pressure pulses during the collapse phase. The growth and collapse of micron-sized bubbles near propeller blades holds the key to understanding the deleterious effects of cavitation [1,2]. The interaction between underwater explosion (UNDEX) bubble and warship has important naval applications [3–6]. Early in 1917, Rayleigh [7] developed a spherical bubble model (Rayleigh–Plesset equation) based on the incompressible velocity potential theory, which could be used to explain the very high pressure near the bubble surface during the contraction stage of a bubble. However, the bubble cannot always keep a sphere shape during its whole life, especially near boundaries [8,9] or affected by gravity [10]. The development of a high speed liquid jet is the main feature of a non-spherical bubble. Lauterborn [9] found the velocity of the boundary-induced bubble jet is approximately 120 m/s, which would cause severe damage to the structures. The collapse of the bubble onto a cylinder was found to be the most severe structure load, generating a peak velocity almost twice that caused by the shock wave [11]. The load caused by bubble collapse is complex and not yet fully understood.

Experiment is the most direct method to study the bubble dynamic behavior and the load caused by a collapsing bubble, including UNDEX bubble [3], laser-induced cavitation bubble [12–16], and spark-generated bubble [17,18]. However, the real UNDEX experiment is hard to conduct for high costs and high risk. Besides, the gas inside the bubble is not transparent, so the development of the jet is invisible. The size of the laser-induced bubble and the spark-generated bubble is limited to several micrometers, thus the measurement of the impulsive forces is difficult because the size of pressure gauge is often larger than the bubble size [13]. In Tong's work [13], the transducer is approximately the same size of the bubble diameter. Therefore, the experimental signals just indicate the force in a relatively large area. To sum up, it is still very difficult to measure the pressure caused by the bubble jet impact.

Boundary integral method (BIM) is widely used to study the dynamic behavior of a non-spherical violently oscillating gas bubble for close to four decades [3]. The simulated results trace the main features of the bubble motion, such as expansion, collapse, jet and rebound. In addition, the velocity and pressure in the fluid domain could be calculated to analyze the mechanism of these phenomena. The transition of the bubble from a singly-connected to a doubly-connected form induces circulation in the flow around the toroidal bubble, which becomes a barrier to the numerical simulation of the subsequent bubble motion. Therefore, only a few works

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on the dynamic of toroidal bubble have been published before. Best [19] introduced a cut in the flow domain when jet impact occurs, rendering the flow domain remain singly-connected. Wang [20] came up with a simpler model by placing a vortex ring inside the bubble. The strength of the vortex ring is chosen to be equal to the potential difference of the jet tip and the opposite bubble surface just before the jet impacts. These two models are extensively and successfully applied to handle the toroidal bubble, and the second one is used in this paper.

Valuable studies on jet impact have been performed using BIM. The "splashing" effect [12] occurs after the liquid jet impact onto the boundary with the dimensionless stand-off distances between 0.8 and 1.2, which is a source of very high pressures on a circular ring around the collapsing bubble. Brujan [14] studied the final stage of the collapse of a cavitation bubble close to a rigid boundary. It was found that two high pressure regions are located on the axis of symmetry above and below the bubble, and the high pressure region on the rigid boundary covers only a small area localized around the jet tip. In Wang's work [21], there appears to be an optimal initiation distance for which the liquid jet thus formed is most damaging. The optimum stand-off is found to be around 1.3 in the absence of buoyancy. However, a quantitative relationship between the impulses and the bubble collapse is still incomplete due to the extremely rapid and complicated unsteady flow phenomena, and there is little information about the rebounding toroidal bubble.

In this work, the motion of a bubble near a rigid wall is studied both experimentally and numerically. Two cases are selected with the stand-off distances being 1.51 and 1.05 times the maximum radius of the bubble. The numerical results of the cases indicate different pressure characteristics due to the direct and indirect jet impacts on the wall. There is always some numerical instability when calculating the pressure load on the rigid wall [21]. In the present study, $\partial\Phi/\partial t$ is evaluated with the auxiliary function method [22] to avoid making finite difference of the velocity potential, thus obtaining a better result of the pressure. At last, a comparison is made between the present model and a hybrid incompressible–compressible method [23,24]. The agreements as well as differences between these two models are discussed.

2. Experiment

This section will give a brief description of the experiment. A schematic of the experimental setup used for studying the motion of a spark-generated bubble near a rigid wall is shown in Fig. 1. Experiments are conducted in a water tank with dimension 500 mm × 500 mm × 500 mm, in which the water is filled up to 400 mm in depth. A steel plate, 300 mm × 300 mm × 8 mm, is placed at the bottom of the tank. The low-voltage spark bubble generation method can be found in Turangan's work [18]. The circuit employed in current bubble generation is based on Zhang [25], including a 6600 μF capacitor and a 220 V DC power supply. A bubble is generated by burning the copper wire with its diameter about 0.25 mm, and captured by the Phantom V12.1 high-speed camera. The camera works at 30,010 frames per second with exposure time 10 μs. The whole experiment section is illuminated from the back with a 2 kW light. More detailed information about the experiment can be found in Zhang [25].

3. Theory

3.1. Boundary-integral method

Because of the large Reynolds number ($Re \sim 10^4$) [26,27] associated to the bubble motion and the short bubble lifetime in comparison to viscous diffusion times, the liquid surrounding the bubble is assumed inviscid and the motion irrotational [14]. Besides, the jet Mach number is larger than 0.1 for about 0.1% of the bubble lifetime [26], so we ignore the compressibility of the flow in the present model. Thus, the velocity potential Φ satisfies the Laplace equation in the flow domain as follows

$$\nabla^2\Phi = 0 \tag{1}$$

According to the Green function [28], the velocity potential at any point in the domain could be expressed as an integral equation

$$\iint_S \left(\frac{1}{|q-r|}\cdot\frac{\partial\Phi(q,t)}{\partial n} - \Phi(q,t)\frac{\partial}{\partial n}\left(\frac{1}{|q-r|}\right)\right) \times dS(q) = \varepsilon(r,t)\cdot\Phi(r,t) \tag{2}$$

where $\varepsilon(r, t)$ is the solid angle of a fixed point r with the integration variable q also situated on boundaries, $\partial/\partial n$ is the normal outward derivative from the boundary S. $G(r, q) = (1/|r - q|) + (1/|r - q'|)$ is the half-space Green function, with q' being the reflected image of q across the wall. This Green function satisfies the zero flux condition through the wall.

In order to solve Eq. (2) numerically, we take an axisymmetric model and discretize the bubble surface into M nodes and N elements. Then, Eq. (2) transforms into M equations

$$\sum_{j=1}^{M}\left(W_{ij}\frac{\partial\Phi_j}{\partial n}\right) = \sum_{j=1}^{M}(M_{ij}\Phi_j) - \varepsilon(i)\Phi_i \tag{3}$$

where W_{ij} and M_{ij} are influence coefficients. The calculation process can be found in Blake [27] and Wang [29].

The dynamic boundary condition on the bubble surface can be written as:

$$\frac{D\Phi}{Dt} = \frac{|\nabla\Phi|^2}{2} + \frac{P_\infty}{\rho} - \frac{P}{\rho} - gz \tag{5}$$

where ρ is the density of the liquid, P_∞ is the ambient pressure of the liquid at the inception point of the bubble, P is the pressure on the bubble surface, g is the gravity acceleration.

The kinematic boundary condition on bubble surface is:

$$\frac{dr}{dt} = \nabla\Phi \tag{6}$$

The pressure inside the bubble is assumed to be uniform and consists of a constant vapor pressure and a volume-dependent noncondensable gas pressure [19]. Here, the surface tension is negligible compared to the high pressure caused by the bubble. Besides, the heat and mass transfers are also ignored [30,31]. Hence, the pressure inside the bubble P_g as a function of the volume can be described as:

$$P_g = P_c + P_{ini}\left(\frac{V_{ini}}{V}\right)^{\vartheta} \tag{7}$$

where the subscript ini denotes initial quantities, ϑ is the ratio of the specific heats for the gas, P_c is the vapor pressure.

3.2. Toroidal bubble

A toroidal bubble is formed after the jet impact upon the opposite bubble surface, i.e. the bubble is transformed from a singly-connected into a double-connected form. In order to handle this problem, some topology changes are made and a vortex ring is introduced inside the toroidal bubble [20]. The strength of