Experimental and numerical study on the dynamic pressure caused by the bubble jet

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Abstract. The high speed liquid jet is an important mechanism of damage to hydraulic machinery by cavitation bubbles, as well as damage to vessels by underwater explosion bubble. In this study, the bubble motion near a wall and the pressure impulse are investigated through experimental and numerical methods. In the experiment, the bubble is generated by the electric discharge, and a high speed camera is used to capture the bubble motion. Numerical studies are conducted using the boundary element method, and the vortex ring model is adopted to deal with the discontinued potential of the toroidal bubble. Calculated results show excellent agreement with experimental observations. Meanwhile, the dynamic pressure caused by the bubble in the flow domain is calculated by an auxiliary function, which improves the accuracy of the results. A highly localized pressure region will be generated on the wall by the bubble jet. The optimal stand-off parameter (the ratio of the distance the bubble center at inception from the wall to the maximum bubble radius) for a most damaging jet formation is around 0.9.

1. Introduction
Studying on the dynamic pressure caused by the bubble jet is of great importance in a wide range of engineering applications, such as cavitation on ship propellers and hydroturbines[1], underwater explosion bubbles[2], seismic airgun-generated bubbles for seabed geophysical exploration[3], bubble jets for increasing drilling rate[4], and micro-bubbles in medical applications[5]. A high speed liquid jet is induced during the collapse phase of a bubble because of the secondary Bjerknes force from a rigid wall. The jet impact is an important mechanism of damage to hydraulic machinery by cavitation bubbles, as well as damage to vessels by underwater explosion bubble [6].

In the recent four decades, the boundary element method (BEM) is widely and successfully used to study the dynamics of a violently-oscillating bubble [7]-[8]. The main characteristics of a bubble can be captured by BEM, such as expansion, collapse and jetting. Besides, the pressure and velocity in the flow domain can be calculated, providing more information to illustrate the mechanism of bubble motion and damage patterns. After the jet threading the bubble, Best [9] introduced a domain cut into the flow in order to compute the motion of the toroidal bubble, and Wang et al. [10] put forward a vortex ring model to deal with the discontinuous potential on the toroidal bubble surface.

In the present study, the dynamic behaviour of a bubble near a rigid wall is investigated through experimental and numerical methods. Much attention is paid on the dynamic pressure caused by the bubble jet. We adopt BEM to capture the bubble motion and use the auxiliary function [11] to...
calculate the pressure in the flow domain. Pressure contours are shown to demonstrate the damage threat by the jet impact. In addition, an experiment is conducted to verify the validation of the numerical model. The effects of two dimensionless parameters on jet impact pressure are also discussed.

2. Theory and numerical method
The liquid surrounding the bubble is assumed inviscid and incompressible, and the motion irrotational. Thus, the velocity potential at any point in the domain could be expressed as an integral equation:

$$\iint_S \left( G(p,q) \cdot \frac{\partial \Phi(q,t)}{\partial n} - \Phi(q,t) \frac{\partial G(p,q)}{\partial n} \right) dS(q) = \lambda(p,t) \cdot \Phi(p,t)$$

where $\lambda(p,t)$ is the solid angle of a fixed point $p$ on flow boundaries with the integration variable $q$ also situated on boundaries, $\partial/\partial n$ is the normal outward derivative from the boundary $S$, $G(p,q)$ is the Green function.

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

$$\frac{D\Phi}{Dt} = \frac{\partial \Phi}{\partial n} n + \frac{\partial \Phi}{\partial \lambda} \lambda$$

$$\frac{D\Phi}{Dt} = \frac{P_s - P_e}{\rho} + \frac{\sqrt{\Phi t}}{2} - gz$$

where $\rho$ is the density of the liquid, $P_s$ is the ambient pressure of the liquid around the bubble, $P_e$ is the pressure on the bubble surface, $g$ is the gravity acceleration.

The pressure inside the bubble is assumed to be uniform and consists of a constant vapor pressure and a volume-dependent noncondensable gas pressure [9]. Hence, the bubble pressure $P_e$ as a function of the volume is described as:

$$P_e = P_{ini} + P_{ini} (V_{ini}/V)^{\gamma}$$

where the subscript $ini$ denotes initial quantities, $\gamma$ is the ratio of the specific heats for the gas, $P_{ini}$ is the vapor pressure.

The vortex ring model is adopted to simulate the toroidal bubble [10]. The auxiliary function method [11] is employed to calculate the pressure on the rigid wall, which avoid making finite difference of the velocity potential. More details about these numerical methods can refer to Wang [10] and Wu [11], respectively.

Here we have scaled length with respect to the maximum radius which the largest bubble under consideration might achieve in an infinite body of fluid $R_m$; pressure by $\Delta P = P_e - P_s$; time by $R_m \sqrt{\rho/\Delta P}$. Besides, three dimensionless parameters are given to describe a bubble: strength parameter $\varepsilon = P_{ini}/\Delta P$, stand-off parameter $\gamma = d/R_m$ and buoyancy parameter $\delta = (\rho g R_m/\Delta P)^{0.5}$.

3. Results and discussion
Experiments are conducted in a water tank with dimension 500mm×500mm×500mm, in which the water is filled up to 400mm in depth. A steel plate, 300mm×300mm×8mm, is placed at the bottom of the tank. The low-voltage spark bubble generation method can be found in Turangan’s work [12]. The circuit employed in current bubble generation is based on Zhang [13], including a 6,600 µF capacitor and a 220V DC power supply. A bubble is generated by burning the copper wire with its diameter about 0.25mm, and captured by the Phantom V12.1 high-speed camera. The camera works at 30010 frames per second with exposure time 10 µs. The whole experiment section is illuminated from the back with a 2kW light. In the experiment, the maximum radius of the bubble is about 15.6mm, and the distance between the initial bubble and the rigid wall is 15.7mm. The initial parameters of the bubble are set as: $\varepsilon = 30, \gamma = 1.01, \delta = 0.012$. In fact, the buoyancy has little effect on bubble dynamics in such a millimetre-sized bubble case. However, the buoyancy parameter is set according to the
experiment for accuracy in calculation. Figure 1 shows the numerical and experimental results of the bubble motion near a rigid wall.

As shown in figure 1, each sequence shows the bubble just after it is created (frame a), during expansion (frame b), at maximum expansion (frame c), during collapse (frame d) and jet formation (frame e). In frame (e), it is clearly seen that a high pressure region is located above the bubble, which drives a high speed liquid jet into the bubble. These phenomena before the formation of a toroidal bubble have been discussed in many literatures. A toroidal bubble is formed after the jet threading the opposite side of the bubble (frame f). Due to inertia, a protrusion appears at the position of jet impact. At the same time, a high pressure region is caused at the wall center by the jet impact. The maximum dimensionless pressure reaches about 33.6. Then, a good portion of the bubble is ‘stretched out’ in the vertical direction (frame g) and contact with the wall directly. The numerical results show that the width of the jet increases as the bubble continues to shrink. The rigid wall will redirect jet to form a radial flow outward along the boundary from the jet axis, which results in a broader jet and a larger high pressure region. As the ‘sideways jet’ propagates along the bubble surface, the splitting may happen in the late stage of the toroidal bubble collapse, which can refer to our latest work [14]. It should be stated that the width of the bubble jet is limited to several millimetres, which is much smaller than regular pressure gauge. So it is very difficult to measure the pressure caused by the bubble jet [15] and there’s no measured data of the jet impact pressure in this work. More effective and accurate measurement techniques need further developing.

![Figure 1](image)

**Figure 1.** Comparison between the numerical and experimental results for a bubble near a rigid wall. The location of the rigid boundary is the lower limit of the frames. The frame width of the experiment is 18mm. The times (unit: ms) of the experiment are: 0, 0.529, 1.882, 2.852, 3.352, 3.441, 3.470, 3.499, 3.529, 3.588, respectively. The dimensionless times of the numerical results are: 0, 0.369, 1.307, 1.699, 2.308, 2.397, 2.415, 2.441, 2.459, and 2.478, respectively. Horizontal and vertical axes are: \( r \leq 1.2 \), \( -1.01 \leq z \leq 1.2 \) in (a)–(e), and \( r \leq 0.6 \), \( -1.01 \leq z \leq -0.1 \) in (f)–(j). The pressure legends represent the magnitudes of the dimensionless pressures.

Obviously, the stand-off parameter and strength parameter have much effect on the dynamic pressure induced by the bubble jet. In the following, the effect of \( \gamma \) and \( \varepsilon \) will be discussed in the following. Firstly, we fix \( \varepsilon \) as 30, and \( \gamma \) ranges from 0.6 to 1.2. The dynamic pressures at the wall center during the collapse phase of the bubble are shown in figure 2. The pressure increases rapidly soon after the jet impact and reaches a peak value afterwards. Then, the pressure decreases gradually due to the decrease of the jet velocity [8]. It is noted that the peak pressures of different stand-off parameter cases vary a lot from each other. There exists an optimal \( \gamma \) for which the liquid jet thus formed is most damaging, denoted by \( \gamma_{opt} \). The optimum stand-off is found to be around 0.9 when \( \varepsilon \) is fixed as 30, which can be explained as follows. Generally, when \( \gamma \) is greater than 1, there exists a water layer between the bubble and the rigid boundary, which would decrease the jet impact pressure. When \( \gamma \) is less than 1, the jet hits the boundary directly without being decelerated by a water layer. Nevertheless, the maximum jet velocity becomes slightly smaller when \( \gamma \) keeps decreasing. Then, we fix \( \varepsilon \) as 100, the dynamic pressures at the wall center during the collapse phase of the bubble are shown in figure 3. The magnitudes of the pressures become larger, and the profile of the curves are similar to that for \( \varepsilon = 30 \). Meanwhile, \( \gamma_{opt} \) is also around 0.9. After the jet impact, several pressure
peaks may appear on pressure curves, which are associated with migration of the bubble, splashing effect and rebounding of the toroidal bubble [8].

![Graph](image1)

**Figure 2.** Evolutions of the dynamic pressure caused by the bubble jet versus time at different stand-off parameters with $\epsilon$ fixed as 30.

![Graph](image2)

**Figure 3.** Evolutions of the dynamic pressure caused by the bubble jet versus time at different stand-off parameters with $\epsilon$ fixed as 100.

4. Conclusions
The dynamic pressure caused by the bubble jet is studied in this paper. The BEM is used to simulate the bubble motion and the results show excellent agreement with experimental observations. Meanwhile, the auxiliary function is adopted to calculate the pressure in the flow domain. A highly localized pressure region is generated on the wall by the bubble jet. The optimal stand-off parameter for a most damaging liquid jet formation is around 0.9. As the strength parameter of the bubble increases, the maximum pressure caused by the jet will increase but the pressure curve profile has little change.

5. References
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Acknowledgments
This paper is funded by the International Exchange Program of Harbin Engineering University for Innovation-oriented Talents Cultivation. The authors are also grateful to the support by the National Science Foundation of China (51379039, U1430236).