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Simulation of bubble dynamics oscillating near a circular aperture made in a curved rigid plate using boundary element method

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ABSTRACT

The dynamics of a spark-generated bubble oscillating near a circular aperture made in a curved rigid plate is investigated using boundary element method. The influences of the standoff distance and the aperture size on the bubble behavior are studied. Based on the relative value of these parameters, four distinct oscillation scenarios would be recognized: (I) two simultaneous (inward and outward) jets, (II) an inward jet directing towards the opening, (III) quasi or fully spherical oscillation without jet and (IV) an outward jet directing away from the opening. In the scenarios with jet, the jet can be formed in the first oscillation cycle or in the second expansion phase, depending on the standoff distance and opening size. A diagram is provided representing four distinctive regions distinguished by the mentioned four different oscillation scenarios. The results also indicate that the damage caused by an underwater explosion bubble to discontinuous structures might not be as serious as to non-perforated structures since the bubble jet would possibly not be formed or this jet is directed away from the opening. The effect of opening on the bubble dynamics might be utilized in the design of the protection tanks on vessel and other practical underwater structures.

1. Introduction

The dynamics of an oscillatory bubble near the different boundaries is of great importance due to its wide range of beneficial applications and destructive effects (Coleman et al., 1987; Ziolkowski, 1998; Lawrie et al., 2000; Hua et al., 2002; Zhu et al., 2002; Fletcher et al., 2002; Marmottant and Hilgenfeldt, 2003; Klaseboer et al., 2005; Le Gac et al., 2007; Dijkink and Ohl, 2008; Wang and Tong, 2008; Sankin et al., 2010; Gonzalez-Avila et al., 2012; Rayleigh, 1917). Corrosion of the ship propellers, turbine blades and hydraulic machineries are among the destructive effects of the bubble oscillation. One of the earliest scientific studies was carried out by Rayleigh (1917) on the corrosion effects of cavitation bubbles on the ship propellers. The vast experimental and numerical studies carried out thus far reveal that the bubble dynamics is affected by the type of the adjacent boundary. In the absence of buoyancy forces, the direction of bubble liquid jet is away from the free surface (Chahine, 1977; Blake and Gibson, 1981, 1987; Blake et al., 1987; Dommermuth and Yue, 1987; Best and Kucera, 1992; Shervani-Tabar, 1995; Wang et al., 1996a, b), and is directed towards the rigid boundary (Best and Kucera, 1992; Crum, 1979; Blake et al., 1986; Baker and Moore, 1989; Harris et al., 1999; Brujan et al., 2002; Zhang et al., 2009, 2013; Shervani-Tabar et al., 2011). The dynamic behavior of a bubble oscillating in close proximity to an elastic/flexible boundary can be very complicated (Blake and Gibson, 1987; Gibson and Blake, 1982; Shima et al., 1989; Tomita and Kodama, 2003; Klaseboer et al., 2006; Ohl et al., 2009). In addition, a bubble represents different behaviors when oscillating near a bounded free surface (Khoo et al., 2005; Lew et al., 2007; Dadvand et al., 2009, 2011; Saleki-Haselghoubi et al., 2014; Saleki-Haselghoubi et al., 2016; Dadvand et al., 2014).

Underwater explosion, also known as UNDEX, has been found to damage the marine machines via two processes: (i) the shock wave emitted by the explosion and (ii) the subsequent pulsating bubble (Cole, 1948; Zhang et al., 2011c; Cui et al., 2013). These two processes are often studied separately as they are of different time scales of millisecond and second, respectively. In a UNDEX, about 53% of the total energy is converted into the shock formation and the remaining 47% is for the subsequent bubble oscillation and migration (Nie et al., 2015). Researches reveal that when an UNDEX-induced bubble oscillates in close proximity to an underwater structure such as a bilge (i.e., the rounded portion of a ship's hull), a high speed jet is formed directing towards the structure that causes local damage to the structure surface (Blake et al., 1986; Cui et al., 2013; Naud'e and Ellis, 1961; Plesset and Chapman,

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1971; Zhang et al., 2011b). Since the UNDEX and the resulting bubble oscillation mechanisms are very complex, experimental study is the most desired approach to investigate them (Cole, 1948). Due to the experimental cost and menace, however, an UNDEX-induced bubble is often replaced by the spark-generated (Blake and Gibson, 1987; Lew et al., 2007; Dadvand et al., 2009; Turangan et al., 2006; Gong et al., 2010; Zhang et al., 2011a) and laser-induced (Mitchell and Hammit, 1973; Lauterborn, 1974; Tomita and Shima, 1990; Gonzalez-avila et al., 2011) bubbles. More details can be found in Gong et al. (2010).

When a ship's hull is attacked by UNDEX bubbles, it might be damaged, deformed and perforated (Cui et al., 2013). The bubble oscillation near a perforated plate was studied experimentally by Wang et al. (2013) and numerically by Liu et al. (2013) using boundary element method (BEM). They found that the dynamic behavior of the bubble oscillating near the solid boundary with a hole is different from that for a bubble adjacent to the solid boundary without a hole. In addition, Dawoodian et al. (2015) studied numerically the bubble dynamics near a perforated plate in a vertical cylinder using a combined BEM-finite difference method. The bubble oscillation behavior in the vicinity of a U-shape bilge is studied experimentally by Zhang et al. (2011a). They found an oblate collapse and a high speed jet toward the U-shape bilge. Cui et al. (2013) investigated experimentally the oscillation of a UNDEX-induced bubble in close proximity to a three dimensional bilge with a circular opening. They replaced the UNDEX-induced bubble by a spark-generated bubble and recorded the bubble oscillation process using a high-speed camera. They found various types of the oscillation scenarios by changing the opening-bubble distance and the opening diameter, and indicated that the damage caused by UNDEX-induced bubble to already deformed structures might not be as serious as to faultless structures since the bubble jet, which is considered as a major threat, would possibly not be formed.

The present study aims to numerically reproduce and extend the bubble oscillation scenarios reported by Cui et al. (2013). For this purpose, the oscillation of a spark-generated bubble near a circular aperture made in a curved rigid plate (a simplified design of the perforated bilge employed in the work by Cui et al., 2013) is studied using BEM. The influences of two key parameters, namely, the opening-bubble distance (standoff distance) and the opening diameter on the bubble behavior are examined. Based on these two parameters, a comprehensive diagram is provided illustrating four distinctive regions distinguished by different oscillation features of the bubble. Using the current numerical procedure one can readily capture the bubble features and examine the influences of several parameters without needing to conduct the costly experiments. It may be noted that the geometry considered in the present work is different from the one used by Cui et al. (2013) in that the former is axisymmetric with respect to the centerline of the circular aperture while the latter is three-dimensional, i.e., it is straight along the direction perpendicular to the image plane. Consequently, the bubble shape in our simulation is always axisymmetric while in the work by Cui et al. (2013) the bubble is 3D, i.e., it is slightly elongated in the direction perpendicular to the image plane. Nonetheless, as shall be seen in the results section, almost all the scenarios of bubble oscillation reported by Cui et al. (2013) can be reproduced by our simplified geometry.

The rest of the paper is organized as follows: in section 2 the mathematical modeling is given; in section 3 the numerical implementation is presented; section 4 deals with the validation of the BEM code; in section 5 the results are presented and discussed and finally the conclusions are given in section 6.

2. Mathematical modelling

2.1. Geometry of curved rigid plate with a circular opening

In this paper, the oscillation of a transient bubble near a perforated curved rigid plate placed in an infinite liquid domain is investigated numerically using BEM. The geometry is symmetric about the z-axis (see Fig. 1). It consists of a straight part and a curved part with a circular opening made at the center of the curved section. The length of the straight part L is considered about seven times the maximum radius of the bubble R_m. The curvature radii R_i and R_o of the curved part as shown in Fig. 1 are set to $1.84R_m$ and $2.0R_m$, respectively. The bending angle of the curved surface is 90°. The diameter of the opening (aperture size) W and the standoff distance H (the distance of the bubble's initial center from the opening center, i.e., point O) are demonstrated in Fig. 1. It may be noted that, since there were not sufficient information about the curvature radii of the curved part of the bilge in the work of Cui et al. (2013), the current geometry is not exactly identical to theirs. In addition, as also stated by Cui et al. (2013), due to small bubble size, the buoyancy effect is ignored in all the simulations carried out in the present work.

2.2. Governing equations

The present numerical study investigates the oscillation of a transient bubble in close proximity to a perforated curved rigid plate located in an infinite liquid domain (see Fig. 1). The flow is considered incompressible, inviscid and irrotational (i.e., potential flow). The governing equations consist of two coupled equations; one derived from the assumption of irrotational flow and conservation of mass (Laplace equation) and the other from conservation of momentum (Bernoulli equation). In the whole fluid domain both the Laplace equation and the Bernoulli equation are therefore assumed to be valid. These equations can be written as follows,

Laplace equation,

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

and Bernoulli equation,

$$\frac{d\Phi}{dt} = \frac{1}{\rho}(p_\infty - p) + \frac{1}{2}|\boldsymbol{u}|^2 - gz \tag{2}$$

where Φ denotes the velocity potential, t is time, ρ is the fluid density, p_∞ and p denote respectively the atmospheric and the instantaneous pressures in the fluid domain, $\boldsymbol{u} = \nabla\Phi$ is the fluid velocity at a point $\boldsymbol{x} = (r, z)$ inside the fluid domain and g stands for the acceleration of gravity. It may be noted that in Eq. (2) d/dt is the substantial time derivative, which is defined as $d/dt = \partial/\partial t + \boldsymbol{u}\cdot\nabla$ where $\partial/\partial t$ is the partial time derivative.

The moving boundary (i.e., the bubble surface) is allowed to deform following the kinematic boundary condition, which states that a fluid element on this surface will stay on it:

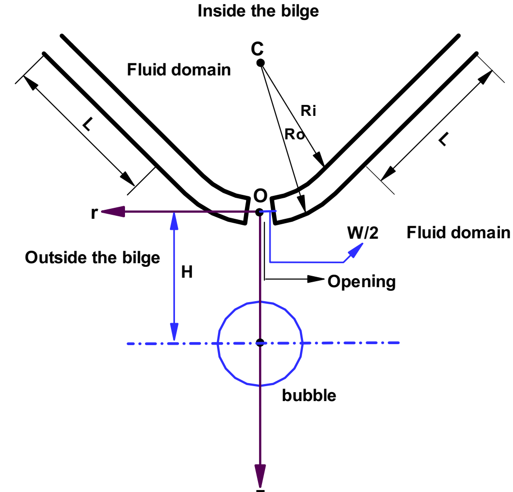

Fig. 1. Schematic geometry of the perforated curved rigid plate, coordinate system and nomenclature of the physical domain.