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Research on the estimate formulas for underwater explosion bubble jet parameters

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ABSTRACT

The underwater explosion bubbles have significant applications in the military, but the characteristics of bubble jet near a solid wall are still not very clear. Due to convenience and high efficiency, the boundary integral method is used to study the characteristics of bubble jet in this paper. The shape of bubble jet is simplified to a cylindrical shape when the jet impacts on the opposite surface, so the characteristics of bubble jet are characterized by three parameters, including the cylindrical width (diameter), the cylindrical height and the jet velocity. By adjusting the charge weight W, the detonated depth H and the stand-off distance parameter γ ($\gamma = (H - h)/R_m$, where h is the depth of solid wall, and R_m is the maximum bubble radius), the relations of the bubble jet width, height and velocity with them are explored, where three appropriate mathematical models are selected. Finally, based on the least square method, three estimate formulas for bubble jet width, height and velocity are obtained, which have good accuracy to predict the bubble jet width, height and velocity when $W = 50\text{–}1000\,\text{kg}$, $h = 50\text{–}500\,\text{m}$ and $\gamma = 0.65\text{–}1.5$. The purpose is to provide a reference for computing the damage of the bubble jet to structures in engineering.

1. Introduction

Warships, submarines and other marine structures as the important military forces may be severely damaged by the explosion of typical weapons (such as mines and torpedoes) in combat environment. After detonation of an underwater explosive charge, a shock wave and a secondary wave pulse generated by bubble are created successively (Cole and Weller, 1948). Besides, for the explosion near the structures, a high velocity bubble jet will be formed towards the structures during the collapse stage of bubble, which may cause extensive damage to the surrounding structures already weakened and damaged by the first shock wave (Barras et al., 2012; Cui et al., 2016; Zhang et al., 2011). The bubble jet is very complicated, the characteristics of which, such as velocity and shape, are determined by a number of factors, including the charge weight, the detonated depth of the charge, the stand-off distance parameter, etc. So far, the features of the shock wave and the pulse pressure induced by the underwater explosion bubble have been clearly understood. However, few literature focus on the characteristics of the bubble jet, and the influences of the charge weight, the detonated depth and the stand-off distance parameter on the bubble jet are still not very clear. So it is of great significance to systematically study the relations between them.

Motivated by military necessities since the beginning of the 20th century, the underwater explosion has been a research hotspot all over the world. Cole and Weller (1948) made a systematic conclusion on underwater explosion, where the semi-empirical formulas on the relations of the shock wave, the maximum bubble radius and the pulsation cycle of bubble with the charge weight and the detonated depth were conducted. Rayleigh (1917) established an analytical formula to describe the bubble motion in the infinite incompressible liquid field. Afterwards, the spherical equation is improved with the liquid viscosity, compressibility, energy dissipation, etc (Geers and Hunter, 2002; Gilmore, 1952; Hickling and Plesset, 1964; Plesset and Prosperetti, 1977). However, the aforementioned spherical equations are inapplicable to the asymmetrical motion when bubble is near the solid wall. For the bubble near the solid wall, some analytical formulas are also established (Chahine and Bovis, 1983; Chahine, 1982; Van Der Geld and Kuerten, 2009), but these formulas are only suitable for the description of very small deformation. For the larger deformation of bubble, especially for the bubble jet, these analytical formulas have too many limitations. For the asymmetrical bubble near the solid wall, the bubble jet is a part of complex hydrodynamics, whose velocity and shape are completely different with the change of the charge weight, the detonated depth and the stand-off distance parameter, so it is impracticable to deduce an analytical formula directly to denote their relations. Thus, it is necessary to explore other approaches to establish their relations.

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The experiment is another important approach to study the underwater explosion. The dynamic responses of various structures subjected to underwater explosion loading for different charge weight and stand-off distance parameter were studied, such as rectangular plates (Hammond and Grzebieta, 2000; Hung et al., 2005; Hung and Hwangfu, 2010; Long et al., 2017; Ramajeyathilagam and Vendhan, 2004; Ramajeyathilagam et al., 2000), circular plates (Klaseboer et al., 2005a; Ming et al., 2016; Rajendran and Narasimhan, 2001), submerged cylinders (Brett and Yiannakopolous, 2008), stiffened plates (Zhang et al., 2017a), ship-type box structures (Wang et al., 2014), surface ships (Zhang et al., 2011), etc. However, few underwater explosion experiments were concerned with the characteristics of the bubble jet or the structural responses subjected to the bubble jet impact (Brett and Yiannakopolous, 2008; Cui et al., 2016; Zhang et al., 2013). The interactions of the cylinder with the shock wave, the bubble pulse wave, the bubble jet and the bubble collapse were studied by Brett and Yiannakopolous (2008), where the bubble jet impact and the bubble collapse were found to be the most severe structural loads. Zhang et al. (2013) did some researches on the influences of different initial charge shape, detonating styles and boundary conditions on the bubble jet direction. Cui et al. (2016) used small charge to analyze the characteristics of the bubble jet near various boundary conditions, where the pressure pulses induced by the bubble jet impact on the solid wall and by the collision of the annular jet were also measured. Those experiments, however, mainly analyzed the bubble jet phenomenon qualitatively, and the relations of the bubble jet velocity and the bubble jet shape with the charge weight, the detonated depth and the stand-off distance parameter were still rarely studied.

With the development of computer, various numerical methods are developed to study the bubble dynamics, and those numerical methods are mainly divided into three categories, including boundary integral method (Brujan et al., 2002; Jayaprakash et al., 2012; Klaseboer et al., 2005b; Li et al., 2015, 2016; Ni et al., 2015; Wang, 2014; Wang et al., 2005), the Euler equations or Navier–Stokes equations coupled with interface capture method or interface tracking method (Barras et al., 2012; Daramizadeh and Ansari, 2015; Doihara and Takahashi, 2001; Hsu et al., 2014; Liu et al., 2017a, 2018; Popinet and Zaleski, 2002), and hybrid numerical approaches (Hsiao and Chahine, 2015; Hsiao et al., 2014; Wang et al., 2016; Zhang et al., 2013, 2017b). Some researchers had done some works on the characteristics of the bubble jet using those numerical methods, but most studies were not systematic. On the basis of the boundary integral boundary, Jayaprakash et al. (2012) numerically and experimentally studied the spark-generated bubble dynamics near a vertical wall, where the characteristics of the bubble jet, such as jet velocity, jet width, jet base radius, jet length, jet equivalent cylinder radius, etc, with time or with stand-off distance parameter were conducted. Ni et al. (2015) also used the boundary integral method to study the spark-generated bubble impact on a solid wall numerically and experimentally, where the variations of the time and the jet tip velocity at the moment of impact with different stand-off distance parameter were discussed. Other researchers also done some works on the pressure generated by the bubble jet impact on the solid wall using the boundary integral boundary (Li et al., 2015; Wang et al., 2005). Popinet and Zaleski (2002) used the front tracking method to analyze the influence of viscosity on jet formation and evolution, where an impact condition that the jet never impacts the other side of the bubble was obtained. Subsequently, the characteristics of bubble jet in the toroidal stage were supplemented by Liu et al. (2018) and Liu et al. (2017a) using the same method. The jet generated by the bubble is usually accompanied with a high velocity, so the compressibility of liquid cannot be neglected when the jet impacts on the solid wall. Hsiao et al. (2014) used a hybrid numerical approach to study non-spherical bubble dynamics near a sold wall, where the bubble dynamics during expansion stage was captured by boundary integral method solver and the bubble jet impact was solved by a compressible finite difference flow solver. The similar works were also done by Wang et al. (2016) using boundary integral method and discontinuous galerkin method. For convenience in engineering, the bubble jet is usually simplified to a cylindrical shape or other equivalent shapes, and then the structural dynamics are computed by the equivalent jet. The liquid jets with various shapes were also extensively studied by a large number of researchers (Foldyna et al., 2009; Guha et al., 2011; Hsu et al., 2013; Kibar et al., 2010).

As mentioned above, the bubble dynamics have been extensively studied using various methods. Owing to the complexity of the bubble jet, the characteristics of the bubble jet and the damage mechanisms of the bubble jet to structure in engineering are still not very clear. Due to convenience and high efficiency, the boundary integral method is used to study the characteristics of the bubble jet in this paper, where the shape of bubble jet is simplified to a cylindrical shape when the jet impacts on the opposite surface, so the characteristics of bubble jet are characterized by three parameters, including the cylindrical width (diameter), the cylindrical height and the jet velocity. By adjusting the charge weight, the detonated depth and the stand-off distance parameter, the relations of the bubble jet width, height and velocity with them are explored combined with the least square method. The purpose is to provide a reference for computing the damage of the bubble jet to structure in engineering.

2. Numerical model

2.1. Boundary integral method

After the explosive charge is detonated in water, a high pressure will be formed inside the bubble. Subsequently, under the combined action of the high pressure and infinity pressure, the bubble expands and collapses with a high Reynolds number, where the effect of viscosity on the bubble motion can be ignored generally (Brujan et al., 2002; Klaseboer et al., 2005b). The liquid compressibility is also ignored (Klaseboer et al., 2005a, 2005b). It is assumed that the liquid is undisturbed before bubble expansion and collapse, and the motion and deformation of bubble are thought to be axially symmetrical, as shown in Fig. (1). Therefore, the liquid velocity can be expressed as the

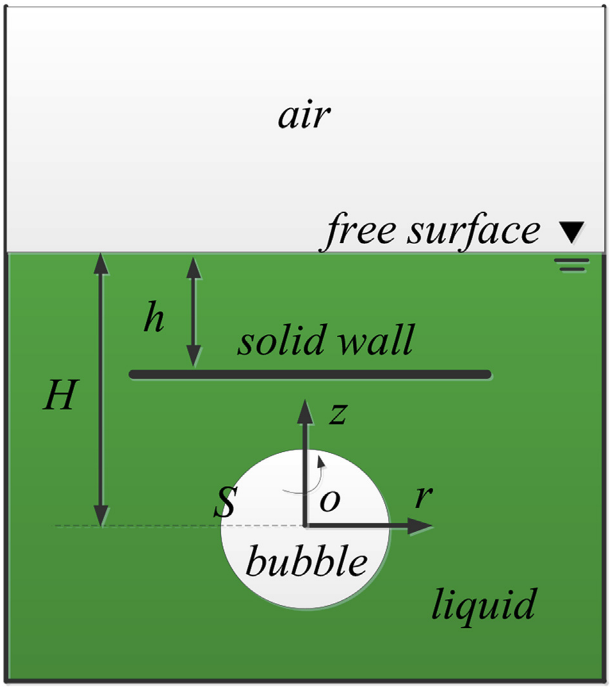

Fig. 1. Relative position of underwater explosion bubble with solid wall and free surface.