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A numerical study on the underwater explosion bubble pulsation and the collapse process

Ching-Yu Hsu [a], Cho-Chung Liang [b], Anh-Tu Nguyen [b,*], Tso-Liang Teng [c]

[a] Department of Marine Mechanical Engineering, ROC Naval Academy, Taiwan, ROC
[b] Department of Mechanical and Automation Engineering, Da-Yeh University, Changhua, Taiwan, ROC
[c] Hsiuping University of Science and Technology, Taichung, Taiwan, ROC

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ABSTRACT

The dynamic underwater explosion bubble process is a complex phenomenon with many facets to consider. After detonation, the shockwave quickly strikes nearby structures. The bubble oscillation may then substantially damage the structures, even if the bubble pulse is not large. This is because other effects, such as whipping or water jet impact, often accompany the bubble pulse. This study applied the Eulerian Technique using ABAQUS software to simulate the process of underwater bubble explosion, pulsation and collapse. This approach allows many materials to be used in an Eulerian element and manages with large deformation of materials such as flows and gases. The simulated bubble is equivalent to a bubble generated by 55 g of TNT. Although boundary conditions simplify the model, the method is feasible for simulating bubble dynamics and provides acceptably accurate results on bubble migration in water, pressure pulse, water jet formation, and flow field velocity surrounding the bubble. Future research can use this method to study bubbles, including their interaction with free surfaces and the submerged structures or floating structures.

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1. Introduction

Two crucial and distinct phenomena are usually involved in an underwater explosion. The first phenomenon is the quick propagation of an underwater shockwave in the water. If the shockwave encounters the free surface of water and structures, the reflection and refraction of the shockwave may cause other phenomena, such as local cavitation and bulk cavitation. Such phenomena can reproduce loading pressure on the structures. The second phenomenon involves the motion of high temperature and pressure gas bubble, which occurs over a longer period (Cole, 1948). Because the initial pressure of gas bubble is much higher than the equilibrium hydrostatic pressure, the bubble expands rapidly and its internal pressure decreases gradually, but the motion persists because of the inertia of the outward flowing water. At a later time, the gas pressure falls below the hydrostatic pressure of the surrounding water. The bubble expansion continues until the velocity of the fluid surrounding the bubble vanishes, the bubble begins to contract at an increasing rate. The inward motion of the fluid remains until the gas is compressed, the bubble contraction is reversed abruptly. The bubble can experience repeated circles of expansion and contraction. As the bubble approaches minimum volume, the bubble produces secondary pressure pulses. Furthermore, under the buoyancy effect, the bubble tends to migrate toward the water surface during its process. Fig. 1 depicts this sequence of events (Cole, 1948).

Many studies have examined underwater explosion bubble phenomena using experiments and simulations. These studies have explored the non-compressive radial motion of bubbles without gravity, bubble motion with gravity, the effects of compressibility and non-spherical form on bubble motion, and the effects of different boundaries, free surfaces, rigid structures and deformable structures. According to Cole (1948), Ramsauer (1923) is cited in Cole (1948) conducted one of the earliest systematic bubble motion measurements. Ramsauer identified the upward bubble motion and the relationship among maximal radius, depth and charge weight. Although his experimental results correspond to the simple theory, his method provides limited information on isolated bubble points. High-speed motion photographs are a more powerful tool for studying bubble migration. Edgerton first applied this method by using such photographs to determine that bubbles rise slightly when they first expand and rapidly sink below their initial position. Recently, numerous researchers have conducted theoretical and experimental bubble studies.

Spark and laser techniques have recently become more popular for generating bubbles because of their advantages, which include relative safety, cleanliness, and compactness. Such techniques

* Corresponding author. Tel.: +886 4 8511223; fax: +886 4 8511223.
E-mail addresses: tuna_3003@yahoo.com, tuna3003.vn@gmail.com (A.-T. Nguyen).

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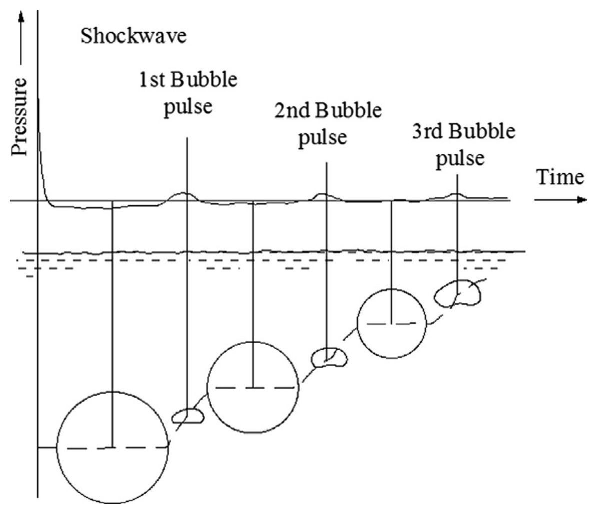

Fig. 1. Pressure waves and bubble phenomena of underwater explosion.

enable high-quality bubble dynamic observation at a lower cost than do experiments involving explosives. Gibson and Blake (1980) and Lew et al. (2007) have used spark-generated bubbles. Bubble images were captured on high-speed cameras at a rate of over 10,000 frames per second (FPS). Gibson and Blake (1980) focused on the behavior of bubbles adjacent to flexible and rigid boundaries, and Lew et al. (2007) studied the development of water jets produced by bubbles near plates with holes and without holes. Remarkable laser technology applications include research by Brujan et al. (2002) and Lee et al. (2011). An AQ-switched Nd-YAG laser system was applied to generate the bubbles for various study purposes. Brujan et al. (2002) investigated the temporal evolution of liquid jet shockwave emission in the bubble collapse phase near a rigid body and examined the splash effect using high-speed photography. They also used the boundary integral method to determine velocity fields and pressure contours in the liquid surrounding a bubble. Lee et al. (2011) successfully measured shockwaves and bubble wall speeds by using an ICCD camera demonstrating that the first shockwave generates strong pressure, followed by a weak rebound of a secondary shockwave.

Although spark and laser techniques have benefits, experiments using real charges are crucial because they help prevent the effect of unpredictable factors on research results. Klaseboer et al. (2005) conducted one of the few charge experiments relevant to the current study. They experimentally and numerically examined the interaction between underwater bubbles and nearby rigid and resilient submerged structures in a test pond. Hexocire charge weights ranged from 10 to 50 g and were placed at various distances from the structures. Bubble migration was observed in a free-field environment and near horizontal and vertical plates.

Many researchers have used the numerical method, which is essential technique for solving bubble problems. The boundary element method (BEM) is a numerical computational method for solving linear partial differential equations formulated as integral equations. The BEM uses only surface elements that are material interfaces or assigned boundary conditions. Therefore, this method is used to simulate bubble dynamics because it requires less time for data preparation; is easier to change the applied mesh; is useful for problems that require re-meshing; is highly accurate; requires less computer time and storage by using fewer nodes and elements; and allows users to filter out unwanted information and focus on a particular internal region, thereby reducing computer use time.

A bubble oscillation close to the free surface creates a free surface spike. Wang et al. (1996), Zhang et al. (1998), and Pearson et al. (2004) have examined this phenomenon. Wang et al. (1996) provided valuable information on the effects of strength parameters and on the initial pressure at various buoyancy parameters of the bubble rebounding in connected form. Zhang et al. (1998) proposed a directed procedure for computing solid angles on the free surface. This method was successfully incorporated into a 3D model and applied to the interaction between two bubbles parallel to the free surface. Pearson et al. (2004) used a nonlinear node distribution on the free surface to calculate the necessary elliptic integrals. Their refined method accurately calculated the motion of one or more bubbles near an infinite surface.

During the bubble collapse phase, bubbles become toroidal during water jet formation. Various techniques have been used to address simulation difficulties, such as converting a single-connected bubble to a double-connected toroidal bubble and encountering overcrowded elements near the water jet tip. Wang et al. (1996) placed a vortex ring at a geometric center of the bubble cross-section on impact (a vortex ring can be placed anywhere within the bubble). The vortex ring accounted for the double connectivity of the bubble. Zhang et al. (2001) extended this research and used a 3D vortex ring to represent the flow circulation from jet impact and to facilitate flow calculation in the post-impact toroidal phase. Zhang et al. (2001) used several novel techniques, including a weighted-average scheme, adaptive mesh refinement, and a smoother scheme based on the least-squares principle to simulate the essential physics of bubble jetting, flow circulation surrounding the toroidal tube, and the rebounding of the toroidal bubble near a rigid wall with the effect of buoyancy.

To ensure that the mesh was stable and smooth during bubble evolution, Wang et al. (2003) introduced a new regulation mesh technique, the elastic mesh technique (EMT). The EMT allows a significantly larger time increment to be used and effectively avoids the mesh refinement requirement within a reasonable precision range. Wang et al. (2005) seeded a vortex ring inside the bubble form to account for circulation and introduced a model for gas bubbles close to a rigid wall during the collapse phase. Investigating the high-pressure impulse acting on the wall during jet impact indicated that the high-speed water jet may damage a surface.

By using advanced techniques, previous research, for example Klaseboer et al. (2005) and Zhang et al. (2008a, 2009), has nearly clarified the interaction between bubbles and complex floating or submerged structures. Studies have also examined the effect of factors such as gravity and buoyancy on the bubble dynamic process. Zhang et al. (2008a) coupled a BEM solver, which is used for calculating bubbles, with the finite element method (FEM) solver, ABAQUS, which solves the structure part response. Their results showed an agreement with experimental results. They also found that the whipping effect of a ship when interacting with a bubble occurs when the pulsating frequency of the bubble matches the low-order eigenfrequency of the ship.

The application of finite element program for solving UNDEX bubble problem has been addressed in the previous researches (Chisum and Shin, 1997; Abe et al., 2007; Barras et al., 2012), in which multiple materials in Eulerian solver was used to simulate the water, the air, and detonation gas products. The behavior of gas bubbles in the vicinity of simple boundaries was simulated and the effects of mesh on the accuracy of numerical calculation were estimated. However, the early works only focused on the 2-D calculation and the interaction between UNDEX bubble and complex structures are still controversial.

This study used the Eulerian technique in ABAQUS to simulate the first oscillation cycle of a 3-D UNDEX bubble in a free field. The availability of many materials in this technique allowed the simultaneous simulation of three materials, explosive gas product, air, and water, in the same Eulerian domain. Using the Eulerian

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