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Numerical study on motion of the air-gun bubble based on boundary integral method

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A B S T R A C T

To simulate the motion of the non-spherical bubble generated by air gun, boundary integral method is used in conjunction with the basic theory of the air gun. The time length of the bubble aeration τ (i.e., the close time of the air gun), the utilization efficiency of the gas inside the air gun chamber η, the heat transfer coefficient α and other key parameters of the air gun are employed to control the motion of the bubble. In the simulation of a single air gun bubble with buoyancy, the vortex ring model is used to simulate the motion of the toroidal bubble after jet impacts, and it is extended to the multiple vortex rings in the simulation of the interaction between two clustered air gun bubbles. Some new findings are summarized as follows: (i) Under the effect of the buoyancy, the shape of the bubble becomes non-spherical at later phase of bubble collapse, but the deformation seems to have little effect on the far-field pressure. (ii) For the clustered air gun bubbles, the primary-to-bubble pulse ratio will reach a maximum when the standoff distance d is about 1.6 times maximum radius of a single bubble. (iii) Primary-to-bubble pulse ratio is relative large at a small firing depth of the air gun H (the vertical distance from the bubble center to the free surface).

1. Introduction

As a mechanical wave, sound waves decay slowly in the seawater as compared to electromagnetic waves. Therefore, sound waves, especially with high frequencies such as ultrasonic waves, are commonly used to detect the objects on or under the water surface, including other vessels and submarines. Besides, sound waves also play important roles in marine prospecting, but usually the frequencies of the sound waves are relatively low to improve their penetration. Among kinds of seismic sources, the most widely used ones are seismic air guns which can produce relative good low frequency acoustic signals (sound waves). As air guns fire, sound waves are emitted to the water almost at once, and a part of them will penetrate the inner structure of the seabed, and a part of them will be reflected to the free surface at the surface of different medias. According to the reflected waves recorded by receivers at the sea surface and the reflection characteristics of sound waves between different medias, we then can get the comprehensible information about the subsurface (Caldwell and Dragoset, 2000). The sound wave acts like a bright lamp illuminating the inner structure of the earth.

Except for the enough low frequency components, the sound waves are often required to have enough energy to meet the deep vertical penetration and far horizontal propagation (Caldwell and Dragoset, 2000). To improve the detection resolution of the sources, a large number of numerical studies on air guns have been done. Ziolkowski (1970) built the first physical model of the air gun with the spherical bubble model proposed by Gilmore (1952). Due to the wavelength of pressure wavelet was quite long as compared with bubble radius, the non-spherical deformation of the bubble was ignored in the calculation of the fluid pressure at the far-field observation point. Other researchers later made a series of modifications to Ziolkowski's model, including the bubble aeration (Landrø and Sollie, 1992), the heat transfer between bubble and its surrounding water (Landrø and Sollie, 1992; Li et al., 2010), the viscosity effect (Langhammer and Landrø, 1993a), the temperature effect (Langhammer and Landrø, 1993b), the vertical rise of bubble (Li et al., 2010) and damping factors (Graaf et al., 2014c; Langhammer et al., 1995) etc.

Based on the approximation of Giles and Johnston (1973), Ziolkowski et al. (1982) extended the theory of a single air gun to an air gun array. Each bubble in the array was assumed as a source point and oscillated in a pressure field caused by the other bubbles. This method is quite effective in the calculation of the far-field pressure generated by the air gun array without clustered guns. But for the array with clustered guns (Laws et al., 1990; Li et al., 2011; Strandenes and Vaage, 1992), especially when the maximum radius of one bubble exceeds the standoff distance between two bubbles, the center of one bubble may become a point of another, which may lead to the divergent of the pressure and calculation termination. In fact, the interaction between two small spaced bubbles is complicated and often accompanied by the occurrence of tear and fusion. However, clustered air guns are commonly used for improving the primary-to-bubble pulse ratio of the signal in engineering, and so finding

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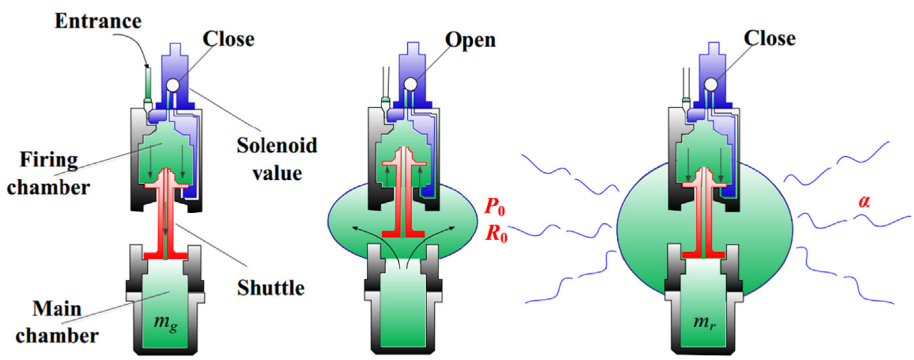

Fig. 1. Basic principle and key parameters of an air gun.

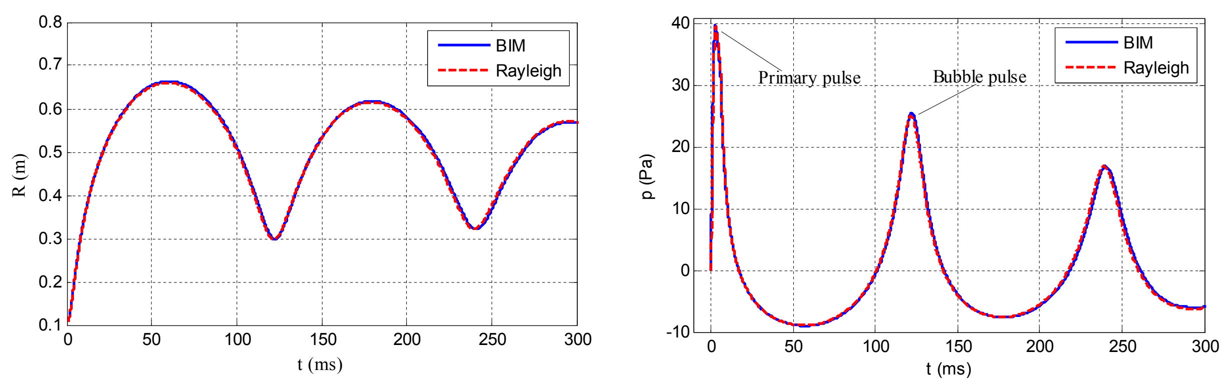

Fig. 2. A comparison of the theoretical results of the air gun bubble calculated with BIM and the model of Rayleigh (1917). (a) Time history of the bubble radius; (b) time history of the fluid pressure at far-field observation point (9000 m below the bubble).

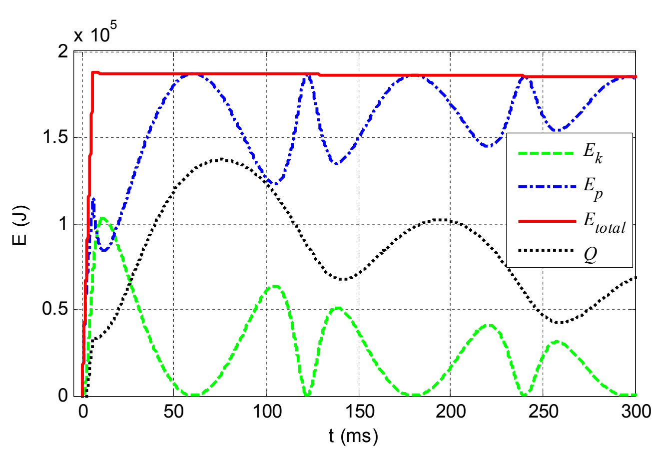

Fig. 3. Time history of the kinetic energy E_k, the potential energy E_p, total energy E_{total} and heat loss Q.

a way to calculate the fluid pressure caused by the clustered air guns is quite meaningful.

Recently, some countries attempted to use the pressure waves generated by the air guns to the shock testing naval ships. The fluid pressure at the near-field observation point becomes one of the worth studying topic. Air gun bubbles observed in the experiments are usually non-spherical (Graaf et al., 2014a, b; Langhammer and Landrø, 1996) on the influence of the buoyancy, the free surface, or the air gun body etc. Such as the bubble generated by the four openings air gun, four distinct bubbles are developed from the jets of air released through the four openings of the air gun and they eventually merge together with the oscillation of the bubble (Graaf et al., 2014a,b). If we continue use the spherical bubble model to calculate the fluid pressure near the bubble, the results will be largely inconsistent with the real situation.

In this paper, boundary integral method (BIM) is applied to simulate the non-spherical motion of the air gun bubble. Although BIM is not predominant in the simulation of bubble fusion and tear as compared with finite volume method (FVM), it can accurately capture the boundary of the bubble surface and easily obtain the pressure at the far field (such as 9000 m far away from the bubble). With BIM, non-uniform fluid pressure surrounding bubble is successfully calculated and the divergence in the simulation of the clustered air gun bubbles is overcome. In section 2, we introduce the basic theory of BIM and air gun. In section 3, we compare the far filed pressure calculated by different methods at first, and then we investigate the time variation of the potential energy and kinetic energy etc. Good agreement of the pressure is found between BIM and the spherical bubble model. The bubble aeration and heat loss considered in BIM generally satisfy the law of conservation of energy.

In section 4, we firstly investigate the effect of the bubble buoyancy to the fluid pressure at the far-field observation point. After that, we study the motion of two clustered air gun bubbles. With the model of the multiple vortex ring (Zhang et al., 2015), motion of the bubble after jet penetrates is also simulated. Through the analysis of the effect of the non-dimensional distance between two bubbles, a critical value (~1.6) is found at which primary-to-bubble pulse ratio *PB* will reach a maximum. Then, we investigate the interaction between the bubble and the free surface. For the deformation of the free surface is not what we cared about, the image method is adopted in this paper. With this method, the interaction between the bubble and free surface is equivalent to the interaction between the bubble and its image. Finally, the motion of the bubble under the effect of the air gun body is studied.