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Interaction between reflected shock and bubble in near-wall underwater explosion

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Abstract

Shock and pulsating bubble, as two processes for structure damage in underwater explosion, are often studied separately due to their different time scales. In this study, we would pay particular attention to the interaction between them in underwater explosion nearby a wall by finite volume method. In order to capture the shock precisely, it is an issue at priority how to properly select grid density and artificial viscosity. Then a "two-step" strategy is adopted to overcome the bottleneck of high computing requirements in CPU time and memory. The shock reflection, bubble oscillation and the interaction between them along with resultant load are presented and discussed.

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Keywords: underwater explosion; shock bubble interaction; finite volume method; non-spherical charge

1. Introduction

In the underwater explosion (UNEX), about 53% of the total energy is converted into the shock formation, while the remaining 47% is for the subsequent bubble oscillation and migration [1]. Since the time scales of the shock and bubble oscillation are of the different order of millisecond and second, respectively, the whole process of UNEX is conventionally divided into two phases and studied separately [2-3]. UNEX shock in the free field can be predicted precisely using the scaling law by Cole [4] and Zamyshlyayev [5]. Numerical analysis of explosive bubble by using CFD with interface-capture algorithm, BEM or meshless method further deepens the understanding of its migration and deformation features. As for UNEX nearby a wall, however, the interaction between the reflected wave and the bubble along with consequent UNEX loads and structure responses is scarcely dealt with. Therefore, the two phase

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coupling is particularly focused on in this study by Finite Volume Method (FVM) based on the properly selected grid density and artificial viscosity.

2. Equation of state

Besides the conservation laws of mass, momentum and energy, the standard JWL (Jones-Wilkins-Lee) equation of state (for detonation products) and Tait equation of state (for water) expressed as Eqs. (1) and (2), respectively, are used.

$$\begin{cases} p = A\left(1 - \frac{\omega\eta}{R_1}\right) exp\,(-\frac{R_1}{\eta}) + B\left(1 - \frac{\omega\eta}{R_2}\right) exp\,(-\frac{R_2}{\eta}) + \omega\eta\rho_0 e \\ \eta = \rho/\rho_0 \end{cases} \quad (1)$$

where ρ_0 is the reference density; A, B, R_1, R_2 and ω are constants; e is the internal energy. For TNT of density 1580 kg/m3, A=3.712×10^{11} Pa, B=3.231×10^9 Pa, R_1=4.15, R_2=0.95, ω=0.3 and e=4.29×10^6 J/kg.

$$p = A(\rho/\rho_w)^n - B \quad (2)$$

where both A and B equal to 0.2986 GPa, n equals to 7.15 for medium intense shock (pressure less than 2.94GPa), ρ_w the water density.

3. Selection of two parameters: grid density and artificial viscosity

Our trial simulations show that the accuracy of the shock phase is considerably dependent on the artificial viscosity and mesh size. Hence, we need to consider how to select these two parameters appropriately. As plotted in Fig.1, the pressure peak is increasing with grid density and the shock pulse exhibits a contrary trend. Though the influence of the artificial viscosity is not as sensitive as that of the grid density (see Fig. 1), it is still indispensable to avoid unphysical fluctuation and capture shock precisely. Based on the scenario analysis, the grid density and artificial viscosity are finally suggested as 25 to 60 and 0.1 or 0.2, respectively.

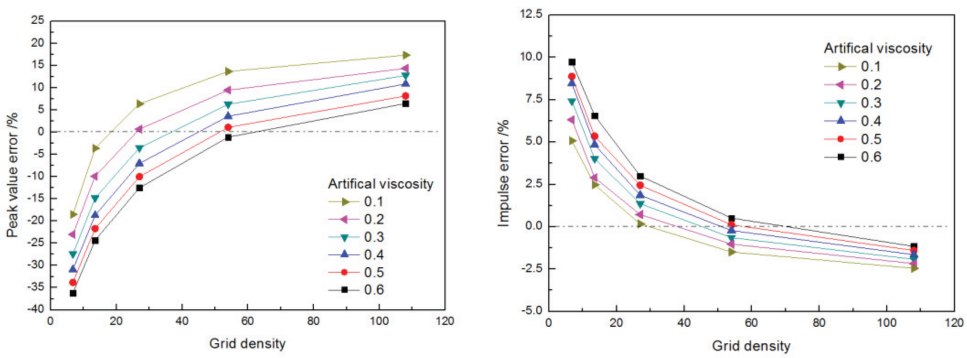

Figure 1: Influences of the grid density (element numbers in a characteristic length of the charge) and artificial viscosity. (a) and (b) are the peak value and impulse errors, respectively. The reference values marked as dot dash line are the values calculated according to Cole's similarity law for UNEX shock [4].

These parameters are further verified by comparing the simulated pressure profile of 1 kg spherical TNT detonated 5m under water surface with the experiments. As shown in Fig. 2, better agreements are observed with a phase delay due to the different initial moment defined.

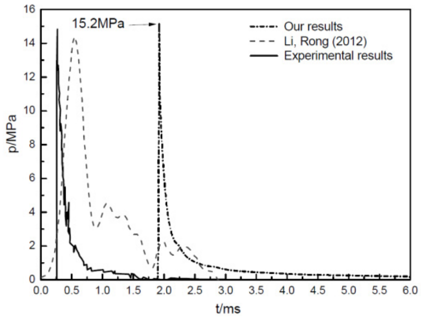

Figure 2: Pressure-time curve at 3m from the charge center. The spherical shaped charge weighted 1kg is detonated 5m under the water surface. The dot dash line is our result, while the dash line and solid line are the simulation results and experimental results, respectively, from Ref. [6]

4. Results and discussion

Charges in warheads actually are non-spherical. More practically, a cylindrical shaped charge is used for simulation. Fine mesh is required when simulating the shock according to the previously suggested grid density. As for the bubble phase simulation, a larger computational domain and more time consumption are required. Thus, it has a strict demand for computer resources. A "two-step" strategy is introduced to overcome this difficulty: 1) examining the near-charge zone by finer mesh size, 2) mapping results of the near-charge zone to the entire computational domain with a coarser mesh as initial condition by interpolation. The shock evolution is illustrated in Fig. 3, the shock-bubble interaction in Fig. 4 and UNEX load in Fig. 5.

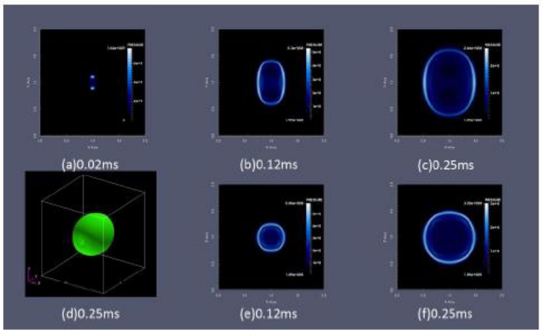

Figure 3: Underwater shock generated by a cylindrical shaped TNT. The charge is placed 2m away from a rigid wall, 10m below the water surface; it is 0.5m long with density 1580 kg/m3 and weight 4kg. (a) - (c) are horizontal slices passing through the neutral axis of the charge, while (e)-(f) the perpendicular slices; (d) is the 3D profile of the shock.

Fig. 3 illustrates the ellipsoidal shock in the early phase. As we know, the shock speed decreases with dropping pressure. On the other hand, the shock pressures at the two ends of the charge decays more rapidly than those at the lateral side . Hence, the decay rates of the propagation speed at two ends are higher than in the other directions, thus resulting in the formation of final spherical shock.

From Fig. 4(d) and 4(e), reflection occurs forming the semilunar shock profile when the shock hits the wall. The influence of the charge shape is further weakened according to the semilunar profile. Therefore, the shock can be roughly considered as spherical when the explosion distance is large. Before the reflected shock reaches the bubble, the expanding speed of the bubble surface is about 90m/s as shown in Fig. 4(a). About 2.4ms after the detonation, the reflected shock hits the bubble. The expanding speed of the bubble's front and rear surfaces becomes asymmetric implying compression of the bubble. The maximal difference in expanding speeds can be as high as 16 m/s as shown in Fig. 4(b). This difference is reduced to 3m/s within 4 milliseconds around. On the other hand, the bubble affects the propagation of the reflected shock; a compression wave is reflected in our case as shown in the Fig. 4. A compression wave or an expansion wave can be reflected back theoretically when the shock hits the bubble, which is closely related to the bubble state: expanding or contraction.

When the shock passing through, a long duration of low pressure appears as shown in Fig. 5 corresponding to the suction effect of UNEX. Specifically, the bubble becomes over expanding beyond 80 percent of its first cycle, which is responsible for the long duration of suction effect. Furthermore, the pressure field turns out more complex owing to the interaction between the incoming bubble and reflected shock wave.

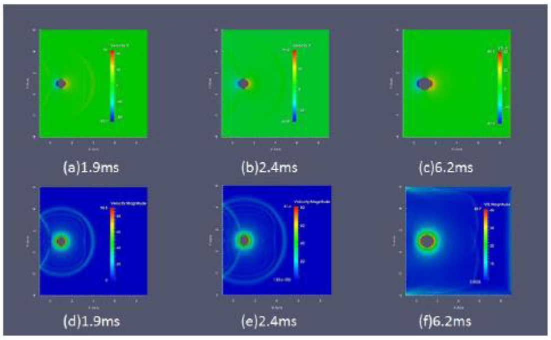

Figure 4: Interaction between the reflected shock and the expanding bubble (horizontal slices). (a)-(c) are the x component of velocity; (d) -(f) are the absolute speed. The round in the calculation region is the explosion product, i. e. the explosion bubble. The rigid wall is at the left boundary of the computational domain.

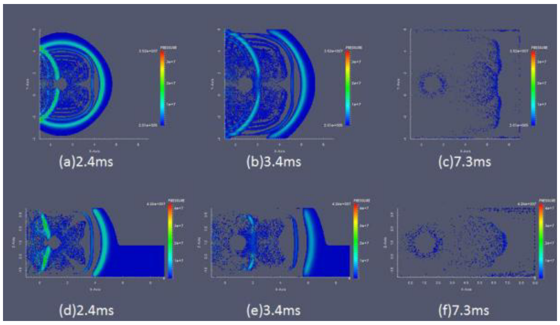

Figure 5: UNEX pressure field. (a) - (c) are horizontal slices passing through the neutral axis of the charge, while (d)-(f) the perpendicular slices. The domain where pressure lower than the hydrostatic pressure of the charge centroid is omitted.

5. Conclusions and future work

In the UNEX, the charge shape only affects the shock in the early phase and usually has insignificant influence on the bubble dynamics. However, strong interaction occurs between the reflected wave from the nearby wall and the incoming bubble in the near wall UNEX. In this circumstance, the bubble becomes asymmetric (the difference of expanding speed can be as high as 16m/s) and the propagation of the reflected shock is affected by incoming bubble as well. The pressure field of near-wall UNEX corresponding to the structural response becomes more complex when the shock-bubble interaction occurs.

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