DAMAGE RESPONSE OF HULL STRUCTURE SUBJECTED TO CONTACT UNDERWATER EXPLOSION
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Abstract. A high-pressure shock wave was produced during a process near-field underwater explosion, which led to serious damage into structures. A Smooth Particle Hydrodynamic (SPH) method is suitable for solving problems with large deformations. Hence, it is used to investigate pressure characteristics and dynamic response of hull structures subjected to near-field underwater explosion. Effect of free surface was taken into consideration. Propagation of shock wave in multi medium and its dynamic response to hull structures were analyzed.

1 INTRODUCTION

The probability of ship hull structure subjected to near-field underwater explosion increased with the wide application of precision guided weapons [1]. Therefore, in order to enhance ship's survivability, it is of great significance to study the damage mechanism of hull structures under near-field explosion. Many researchers both at home and abroad have studied underwater explosion and its damage into structures theoretically, experimentally and numerically [1-16]. With the rapid development of numerical technology, numerical simulation has become one of the main means to investigate underwater explosion. The traditional mesh methods have disadvantages of mesh distortion in the simulation of underwater explosion. However, SPH method with Lagrangian and particle properties is suitable for solving such problems as material motion tracking and strong discontinuous capture. Swegle *et al.* [10] discussed the related problems of stability in solving underwater explosion by SPH method. Liu *et al.* [11-13] demonstrated the feasibility of SPH method in solving underwater explosion problems through a large number of numerical tests. However, rare researches have reported the application of SPH method to near-field underwater explosion and its damage to hull structures, especially considering coupling effects of free-surface and damaged structures.

In this paper, a SPH model of hull structure subjected to near-field underwater explosion is first established. Then shock-wave propagation near hull structures and free surface and its damage into structures were studied. On this basis, effect of charge material on damage to structures was discussed. The obtained results provide reference to dynamic response of ship structures subjected to underwater explosion and design of protective structures.

2 THEORETICAL AND NUMERICAL MODEL

2.1 Underwater explosion

Underwater explosion load [17] is composed by shock wave and bubble respectively generated in the early and later stages of explosion and bubble in the later stage, which is an important basis for prediction of structural dynamic response and anti-explosion design. The shock wave with high pressure and the bubble with long cycle can cause local and overall damage into structures, respectively. The shock wave which is the main impact load instantaneously results in the local damage for near-field underwater explosion while the bubble pulsation should be considered for mid-and far-field explosion [18]. This paper investigated the dynamic response of hull structures subjected to near-field explosion; hence, the shock-wave load is mainly analysed and studied.

2.2 Governing equation for underwater explosion

Large deformation is caused by near-field underwater explosion in a very short time, which may result in mesh distortion for the tradition mesh method. Thanks to Lagrangian and particle properties SPH method has natural advantages of dealing with problems of underwater explosion. The distortion of physical quantities is caused when the standard SPH method is used to solve problems with a large density ratio. Therefore, a modified SPH is used in this paper, given by [11]

$$\begin{cases} \dfrac{d\rho_i}{dt} = \rho_i \displaystyle\sum_{j=1}^{N} \frac{m_j}{\rho_j} (\boldsymbol{v}_i^b - \boldsymbol{v}_j^b) \frac{\partial W_{ij}}{\partial \mathrm{x}_i^b} \\ \dfrac{d\boldsymbol{v}_i^b}{dt} = \displaystyle\sum_{j=1}^{N} \frac{m_j}{\rho_i \rho_j} (\sigma_i^{ab} + \sigma_j^{ab} + \Pi_{ij}) \frac{\partial W_{ij}}{\partial \mathrm{x}_i^b} \\ \dfrac{de_i}{dt} = \dfrac{1}{2} \displaystyle\sum_{j=1}^{N} \frac{m_j}{\rho_i \rho_j} (\sigma_i^{ab} + \sigma_j^{ab} + \Pi_{ij}) (\boldsymbol{v}_i^b - \boldsymbol{v}_j^b) \frac{\partial W_{ij}}{\partial \mathrm{x}_i^b} \end{cases} \tag{3}$$

where ρ is density; v is velocity; a and b are directions along axes; p is pressure; e is energy; t is time; x is coordinates; W_{ij} is smoothed function of a pair of particles j and i; Π_{ij} is artificial viscosity [11]; σ is stress composed of isotropic pressure and viscous shear stress.

(1) Stress of explosive products

The viscosity of explosive products and water is too small to be ignored. The stress can be obtained by the solution of pressure. Jones-Wilkins-Lee and Mie-Gruneisen equation of states (EoS) are used for these two media, expressed as [19]

$$p = A\left(1 - \frac{\omega\eta}{R_1}\right) e^{-\frac{R_1}{\eta}} + B\left(1 - \frac{\omega\eta}{R_2}\right) e^{-\frac{R_2}{\eta}} + \omega\eta\rho_0 e, \tag{4}$$

where p is pressure; η is the ratio of densities between explosive products and initial explosive; ρ_0 is initial density of initial explosive; e_0 is initial energy; A, B, R_1 and R_2 are constants.

(2) Stress of water

When the water is in expansion state, the EoS is given by [20]

$$P = \frac{\rho_0 C^2 \mu[1 + \left(1 - \frac{\gamma_0}{2}\right)\mu - \frac{a}{2}\mu^2]}{[1 - \left(S_1 - 1\right)\mu - S_2 \frac{\mu^2}{\mu + 1} - S_3 \frac{\mu^3}{\left(\mu + 1\right)^2}]^2} + \left(\gamma_0 + a\mu\right)e, \tag{5}$$

while when it is in compressive state, the EoS is expressed as [20]

$$P = \rho_0 C_0^2 \mu + \left(\gamma_0 + a\mu\right)e, \tag{6}$$

where C is sound velocity; ρ_0 is the initial density of water; $\mu = \eta - 1$, η is the ratio of density before and after the explosion; γ_0 is Gruneisen coefficient ; S_1, S_2 and S_3 are the fitting coefficients.

(3) Stress of steel

Mie-Gruneisen EoS is used [21]

$$p(\rho, e) = (1 - \frac{1}{2}\Gamma(\zeta - 1))p_{\mathrm{H}}(\rho) + \Gamma \rho e, \tag{7}$$

where， Γ is Gruneisen coefficient， p_{H} is the pressure in the Hugoniot curve [11].

A shearing force in a metal liner with high shear strength is considered and Johnson-cook damage model is used [22].

3 NUMERICAL SIMULATION

A SPH model of hull structures near free surface subjected to near-field underwater explosion is established. Propagation of shock wave and its damage into structures are analysed.

3.1 NUMERICAL MODEL

Numerical model of ship structures attacked by a charge was simplified in Fig. 1. TNT and steel were used as materials of the charge and the structure, respectively. The surrounding water has a length of l_1 and a width of l_2. The thickness of the steel is d_1 and the length of the charge is d_2. The detailed geometrical parameters are shown in Tab. 1.

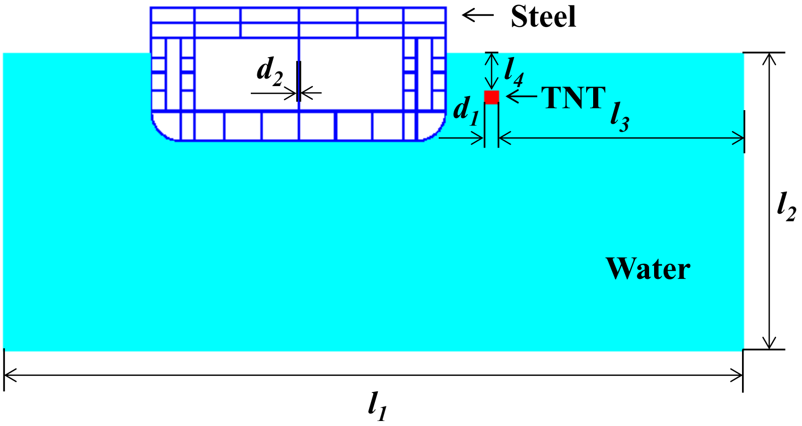

Figure 1: Numerical model

Table 1 Dimensions of the model

l_1	l_2	l_3	l_4	d_1	d_2
5.0	2.0	1.65	0.25	0.01	0.10

3.2 Results and discussion

Damage process of the hull structure was illustrated in Fig. 2. A spherical shock wave (SW1) propagated in the water and peaked at about 2 GPa at $t \approx 40\,\mu s$ in Fig. 2(a). When SW1 arrived at the steel a reflected shock wave (RSW1) was generated due to higher impedance of steel than that of water. Besides, a shock wave was also produced in the steel at about $85\,\mu s$. The shape of the explosive products has transformed from cubic to spherical in Fig. 2(b). At about $110\,\mu s$ SW1 reached the free surface in Fig. 2(c), resulting in a reflected rarefaction wave (RRW1). Fig. 2(d) shows that the shape of RSW1 developed to a non-spherical one. With the propagation of RRW1, the pressure around the free surface was low. It was found that the propagation velocity of the shock wave in the steel was much higher than that in the water in Fig. 2(e). The explosive products expanded in the water in Fig. 2(f). The free surface moves with the effect of the shock wave, with “spike” produced in the free surface. At about $205\,\mu s$ the pressure diminished to about 855 MPa, with a plastic deformation of the steel.

The spike increased with the effect of impact load. A hole was generated at the outer steel at about $305\,\mu s$. With the further effect of the high-pressure shock wave, the diameter of the hole increased. The surrounding water poured into and impacted the inner structure in Fig. 2(g). Due to the energy consumption of the reinforced and the spike the damage in the upper structure was declined.

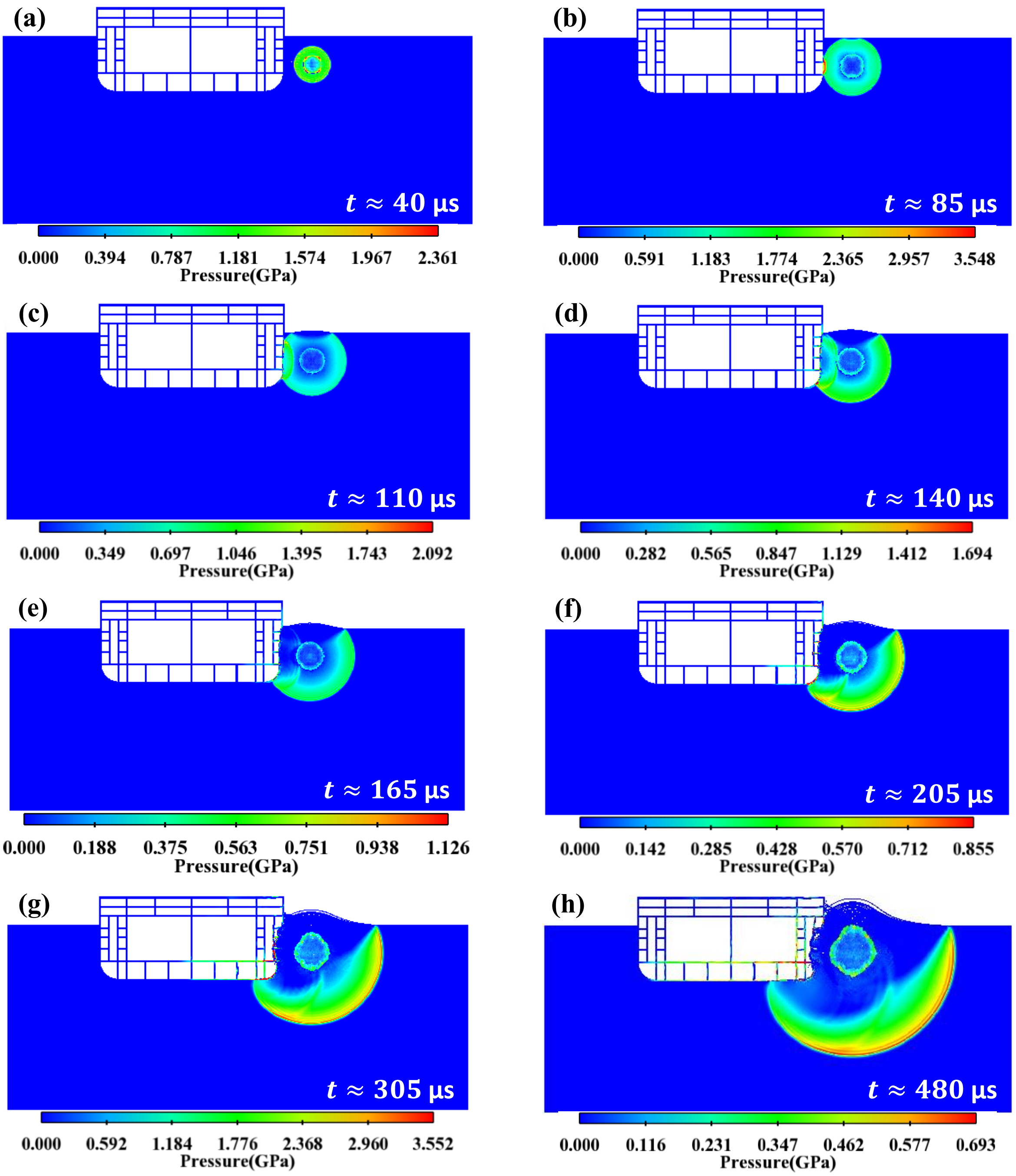

Figure 2: Pressure distribution in the process of underwater explosion; (a)-(f) correspond to moments at 40 μs, 85 μs, 110 μs, 140 μs, 165 μs, 205 μs, 305 μs and 480 μs.

5 CONCLUSIONS

The SPH method is used for the simulation of hull structures subjected to contact underwater explosion. Propagation of shock wave and its damage into structures were analysed. Conclusions were summarized as follows. Complex waves were produced in the process of structures subjected to underwater explosion. The superposition of these waves led to complex pressure distribution. The phenomenon of "spike" was found and the truncation effect on the shock wave was caused by the free surface. It indicates that the shock wave has obvious irregular reflection effect near the free surface. Under the combined effect of transverse wall and "spike" which dispersed shock wave energy, the damage into the upper part of the side structure was weakened. The hole of the hull structure increased with the propagation of shock wave. After the water entered the hull, the inner structure was damaged.

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