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Numerical Simulation of Damage to Ship Structure by Underwater Contact Explosion Shock Wave

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The purpose of this paper was to study the damage mechanism of the underwater contact explosion test of the model structure, which provided a basis for the protection mechanism of the side protective structure. This paper adopted an energy principle method to analyze and study the damage mechanism of underwater contact explosion test of ship protection structure model, and then used the software for numerical calculation. The dynamic curves of stress, strain and displacement of typical parts of the ship protection structure model were obtained. After comparing the experimental data, the numerical results were reasonable and credible.

1. Introduction

Underwater explosion is a highly complex nonlinear physical process and can bring great damage to the surface ships or submarines. Far field underwater explosion is mainly caused by elastic response or local plastic deformation of ship, while close or contact underwater explosion can cause the ship to break or even break, which is the main cause of ship capsizing. With the increasing recognition of the importance of ship survivability, more and more attention has been paid to the research of anti shock and anti shock capability of ship side protection structures. It costs a lot to carry out physical test and research on the side protective structure, therefore the typical part of the side protective structure can be properly reduced to an appropriate model structure. Under the action of underwater explosion load, the simple structure can be calculated according to the empirical formula. However, taking into account the complexity of the underwater explosion mechanism and the structure of the actual ship, plus the linear and nonlinear problems, it is impractical to put the theoretical calculation method into engineering applications, and it is difficult to obtain analytical solutions. The shortcomings of the experimental study were also obvious: the cycle was long and required a lot of argument and preparation work; equipment was expensive; repeatability was low; measurement was difficult, and the success rate was low (Zhang et al., 2012).

The method of numerical simulation can overcome the inconvenience which is caused by theoretical research and experimental research. Although the numerical solution is not as accurate as the analytical solution, it is sufficient to use the error in a certain range, if it is used properly. This is sufficient for the engineering application, and the numerical simulation is low, the cycle is short, the repeatability is high, and information is detailed. Therefore, with the development of high-speed computer, underwater explosion numerical simulation method is also booming. From the 1950s onwards, the United States began to strongly support the underwater explosion numerical simulation algorithm to explore the study; after 30 years of development, in the 1990s, a variety of underwater explosion methods and commercial software were formed, wherein ABAQUS was more famous. The software used in the calculation of underwater explosion load and structural damage has its advantages while the focus is different. Due to the use of numerical methods, it is possible to study the underwater explosion loads, especially shock waves, bubbles and cavitation, and the understanding of the mechanism is clearer (Hou et al., 2007; Chen et al., 2009; Zhang et al., 2014; Liu et al., 1994).

Through the current research on the subject situation can be roughly derived from the existing problems, summarized into the following aspects: (1) study on dynamic response mechanism of ship structure under underwater explosion load. Under the underwater explosion load, the dynamic response of the structure is

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large in deformation, high in nonlinearity, and instantaneous in dynamic response of fluid-solid coupling. In the study of the structure, the current theoretical research is not very full and perfect in terms of the loading method of the explosive load, the constitutive equation of the structure and the state equation of the fluid material, and the failure criterion of the structural material, etc. At the same time, there is less research on the effects of sound field and thermal field on the structure. (2) Study on structural crack of warships under underwater explosion load. Although the current science and technology is very advanced, due to the large structure of the ship in the construction and use, there must be certain welding cracks and defects. Under the impact of weapons and underwater explosion load, these cracks or defects will expand and break, thereby impacting the ship structure. There is not much research on this issue. (3) Application of numerical calculation in underwater explosion load to ships. Under certain theoretical analysis, the numerical calculation can solve the dynamic response of the ship structure under the underwater explosion load. However, numerical calculation also has some problems: material constitutive equation, fluid state equation, cell mesh distortion, etc., all of these will have an impact on the calculations. How to simulate the actual situation in a more reasonable, effective and real way remains to be further studied. Based on the existing theory, the damage mechanism of ship protection structure under underwater contact explosion load was analyzed. This paper analyzed the phenomenon of underwater contact explosion test of ship protection structure, and studied it according to the previous theory. Finally, the dynamic response of the ship protection structure under the underwater contact explosion load was numerically calculated by using the calculation software. By comparing the numerical results with the experimental results, a more reasonable model and calculation method were obtained, which can be compared with the real simulation test (Aman et al., 2011).

2. Basic theory of underwater explosion

Explosion is defined as the transformation of energy from one form to another or several forms in a relatively short period of time and in a relatively small space with a strong mechanical effect. Condensed explosives refer to liquid and solid explosives. Compared with the gas explosives, the difference lies in the characteristics of large density, high burst speed, detonation pressure, high energy density, explosive power and the like, in addition to the different forms of aggregation, therefore, the condensed explosive is widely used in military affairs. The process of explosion can be divided into three stages: (1) energy accumulation, the formation of high energy density state is a slow process; (2) the explosive state of energy is released, and the released state interface is driven by supersonic velocity in the system. Or under certain conditions, the "hot spot" of energy release is generated everywhere, and the hot spot generation rate increases rapidly. Finally, the explosive release of the whole system energy is formed, which belongs to the fast process; (3) the released energy diffusion and propagation, and the surrounding medium interaction. One is propagated in the form of radiation (electromagnetic waves, particle beams and radiant heat); the other is propagated in the form of shock waves and is also a fast process (Shin, 2004.).

Detonation is accompanied by a chemical reaction of the shock wave; usually, the precursor shock wave acts on explosives, inducing high temperature and high pressure chemical reaction, and the released energy supports the shock wave to continue to advance. On the basis of experimental study of gas detonation, in the 19th century, a relatively complete theory of detonation wave fluid mechanics, called Chapman (Jouguet) theory, was proposed, which is also referred to as CJ theory; the detonation wave is reduced to a strong discontinuity, so that the detonation wave can be treated by the fluid mechanics method without having to consider the chemical reaction process, as long as the reaction heat (detonation heat) is known, the CJ theory considers the one-dimensional problem in the plane, and the CJ condition that must be followed in the detonation wave propagation was proposed.

Detonation wave was actually a shock wave with chemical reaction, and the three conservation laws were applicable to it. The formulas of the three conservation laws were as follows (Liang and Tai, 2006):

Conservation of mass:

$$m = \rho_0 (D - u_0) = \rho (D - u) \tag{1}$$

Momentum conservation:

$$\rho_0 (D - u_0)^2 - \rho (D - u)^2 = p - p_0 \tag{2}$$

Conservation of energy:

$$m\left[e_0 + \frac{1}{2}(D - u_0)^2 - e - \frac{1}{2}(D - u)^2 + Q_v \right] = p_0 u_0 - pu \tag{3}$$

In addition to the three conservation equations used to calculate detonation, the state equation should also be used to describe the thermodynamic relationship between detonation products. When the detonation product is formed, its temperature near the CJ point is up to several degrees, and the pressure is up to dozens of GPa. At the same time, the study of the state equation of the detonation product of explosives is difficult in theory and practice. But some idealistic and simplified assumptions can be made, and various models can be used to describe the state change of explosive detonation products. Because of the complex reaction process in the detonation process, the various theoretical models proposed include some parameters that need to be tested. When the detonation product of condensed explosive is approximately solid, the following equation of state is put forward by Davis:

$$p = Av^{-r} + \frac{B}{V}T \tag{4}$$

The explosion process in water includes the initiation of the explosive and the propagation of the detonation wave in the explosive. The detonation wave reaches the water interface and the water action produces the initial shock wave. The shock wave is free from the product, and the expansion and contraction of the detonation product form pulsating bubbles. Compared with air explosion, there are three main differences between underwater explosion and air explosion: First, for the same charge explosion, the water shock wave pressure is much larger than the air; Second, the pulse width of underwater shock wave is much smaller than that of air shock wave; Third, the shock wave velocity in water is approximately equal to the velocity of the wave front. Due to the large density of water and the presence of hydrostatic pressure, the detonation product is much slower than in the air. The sound velocity in the water is relatively fast, when the water content increases, the water velocity will drop rapidly. In addition, the explosion of bubbles occurs in deep water explosion.

When the explosive explodes in the homogeneous and quiescent water, the explosion product with high pressure expands outwards rapidly, thus the initial shock wave is formed in water, and the rarefaction wave is emitted by the explosion product. At the same time, with the propagation of shock wave in water, the wave front pressure and velocity decrease rapidly, and the wave width continues to widen. When the initial shock wave is formed, the explosion product begins to expand, and the surrounding water moves along the radial direction in the form of bubbles. When inflated to a certain extent, the bubbles will shrink. This process is usually referred to as bubble pulsation. When the bubble pulsates, the water will form sparse waves and pressure waves. In addition to the above shock wave and bubble pulse, underwater explosion can produce complicated water flow when a free interface or obstacle is encountered. Since this part of the paper is to study the destruction function of the underwater contact explosion on the structure, the bubble pulsation and other forms are disregarded, therefore, the theory of shock and detonation products in water will be introduced in this paper.

3. Numerical calculation of underwater contact explosion

In this paper, ALE algorithm for numerical calculation was adopted, and the feature of ALE method was that the mesh used was neither the fixed grid of Euler nor the same volume mesh as lagrange. But every step (or every few steps) constructed a suitable mesh according to the boundary of matter. Manual partitioning was usually used to process distorted meshes, and ALE algorithm can be regarded as an algorithm for automatic re-partitioning.

(1)State equation of explosives

The equation of state is an equation that describes the relationship between pressure P_1, the internal energy e, and the specific volume v (or density ρ). For condensed explosives, the pressure of the detonation product in the numerical calculation was generally calculated from the JWL equation of state, and its specific form was (Jin and Ding, 2011):

$$P_1 = A(1-\frac{w}{R_1 v})e^{-R_1 v} + B(1-\frac{w}{R_2 v})e^{-R_2 v} + \frac{wE_1}{v} \tag{5}$$

where, w, A, R_1, R_2: the constant of passing the experiment;

B: the constant of passing the experiment;

E1: initial internal energy;

The explosive is described by high speed explosive combustion material and JWL equation of state. The parameters of TNT used in this paper were as follows:

ρ_1=1631.okg/m^3, D=6717.4m/s, PCJ=1.85e^{10}Pa, A=5.409e^{11}Pa, B=9.4e^{9}Pa, R_1=4.5, R_2=1.1, w=0.35

(2)Equation of state of air

The air was described by the LINEAR-POLYNOMIAL multilinear state equation (Zhang et al., 2011):

$$P_2 = c_0 + c_1\mu + c_2\mu^2 + c_3\mu^3 + (c_4 + c_5\mu + c_6\mu^2)E_2 \tag{6}$$

Where, $\mu=\rho_3/\rho_2-1$; c_0, c_1, c_2, c_3, c_4, c_5, c_6: constants defined by experiments
E_2: energy per unit volume
In this paper, the value of each parameter in the state equation is:

$$c_0 = c_1 = c_2 = c_3 = c_6 = 0 \tag{7}$$

$$c_4 = c_5 = \gamma - 1 \tag{8}$$

Where, γ: specific heat ratio;
Through the above formula, we can get the equation of state of air:

$$P_2 = (\gamma - 1)\frac{\rho_3}{\rho_2}E_2 \tag{9}$$

The air material parameters which were used in this paper were as follows:
ρ_2=1.28kg/m^3, c_4=c_5=0.4, E_2=2.5e^{5}Pa, V_0=1.0
(3) Water state equation
The most commonly used equation of state under the impact of the impact load is the Mie-Grunesen equation of state:

$$P_3 = A(u) + B(u)E \tag{10}$$

On the compression situation (ζ=η-1>0)

$$A(\zeta) = \frac{\rho_0 c_0 \zeta[2 + (2-\gamma_0)\zeta - (\gamma_0 - a)\zeta^2]}{2[1-(s_1-1)\zeta - s_2\frac{\zeta^2}{(\zeta+1)} - s_3\frac{\zeta^3}{(\zeta+1)^2}]^2},\ B(\zeta) = (\gamma_0 + a\zeta) \tag{11}$$

$$\begin{cases} \eta = \dfrac{v_0}{v} = \dfrac{\rho}{\rho_0} = \dfrac{1}{v_{rel}} = \zeta + 1 \\ \zeta = \eta - 1 = \dfrac{v_0 - v}{v} = \dfrac{dv}{v} = \dfrac{1}{v} - 1 \end{cases} \tag{12}$$

On the stretching situation (ζ=η-1<0):

$$A(\zeta) = \rho_0 c_0^2 \zeta,\ B(\zeta) = (\gamma_0 + a\zeta),\ \zeta_s = c_0 + s_1\zeta_p + s_2(\frac{\zeta_p}{\zeta_s})\zeta_\rho + s_3(\frac{\zeta_\rho}{\zeta_s})^2\zeta_p \tag{10}$$

Where c_0: sound speed; s_1, s_2, s_3: the input material constant;
E_3: internal energy per unit volume.
The material parameters of the water used in this paper were as follows:
ρ=1000kg/m^3, c0=1484kg/s, s_1=1.979, γ_0=0.11, a=3.0, V_0=1.0, E_3=307200Pa

4. Analysis of numerical results

The explosive used in this experiment was TNT/RDX mixed charge, the explosive charge of RDX was equivalent to TNT explosive, and then 25g, 250g and 500g of the charge were taken respectively. Because of the computer time and so on, this paper only carries on the numerical calculation to the 25g and the 250g two kinds of charge in the experiment. In the numerical calculation of this paper, the steel plate was modeled by three-dimensional shell element, and the explosive, air and water were modeled by solid element. The steel plate was coupled to a eulerian body composed of explosives, air and water. The ALEalgorithm was used in the calculation process: the failure criterion of steel plate was based on any of the following criteria: (1) failure pressure; (2) failure principal stress; (3) failure equivalent stress; (4) failure principal strain. To satisfy any one of them, the steel plate was destroyed.

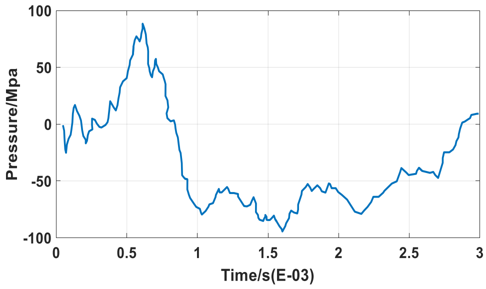

Figure 1: The pressure curve of the unit at I point in each layer of steel plate(25g)

In the experiment, the dynamic response of some key points was recorded using PVDF, as shown in Table 1.

Table 1: Observation pressure of 25g charging point

Observation point	Test pressure value	Numerical pressure value
1	10.79	8.61
2	7.45	8.22
3	16.26	19.82
4	5.25	2.23
5	6.32	3.42
6	-	0.21

The pressure curve of the unit at the same location was shown in Figure 1. The diagram represented the pressure curve at the I point of each layer of steel plate. The first layer of steel was subjected to greater pressure, the pressure on the rear plate was relatively small, which indicated that the main energy produced by the charge explosion acted on the first layer of steel plate and had no great influence on the rear plate.

Fig. 2 was the strain curve of the observation unit at the I point in the 250g explosive plate. The diagram represented the strain curve of the element at the I point of each layer of steel plate. Therefore, the observation unit had been destroyed, so the strain became zero after reaching the limit strain. The strain at the corresponding location of the second, third layer steel plate was smaller. The blast shock wave had little effect on the fourth ply steel plate, so the strain was smaller.

Table 2 listed the test and numerical values of the pressure at the same position. The values in the table were the peak values of the first wave of the pressure shock wave. It can be seen from Table 2 that the results obtained by experiment and numerical calculation were basically in the same order of magnitude.

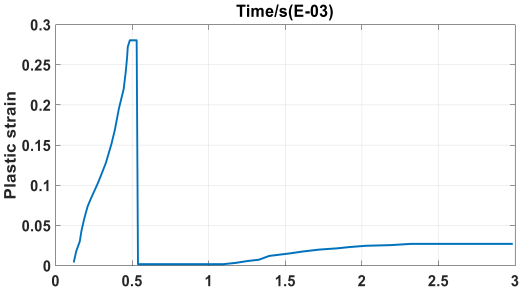

Figure 2: The pressure curve of the unit at I point in each layer of steel plate (250g)

Table 2: Observation pressure of 250g charging point

Observation point	Test pressure value	Numerical pressure value
1	16.11	12.16
2	35.22	22.21
3	7.91	6.97
4	0	16.28
5	1.90	1.35
6	1.60	1.05
7	0.96	0.81

5. Conclusion

In this paper, the ship protection structure is simplified to the model structure, and the damage mechanism of the model structure under the underwater contact explosion load is analyzed theoretically, the experimental research and the numerical calculation work. In the case of appropriate modeling and calculation parameters, and using the software LS--DYNA calculation, we can get more reasonable results. By comparison and analysis, the numerical results of this paper are credible, and the calculation method is feasible.

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