Study on the influencing factors of underwater unexploded ordnance destruction based on shaped charged jet

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Abstract: In order to study the influence of the stand-off distance and the waterproofness on the penetration effect of liner shaped charge (LSC) jet to destroy underwater unexploded ordnance, the LS-DYNA finite element program was applied to simulate the process of the metal jet formation and penetration into steel plate under different stand-off distances and waterproof condition. On the basis, the model experiment was carried out. And combing the experimental and numerical result, it can be found that, if no waterproof measures is adopted the metal jet will directly get contact with the water, the unexploded ordnance will not be successfully destructed, moreover, with the increase of the stand-off distance, the shaped charge jet works more ineffectively.

1. Introduction

The large amount of unexploded underwater ammunition left over during the war poses a serious threat to the normal operation of military vessels and civilian fishing vessels, and the safety of the relevant operators cannot be guaranteed reliably. Therefore, it is urgent to develop a device which can safely and effectively carry out the blasting destruction of large-caliber underwater ammunition. After explosion, the shaped charge jet can instantaneously get into the formation of metal jet with high temperature and high pressure [1], and it can effectively destroy typical target object, such as, metal plate, reinforced concrete, etc. Since the shaped charge cutter have the characteristics of small volume, small quantity of explosive, high power and high utilization rate of explosive, it has been successfully applied to the destruction of unexploded ordnance on land. However, due to the relatively complex underwater working environment, it is very difficult for the successful application of shaped charge cutter to unexploded ordnance destruction.

In order to study the influence of stand-off distance and waterproof condition on the destruction effect, the numerical simulation analysis of underwater shaped charged jet forming and penetration process after detonation of shaped energy cutter is performed. Through the underwater explosion
model test, the damage effects of model projectiles under different stand-off distances and waterproof conditions are compared and analyzed. The numerical simulation results are in agreement with the experimental result, and relevant conclusions can provide some reference for the application of shaped charged cutter to the underwater unexploded ordnance destruction.

2. Numerical Simulation Study

Based on LS-DYNA dynamic finite element program and ALE algorithm, the numerical simulation of underwater unexploded ordnance destruction by shaped charge cutting is studied in this paper.

2.1. Numerical simulation model

2.1.1. Finite element model. As the geometric symmetry, it numerical model can be simplified into 1/4 of the real mode, as shown in figure 1. The model consists of four parts, namely, 8701 explosive, liner (lead-antimony alloy), jet forming medium (air or water) and target plate (A3 steel). Explosive, liner, air or water are meshed by Euler grid, and the target plate is modeled by Lagrange grid. The process of jet penetration is simulated by fluid-structure interaction method, and the hourglass control is applied. In order to reduce the computational complexity, dense grids are used in the target and jet action area, while gradient grids are used in the rest of the air area. And nonreflective boundary is adopt on the boundary nodes to avoid pressure reflection. The shaped charge is denoted at the center of the top.

2.1.2. Material Model. The pressure generated by the expansion of the detonation product of 8701 explosive and the jet is depicted by the Jones–Wilkens–Lee (JWL) equation of state (EOS). The Steinberg model was employed to model the dynamic mechanical behavior of the shaped charge liner. The Johnson-Cook (J-C) model is useful to model the high rate deformation of many materials including most metals [2] and employed to depict the dynamic mechanical behavior of the target plate. In order to model the air and water medium, material type 9 of LS-DYNA (*MAT_NULL) was used, and Gruneisen and linear polynomial state equation were respectively adopt to determine the pressure of air and water. The parameters [3] of explosive and liner are shown in table 1 and table 2, respectively.
### Table 1. 8701 explosive.

| Density (g/cm³) | A (Gpa) | B (Gpa) | R₁ | R₂ | W  | C-J detonation velocity (m/s) | C-J detonation pressure (GPa) |
|----------------|---------|---------|-----|-----|----|-------------------------------|-------------------------------|
| 1.69           | 852     | 18      | 4.6 | 1.3 | 0.25| 8300                         | 29.6                         |

### Table 2. Shape liner.

| Density (g/cm³) | Shear modulus | Truncation pressure | Material Constants |
|-----------------|---------------|---------------------|--------------------|
| 11.3            | 0.086         | -9                  | β  n  b  h         |
|                 |               |                     | 110  0.52  11.63  0.00116 |

2.2. *Analysis of jet forming process*

Shown in figure 2 and figure 3 are respectively the jet forming process after the charge initiation in the water and air. It can be seen that, since the resistance of air to the jet is smaller than water, the formation and stretching process of metal jet in air is relatively smoother, in addition, owing to the gasification and cooling effect of water medium, the jet in water cannot get effective stretching and be formed, thus, it is more difficult to form metal jet with large aspect ratio.

![Figure 2. Jet forming process in air medium.](image)

![Figure 3. Jet forming process in water medium.](image)
2.3. Analysis of jet penetrating process

2.3.1. Effect of stand-off distance Figure 4 and figure 5 respectively shows the metal jet penetrating process at different stand-off distance $h$ of 0mm and 4mm after the underwater explosion of LSC. By comparison, it can be seen that the water medium will not directly affect the jet stretching at stand-off distance of 0mm, and the explosion products will be more directed to the air accumulator due to the existence of water pressure.

![Figure 4](image1.png)  ![Figure 5](image2.png)

*Figure 4. Jet penetrating process ($h=0$mm).*

*Figure 5. Jet penetrating process ($h=4$mm).*

Therefore, the cutting effect of the metal jet is much more significant, and the target plate with a thickness of 3cm gets totally penetrated. When the stand-off distance is set to 4mm, a small amount of water medium can immediately flow into the air accumulator after the detonation, after then, and then, under the effect of explosive products, the water medium cannot flow into the energy accumulator again. Accordingly, the target plate also gets deep penetration of 25 mm, even though there is a stand-off distance of 4mm.

![Figure 6](image3.png)

(a) $h=0$mm  (b) $h=4$mm

*Figure 6. Different penetration depth at different stand-off distance.*
2.3.2. Effect of jet forming medium. As shown in figure 8 and 9, the cutting effect of target plate set in the air is mainly formed by metal jet. However, when the accumulator is filled with water, the metal jet cannot get into formation and directly impact the target plate under the effect of water resistance, consequently, the penetration effect of the target plate is mainly caused by the high pressure in the water , which sharply increase due to the concentrating energy in explosion, as the same result, the shape of the cut is not very regular.

![Figure 7. Penetration depth of steel plate][3].

The pressure curves of the points at different distances (0 mm, 5 mm and 10 mm) from the bottom of the axis of the LSC are depicted in figure8, and the point at the distance of 10mm is located at the boundary between the plate and the air or water medium. It can be clearly seen that the pressures in air and water are totally different during the formation and stretching of the metal jet. The time difference of peak pressure at different distances in air medium is large. The peak pressure occurs at the arrival of the metal jet and the maximum pressure is only 7.5 GPa, and then, the pressure drops rapidly to the normal pressure. Meanwhile, the pressure at the boundary remarkably oscillates due to the reflection and transmission effect. Nevertheless, the pressure of each point in water medium rises suddenly almost at the same time, and it attributes to the faster sound velocity in the water medium. As shown in figure8(b), the water pressure firstly comes to the summit (9GPa) at 16μs. Then, the water pressure jumps again to about 12 GPa at 40μs due to the convergence of energy, after that the mass pressure decreases rapidly, and then slowly oscillates down to a stable state. Owing to the slower pressure attenuation in the water medium, the metal plate suffers a longer penetration process.
Figure 8. Pressure curves at different distance.

3. Experimental Study

3.1. Experimental setup

The test was carried out in an explosion water tank with a size of 2.2m × 2.2m × 2.2m (figure 9). As shown in figure 11, the test device consists of a fixed plate, a screw, a closure member and a hollow tube. A cylindrical charge (TNT) weight of 1g and a flexible shaped charge (FSC) with a length of 13cm were respectively set at the outer and inner wall of the tube.

The hollow tube was made of 45 # steel, and the outer diameter and the axial length of the tube were both 20 cm. Tubes with different thickness (t=1 mm, t= 2 mm) were compared in the model test. The fixing plate is a hollow metal plate with a size of 30 cm×30 cm×1 cm. The hollow metal tube is fasten between the two fixing plates through the bolts, and the waterproof material is pre-coated between the fixing plates and the cylindrical shell to ensure its waterproofness. The water-storage depth in the tank is 2 m, and the metal tube is set at the depth of 1m.
3.2. **The result and analysis of the experiment**

Four tests were performed in this work. In table 3 is shown the experimental conditions and results, where the tests were numbered from Exp1 to Exp4. Stand-off distance, deformation parameters and failure characteristics were listed for each test, and WF, WT, a and b respectively represent the waterproofness of the FSC, the waterproofness of the tube, the length and the width of the incision. By comparing with the test data and the damage effect of the tubes, it can be found that the tube thickness, the waterproof condition and the stand-off distance all remarkably affect the penetration effect caused by the metal jet, and also determine whether the residual jet has enough impact energy to induce the explosive charge.

Shown in figure 13(a) is the damage effect of the tube in Exp1, the metal tube undergoes severe plastic deformation in the near-explosion zone, and a butterfly-shape deformation occurs. Due to the violent impact of the detonation products and the shaped charged jet, the material near the incision area is subjected to high temperature and pressure, resulting in thermoplastic instability, and the failure material is approximately in a fluid state. Additionally, owing to the curved surface structure and the thin shell thickness of the tube, an elliptical depression comes into being accompanied by with a large total deformation, and the incision is obviously stretched inward to form a lip turning. It is worth noting that since the residual jet still has strong impact kinetic energy, the cylindrical charge set on the inner wall of the tube is induced, which lead to the impact force in the opposite direction during the forming of the incision and the stress concentration in the impact region, which is account for the formation of local fracture and an inward meshing bulge.

Figure 13(b) shows the penetration effect of the flexible shaped charge without waterproofness at the accumulator (Exp2). Compared with the damage effect of the tubes with good waterproof condition, as a result of the cooling and obstruction of the water medium, the jet is significantly affected in the early stage of the stretching movement. As the metal jet reaches the shell surface, the tube cannot be penetrated by the jet due to the low kinetic energy and temperature, and only a slender groove occurs. Nevertheless, the tube still gets pronounced global deformation and local deformation, which is arising from the energy accumulation effect.

The final deformation of Exp3 is shown in figure 13(c), and it can be directly found that the deformation area, the size and inversion degree of the incision all remarkably decrease by comparing with Exp1, and it is for that the filling water provides a ‘foundation pressure’ [4] during the impact and response process for the tube to resist the impact of the metal jet, which can effectively change the concentrated transmission load into distributed load [5]. However, the residual jet still induces the detonation of the cylindrical charge, resulting in a certain meshing bulge in the middle section of the cutting. Figure 13 (d) is the damage effect of the tube with the FSC set close to the outer surface. Because of the small size of the shaped charge, the penetration ability of the jet reaches the strongest at the stand-off distance of 0mm.
Table 3. Experimental condition and result

| No. | $h$ | WF | WT | $a$/mm | $b$/mm | Damage effect |
|-----|-----|-----|-----|--------|--------|---------------|
| Exp1 | 2   | √   | √   | 127    | 12     | Partial crack at the front zone of the tube, with butterfly-shaped incision and obvious lip turning on the back of the tube. |
| Exp2 | 2   | ×   | √   | 102    | 0      | Obvious deformation with no penetration, undulate fold at the front zone of the tube and pronounced bulge at the back zone of the tube. |
| Exp3 | 2   | √   | ×   | 91     | 10     | Partial crack at the front zone of the tube with slender crack, small bulge at the back zone of the tube with small lip turning. |
| Exp4 | 0   | √   | √   | 195    | 60     | Elliptical incision at the front zone with obvious deformation, undulate fold at the front zone of the tube with obvious lip turning at the back of the tube. |

Figure 13. Damage effect of the tube.

4. Conclusions

In this study, the shaped charge jet formation process was studied by numerical simulation with LS-DYNA finite element program. And metal tubes with cylindrical charge set in the inner wall were applied to model the underwater unexploded ordnance. Combined with numerical simulation and experimental results, the conclusions are as follows:

1. The numerical simulation results are in agreement with the experimental results, which also performed that the selected numerical simulation method can be used to effectively analyze the
problems related to the underwater unexploded ordnance destruction.

(2) The resistance and the cooling effect of gasification of water medium can significantly affect the stretching process of jet forming and seriously weaken the penetration effect of underwater shaped jet, therefore, it is essential to take measures for waterproofness.

(3) Small stand-off distance or close setting can make sure the damage effect of the Perfro shaped charge jet when the size of FSC is very small.

References

[1] Tamer E, Ahmed E and Li Q M 2018 *International Journal of Mechanical Sciences* **136** 234-42

[2] Zhang Z F, Wang L K and Silberschmidt 2017 *International Journal of Impact Engineering* **103** 38-49.

[3] Pan S C, Zhong M S and Xie X B 2017 *Explosive Materials* **46** 31-6

[4] Gao F Y, Ji C and Long Y 2014 *Lat. Am. J. Solids Struct* **11** 1924–40

[5] Wu J Y, Chong j and Yuan L 2018 *Thin-Walled Structures* **127** 654-65