Numerical simulation of jet formation underwater by focusing annular liner

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Abstract. Basing on the application background of anti-submarine torpedo using shaped charge technology, a new structure of shaped charge liner named focusing annular liner was designed. The Autodyn-2D software was used to simulate the jet formation of this liner underwater. The result shows that: Through two times of convergence, the focusing annular liner can form one jet, this jet is thicker than normal jet. And during Secondary convergence, jet velocity and collision pressure are greatly increased.

1. Introduction

Since the modern military submarine came out in the late 19th century, it has played an important role in two world wars and many international affairs after the war. Therefore, the navies of many countries pay more attention to the construction and performance improvement of submarines, and vigorously develop submarine technology. Due to the improvement of submarine combat performance and its increasing role in sea combat operations, anti-submarine becomes an increasingly prominent problem, which will also be an extremely arduous task. With the continuous progress of science and technology, the traditional explosive torpedo, relying on the shock wave and bubble pulse formed by the explosion in the water, has been difficult to damage the modern submarine. Later, through research, it was found that the torpedo with shaped charge technology can damage submarine targets effectively [1-3].

The annular shaped charge [4,5] replaces the normal conical liner with an annular liner. The sectional drawing along the charge axis is W-shaped. The jet formed by the annular liner is a large diameter ring, which can cut a large hole for the target and open a channel for the main warhead to enter smoothly. If the annular cone of the annular liner is deflected to a certain angle, a new shaped charge structure is obtained. Grace et al. [6] presents the physical design of a staged shaped charge and its principal of operation. And the staging mechanism and liner collapse are described by both analytic and hydrocode approaches (HEMP). Chick et al. [7] investigated the cookie-cutter devices which was based on the linear shaped charge geometries, results showed that the jet formed by this structure was
unstable, it could not cut a circle from the target effectively. Dong et al. [8] proposed a new charging structure (makes the jet formed by the annular charging structure converge again on the charging axis), and analyzed the feasibility of the scheme through engineering calculation, then concluded that the jet after the secondary convergence has the advantages of higher quality and longer continuous stretch length. Wang [4] et al. put forward the equal impulse method when designing the structure of the annular shaped charge, the impulse acting on the corresponding micro element of the inner and outer cover is equal, which can ensure that the annular jet is not skewed. Wang [9] et al. designed a new type of liner named star shaped liner, which is composed of four wedge-shaped liners. The jet formed by the liner converges twice at the charging axis, and finally forms one jet. Zhang [10] et al. established the finite element model of the annular shaped charge with deflection angle, and presented the numerical simulation on the secondary convergence of jet and its process of penetrating targets, then obtained the optimized structure parameters of the liner, the results showed that the secondary convergence can increase the jet speed and increase the depth of penetrating. Based on the application background of anti-submarine torpedo using shaped charge technology, designing a kind of annular shaped charge liner and studying its jet formation process underwater, which can provide a new choice for domestic torpedo weapons.

2. Liner structure

We design a kind of annular liner named focusing annular liner. The structure of this liner is shown in figure 1. The difference between the focusing annular liner and the typical annular liner is that there is an included angle $\alpha$ between axis 1 and axis 2. The inner and outer liner are both variable thickness liner, but inner liner is decrease progressively from cone top to bottom and outer liner is on the contrary. This design can ensure that the mass of micro elements converging on the axis 2 is equal. Due to the high pressure produced by the explosive products, the secondary convergence can be unstable, the thicker inner liner can reduce this kind of negative effects.

Figure 2 is a sketch of the process of jet formation. When the charge is detonated, the detonation wave first acts on the cone top, extruding the cone to form the initial annular jet on the axis 1. Due to the existence of the angle $\alpha$, the annular jet will gradually shrink. After a period of time, it will conduct secondary convergence at axis 2, and finally form a new jet. During the secondary convergence, the detonation products can still work on the jet formation. It drives the annular liner accelerate, so the jet velocity after secondary converging is much higher than that of the primary annular jet.

![Figure 1. Structure of liner.](image1)

![Figure 2. Jet formation.](image2)
3. Numerical simulation

3.1. Numerical simulation methods

Autodyn finite element simulation software is used to calculate the process of jet formation of focusing annular liner. The finite element model includes air, explosive, water, liner and wave-shaped, and the Euler method is used during the whole simulation. The initiation point is set at the center of explosive. Because the torpedo has a seeker, there is a cavity in front of the warhead. In the simulation, we add a block of air domain before the charge. All material parameters are taken from Autodyn's own software library. The explosive is Comp B, density $\rho = 1.717\text{g/cm}^3$, detonation speed is 7980m/s, detonation pressure is 29.5Gpa. Liner is copper, density $\rho = 8.93\text{g/cm}^3$. Equation of state (EOS) and strength model of materials are listed in table 1.

| Materials | EOS                  | Strength model |
|-----------|----------------------|----------------|
| air       | Air                  | Ideal Gas      |
| explosive | Comp B               | JWL, Lee-Tarver|
| water     | Water                | Polynomial     |
| liner     | Copper               | Shock          |
| Wave-shaper | Boron Epxy         | Piecewise JC   |

The charge diameter is 100mm, length is 80mm. There is a wave shaper in the charge, it can make the detonation wave fit the liner’s shape better. The height of liner is 40mm, and the included angle $\alpha = 25^\circ$. The finite element model of charge is shown in figure 3. In order to observe the jet velocity, plot 23 gauges in the model. 18 gauges are in the air, 10 of them are near the zone which Secondary convergence taking place, the distance between each of them is 5mm. The other 5 gauges are in the water, the spacing is 10mm. We also set 5 gauges every 20mm in the water to study the velocity attenuation of the jet underwater.

![Figure 3. finite element model of charge.](image)
3.2. Equation of state of water

In most of the time, the working environment of submarines is more than 500m under water. At this depth, the pressure of water has reached 5MPa, which is far greater than the air pressure. In order to simulate the deepwater environment, the water pressure can’t be ignored.

There are two state equations about water in Autodyn material library, one is shock, the other is polynomial [11].

As for the Shock EOS, there is:

\[ p = p_{0} + \frac{\Gamma}{v} (e - e_{0}) \]  
(1)

\[ p_{0} = \rho_{0} c^{2} \mu (1 + \mu) \]  
\[ [1 - (\lambda - 1) \mu]^{2} \]  
(2)

\[ e_{0} = \frac{2 \rho_{0} (1 + \mu)}{\rho_{0} \mu} \]  
(3)

\( \lambda \) and \( c_{0} \) are constants, determined by the shock wave experimental relations.

For the Polynomial EOS:

When water is compressed, \( \mu > 0 \), state equation expression is that:

\[ p = A_{1} \mu + A_{2} \mu^{2} + A_{3} \mu^{3} + (B_{0} + B_{1} \mu) \rho_{0} e \]  
(4)

And when water expands, \( \mu < 0 \), state equation expression is:

\[ p = T_{1} \mu + T_{2} \mu^{2} + B_{0} \rho_{0} e \]  
(5)

\[ \mu = p / \rho_{0} - 1 \]  
(6)

\( \mu \) is the compression ratio, \( \rho_{0} \) is the initial density of water at room temperature, and \( e \) is the internal energy per unit mass.

When water is neither compressed nor expanded, \( \mu = 0 \), equation (4) changes to:

\[ p = B_{0} \rho_{0} e \]  
(7)

As we know, the formula of water pressure is:

\[ p = p_{0} + pgh \]  
(8)

Combining equation (7) and (8), we can get that:

\[ e = \frac{p_{0} + pgh}{B_{0} \rho_{0}} \]  
(9)

Through formula (9) we can see that the water pressure can be given by setting the initial internal energy of water, but it can’t be achieved by the shock state equation. Therefore, choosing the polynomial as the state equation of water, and the specific parameters are listed in table 2.

For the general deep-water explosion, the change of water density in the depth direction can be ignored. Let us consider that the density of water at each depth is equal to 1.0g/cm³. In this paper, the depth of water is 500m, and the initial specific internal energy of water is calculated to be \( e = 1.821893 \times 10^{4} \) J/kg.

| Material | \( A_{1}/GPa \) | \( A_{2}/GPa \) | \( A_{3}/GPa \) | \( B_{0} \) | \( B_{1} \) | \( T_{1}/Gpa \) | \( T_{2}/Gpa \) |
|----------|----------------|----------------|----------------|-------------|-------------|-------------|-------------|
| Water    | 2.2            | 9.54           | 14.57          | 0.28        | 0.28        | 2.2         | 0           |

Table 2. Polynomial equation of water.
3.3. Result and discussion

The process of jet formation is shown in figure 4. As we see, the focusing annular liner can form a jet after secondary convergence. Jet formation is basically down at time of 50μs, it’s quicker than normal jet formation. The jet is much bigger than normal jet, but there is a small cavity near the head of the jet. According to momentum conservation, two objects with equal mass impact obliquely among the axis X will cause the reverse velocity among the axis Y. During secondary convergence, a part of jet may be bounced off, this cause the cavity of jet. After the jet penetrates into the water, due to the pressure of water, velocity of the front of the jet will decrease firstly. But the back of the jet still go ahead with the original speed, it will catch up the front of the jet, the cavity will disappear gradually.

![Figure 4. Process of jet formation.](image)

The first and secondary convergence of jet can be study through velocity profile of jet and pressure contours, as shown in figure 5 and figure 6. After charge detonation, the detonation wave becomes two parts. One bypasses the wave shaper and the other propagates through it. At the time of 8μs, detonation wave starts to work on the cone top, forms the initial annular jet. Secondary convergence is taking place at the time of 23μs. At this time, the pressure has reached 109.8Gpa, which is much bigger than the pressure during first convergence. This huge pressure on the one hand can greatly increase the jet velocity, but on the other hand, it may cause the secondary convergence unstable. We can see jet velocity after secondary convergence is 9820m/s, compare with initial jet’s 4109m/s, it’s a 139 percent increase. Jet will be greatly accelerated during the secondary convergence.
Figure 5. Pressure contours.

Figure 6. Velocity distribution of jet before and after secondary convergence

The X-velocity of each gauges are shown in figure 7. From the pictures we can see, jet velocity can reach more than 1000m/s during secondary convergence. After a short period of time, jet velocity begins to go down until it gradually stabilized. At the time of 34μs, jet starts to penetrate the water and its velocity is 7927m/s. After that, jet move forward against the resistance of water and its velocity slowly decrease. Through calculation, we can get that jet velocity decreases sharply at the beginning of penetration, and then the velocity loss gradually decreases.

Figure 7. X-velocity of each gauges
4. Conclusions
Through numerical simulation, the jet formation by focusing annular liner was studied. The conclusions are drawn as follows:
(1) The charge with a focusing annular liner can form a jet underwater, but it is quicker than normal jet formation. And the jet is thicker than normal jet;
(2) The pressure during jet secondary convergence is much higher than the first jet convergence, it can reach 109.8Gpa. This huge pressure can make jet velocity higher, but may also make the jet convergence unstable;
(3) Secondary convergence can greatly accelerate the jet velocity. Under this charge structure, jet velocity can reach more than 10000m/s, it’s twice of the speed of initial annular jet. And it’s stabilized at the speed about 7900m/s.

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