Study on jet forming characteristics of shaped charge with truncated-liner structure

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Abstract. In order to verify the jet forming characteristics of the shaped charge with a truncated-liner, numerical simulation and X-ray experimental research were carried out. The behavior of the truncated-liner and the top velocity, diameter and morphology of the jet were obtained, and the outcomes were compared with the characteristics of the jet formed by the traditional shaped charge. The results show that the numerical simulations are almost consistent with the results obtained by the X-ray test. The morphology of the two is nearly the same, and the data deviation is less than 6%. The truncated-liner can effectively improve the velocity of the jet head, which can reach more than 10km/s by structural optimization. In addition, the truncated-liner can decrease the diameter of the slug, meanwhile, increase the length of the jet and the quality utilization of the liner.

1. Introduction

The traditional shaped charge generally has the disadvantage of the low-quality utilization rate of the liner. Most of the material of the liner forms a slug with a lower penetration ability. The damage capability of the jet to the target, that is, the aperture diameter and penetration depth, is limited. Besides, the remaining destruction ability of the jet after penetrating the target may be insufficient. In order to improve the penetration power of the shaped-charge jet, that is, to increase the penetration depth and the pore diameter, the speed and diameter of the shaped-charge jet must be enhanced. In order to both improve the velocity and mass of the shaped-charge jet head, it is necessary to make the collapsed angle of the liner equal to or greater than 180° [1].

Therefore, an additional external impulse must be applied to the liner to increase its axial movement speed. It can not only make the collapsed angle of the liner equal to or greater than 180° but also increase the speed of the jet head. Russian researcher VF Minin [1] first proposed the concept of hyper-cumulation shaped charge and verified it by numerical simulations. The results show that this hyper-cumulation method can both increase the velocity and the quality of the jet, and this new effect can be effectively applied to petroleum perforating bombs. Later, VF Minin [2] and IV Minin [3] conducted in-depth research on hyper-cumulation using numerical simulations and found that in a given structure, the jet velocity increased by 25-30%. Domestic scholar Wang Yilong [4] carried out numerical simulation research based on a variety of hyper-cumulation shaped charges reported abroad and optimized the structure of the truncated-liner with the additional body, which showed that it has obvious advantages in speed and kinetic energy. Xu Wenlong [5] used a combination of experiments and numerical simulations to explore the penetrating properties of hyper-cumulation shaped charges.
with 5 different materials as additional bodies, and compared results with a traditional shaped charge. Xu Mengwen [6] used AUTODYN-2D software to study the effects of the material, the thickness and the diameter of the additional body on the speed when the cone angle of the truncated-liner was different and concluded that the truncated charge structure is more suitable for the tradition of large cone angle, and concluded that the hyper-cumulation shaped charges with truncated-liner is more suitable for improving the traditional charge with large cone angle.

Domestic scholars have also done some theoretical work on the hyper-cumulation shaped charge. Xu Wenlong [7] proposed a theoretical calculation method for the formation of hyper-cumulation jets. and provided the relationship among the additional body (material density and thickness), truncated-liner (cone angle, density, and thickness) and the hyper-cumulation jet (velocity and mass. Xu Mengwen [8] proposed a theoretical model for calculating the velocity and mass of the hyper-cumulation jet, revealing the relationship between the characteristics of the jet and the structural as well as the material properties of the additional body.

In this paper, we take the shaped charge with truncated-liner as the research object and combine numerical simulation and X-ray experimental to carry out research on the characteristics of the jet formation process. By comparing the forming process of the jet with the traditional shaped charge, the forming rule of the truncated-liner is verified, which provides technical support for the subsequent optimization of the hyper-cumulation shaped charge.

2. Numerical simulation analysis of forming characteristics
ANSYS AUTODYN finite element software was used to establish a simulation calculation model. By changing whether or not there is a the truncated-liner is used in the shaped charge, the forming characteristics of the jet are numerically simulated and analyzed.

2.1. Numerical simulation model

2.1.1. Traditional shaped charge structure. The traditional shaped charge structure with a diameter of \( \phi 88 \text{mm} \) is used, which consists of a cone liner and a cylindrical explosive with a cone cavity. The liner is made of Oxygen-Free High-Conductivity Copper (OFHC Copper and adopts a single-cone variable wall thickness structure. The explosive material is JH-2 explosive. The specific model is shown in figure 1.

![Figure 1. The simulation model of the traditional shaped charge.](image)

2.1.2. Shaped charge structure with truncated-liner. Based on the traditional shaped charge, a structure with a truncated-liner with a diameter of \( \phi 88 \text{mm} \) is used, which is composed of a truncated-liner, a cylindrical explosive with a cone cavity and an additional body. The material of the liner and the explosive is the same as the material used in the traditional one, and the liner is truncated on the basis of the original structure with a diameter of \( \phi 20 \text{mm} \). Tungsten alloy is used as the material of an additional body with a diameter of \( \phi 44 \text{mm} \) and a thickness of 11mm. The specific model is shown in figure 2.
Figure 2. Simulation model of a hyper-cumulation shaped charge with truncated-liner.

2.2. Material model and specific parameters

The purpose of this model is to calculate the collapse characteristics of the liner driven by detonation products. In order to facilitate analysis, the Euler calculation method is used for numerical simulation. Johnson-Cook constitutive model and Shock equation of state are used for both the liner and the additional body. Explosive is described by the JWL equation of state, and the air is described by the Ideal Gas equation of state. The selected explosive materials and parameters of the equation of state are shown in table 1:

| Material | Density (g/cm$^3$) | C-J Detonation velocity D(km/s) | C-J Pressure $P_{CJ}$(GPa) | A (GPa) | B (GPa) | R1 | R2 | $\omega$ | C-J Energy $E_0$(J/mm$^3$) |
|----------|---------------------|-------------------------------|-----------------------------|---------|---------|-----|-----|--------|-----------------------------|
| JH-2     | 1.717               | 8.35                          | 29.66                       | 618.4   | 6.9     | 4.3 | 0.87| 0.38   | 8.5                         |

2.3. Simulation results and analysis

2.3.1. Traditional Shaped charge. According to the numerical simulation calculations, it can be known that the jet is completely formed at 50us, the head speed of the jet is 6830m/s, and the shape is good. However, the diameter of the slug is large, and the quality utilization rate of the liner is low.

Figure 3. Pressure cloud diagram of the shaped charge at 5us and 10us.
Figure 4. Cloud diagram of jet velocity at 20us and 50us.

2.3.2. Shaped charge structure with truncated-liner. The simulation results are shown in figure 5 and figure 6. According to the simulation results, when using the truncated-liner (with the additional body which has the diameter of $\phi$44mm and the thickness of 11mm), the jet velocity increased significantly, the head velocity reached 9497m/s, the gradient of jet velocity is also increased. Meanwhile, the utilization rate of the liner material improved.

Figure 5. Pressure cloud diagram of the shaped charge at 5us and 10us.

Figure 6. Cloud diagram of jet velocity at 20us and 50us.

3. Experimental Research on Forming Characteristics

In order to obtain the jet-forming characteristics of the shaped charge, tests were conducted on the jet-forming characteristics of the traditional shaped charge and the one with a truncated-liner. By adjusting the light-emitting time of the pulse X-ray machine to obtain the jet shape at different times and used to calculate the speed of the jet head. The results of the shaped charge with the two types of structure are compared to obtain the rule of the shaped charge with a truncated-liner forming the jet.
3.1. Test method

In the experiment, two pulsed X-ray tubes were arranged at an angle of 45°, and the shaped charge was arranged in a vertical manner to ensure that the axes passing through the two X-ray tubes meet after the jet forming. By setting the time for two pulsed X-ray tubes to emit x-rays, one experiment can obtain two X-ray photos at different times. In order to accurately measure the head velocity of the jet, the initiation synchronization setting and reference mark setting need to be performed in the experiment. For the traditional shaped charge, the velocity of the jet head is about 7 km/s according to simulation. For a shaped charge with a truncated-liner, the average velocity of the jet head is about 10 km/s according to simulation. The time when the detonation wave is transmitted to the end of the liner is set as time 0, at this time, the head of the jet is about to reach the end of the liner. In order to observe the shape of the jet formed by the shaped charge, the projectile is placed at a height of 6 cm from the end of the liner to be in the X-ray field of view, and the X-ray photos of the formed jet are taken at 10 μs and 20 μs.

Figure 7. Schematic layout of the X-ray test.

Figure 8. X-ray test site layout.

Figure 7 is a schematic layout of the X-ray test. The aluminum protective shell of the X-ray film is affixed with two upper and lower marking lines. In the test, two X-ray photos at different times were taken for each shaped charge, respectively as t₁ and t₂. According to the position difference (Δ h) of the head and the tail of the jet at different times, the time difference of shooting (Δ t = t₁ - t₂), and the magnification factor of k, the velocity, and diameter of the head and tail of the jet are obtained. The magnification factor k is determined by the relative positions of the X-ray tube, the shaped charge, and the film. As can be seen from figure 7, k_A = AA'/AO and k_B = BB'/BO. In the field test, the trigger line of the X-ray is set at the end of the liner, that is, when the detonation wave propagates to the end of the liner, the X-ray is emitted at the set time interval.
3.2. Test objects

3.2.1. Traditional Shaped charge. The traditional shaped charge is mainly composed of an explosive propellant, a column-shaped explosive and a liner. The material of the liner is OFHC Copper and has a single cone with a variable wall thickness, which is consistent with the simulation model. The explosive is pressed by JH-2 explosive with a density of 1.717 g/cm$^3$. The explosive propellant is JH-14. The structure and dimensions (mm) are shown in figure 9.

![Figure 9](image-url)  
Figure 9. The structure of the traditional shaped charge.

3.2.2. Shaped charge structure with truncated-liner. The structure of the shaped charge with truncated-liner is more complex than the traditional one. It is mainly composed of explosive propellant, explosive 1, explosive 2, truncated-liner, and additional body. The material of the truncated-liner is OFHC Copper, the truncated diameter is $\phi 20$mm. It is consistent with the simulation model. Because of the additional body in the structure, the explosive needs to be pressed in two parts (explosive 1 and explosive 2) and both are JH-2 explosives with a density of 1.717 g/cm$^3$. JH-14 explosive is used for the explosive propellant. The material of the additional body is tungsten alloy, the size is about $\phi 44$mm $\times$ 11mm, and the density is 17.0g/cm$^3$. The truncated-liner structure and dimensions (mm) are shown in figure 10, and the actual object of the shaped charge with the truncated-liner is shown in figure 11.

![Figure 10](image-url)  
Figure 10. The structure of the shaped charge with truncated-liner.
3.3. Experimental results
In the test, the X-ray device emits X-rays at the B port and then emits rays at the A port.

Table 2. The results of the tests.

| The type of the shaped charge | $H$ (cm) | $t_B$ (us) | $t_A$ (us) | $\Delta t$ (us) | $BB'$ (cm) | $BO$ (cm) | $AA'$ (cm) | $AO$ (cm) | $k_B$ | $k_A$ |
|-------------------------------|----------|------------|------------|-----------------|------------|----------|------------|----------|-------|-------|
| Traditional                   | 127      | 10         | 20         | 10              | 276        | 142      | 284        | 135      | 1.9437| 2.1037|
| With truncated-liner          | 127.5    | 10         | 15         | 5               | 279        | 141      | 282        | 135      | 1.9787| 2.0889|

3.3.1. Traditional Shaped charge. The X-ray picture of the traditional shaped charge is shown in figure 12. The shooting times were 10us and 20us, respectively. It can be obtained through numerical simulation that the time required for the detonation wave to propagate to the end of the liner is about 20us. Therefore, the time when the X-ray picture is taken corresponds to 30us and 40us in the simulation (the time when the explosive detonates is set to be 0 in the simulation), as shown in figure 13. The size marked in the X-ray picture is enlarged by the scale factor $k$, and the size in the simulation picture is actual.

Figure 11. The actual object of the shaped charge.

Figure 12. The X-ray photos of the traditional shaped charge.
The diameter of the jet in the X-ray picture is larger, and umbrella-shaped jet particles are scattered on the head. According to table 2 for ratio conversion, the jet head diameter is 4.03 mm and 3.55 mm at 10us and 20us, respectively. The liner material is accumulated on the head of the jet. The maximum diameter of the head is 5.67 mm at 20us. At 10us, the maximum diameter of the slug is 20.09 mm, and at 20us, it’s 17.25 mm. A necking occurred between the slug and the jet, and the diameter of this part is 15.53 mm. By comparing X-ray photos and numerical simulation results, it can be seen that the jet shapes of the two are similar, and the sizes are basically the same.

The speed of the jet head in the X-ray test is:

\[
V_j = \left( Z_{1a} - Z_{1b} \right) / \left( k_a - k_b \right) / \Delta t = \left( 283.07 - 120.11 \right) / \left( 2.1037 - 1.9437 \right) / 10 = 7.276 m / \mu s = 7276 m / s
\]  

(1)

In the simulation at 40us, the maximum velocity of the jet head is 6851 m/s, which is smaller than the jet velocity obtained by the test, and the deviation is about 5.8%.

3.3.2. Shaped charge structure with truncated-liner. The X-ray picture structure of the shaped charge with truncated-liner is shown in figure 14. The time interval between the two X-ray tubes emitting X-rays is \( \Delta t = 5 \) us. At 10us, there are a few jet particles scattered, the diameter of the jet formed is relatively thin, and the diameter of the jet head is only 2.65 mm. At 15us, the head of the jet becomes more slender, and the length with a diameter less than 2 mm is 37.23 mm. At 10us, the maximum diameter of the slug is 15.25 mm, and at 15us, it’s about 16.76 mm. The jet head speed is:

\[
V_j = \left( Z_{1a} - Z_{1b} \right) / \left( k_a - k_b \right) / \Delta t = \left( 274.46 - 155.28 \right) / \left( 2.0889 - 1.9787 \right) / 5 = 10.583 m / \mu s = 10583 m / s
\]  

(2)

The moments in the simulation corresponding to the experimental photos were 30us and 35us, as shown in figure 15. It can be found that the simulated jet shape is basically consistent with the actual jet shape, especially at 35us, the length of the jet with a jet diameter less than 2 mm in the simulation is almost equal to the length in the X-ray picture. In the simulation, the jet head speed is 10040 m / s. The speed obtained by the X-ray test is higher than the simulation, and the deviation is about 5.4%.
The comparison results are summarized in Table 3.

Table 3. The summarization of the results.

| The type of shaped charge | Moment (μs) | The experiment results | The simulation results |
|---------------------------|------------|------------------------|------------------------|
|                           |            | D_{j(head)} (mm) | D_{s-max} (mm) | L_{j} (mm) | V_{j} (m/s) | D_{j(head)} (mm) | D_{s-max} (mm) | L_{j} (mm) | V_{j} (m/s) |
| Traditional               | 10         | 4.03                  | 20.09             | 60.48      | 7276       | 5.00             | 20.50         | 67.3        | 6851        |
|                           | 20         | 3.55                  | 17.25             | 119.45     |            | 5.00             | 18.00         | 112.54      |             |
| With truncated-liner      | 10         | 2.65                  | 15.25             | 77.64      |            | <1mm             | 20.5          | 116.58      | 10040       |
|                           | 15         | <1mm                  | 16.76             | 122.92     | 10583      | <1mm             | 20.5          | 152.38      |             |

4. Conclusion
This paper mainly studies the jet forming characteristics of the shaped charge with a truncated-liner. By comparing with the results of jet formation with the traditional shaped charge, the following conclusions are obtained:

1) In the numerical simulation, the results of the jet formation with the traditional shaped charge and the shaped charge with truncated-liner are basically consistent with the results obtained by the X-ray photos.
ray test, and the shapes are basically the same.

2) Research shows that on the basis of the traditional shaped charge, adding an additional body after cutting off the top of the liner can make it have enough acceleration space during the initial crushing process, and collapse at a higher speed on the axis. The additional body can provide an additional impulse for the collapse of the liner, increase the axial speed, and improve the quality utilization rate of the liner. Make sure that the material of the liner has a high motion pressure when it collides on the symmetry axis. When the detonation product returns when it encounters an obstacle, the collapse angle of the liner material will change to become equal to or greater than 180°, forming a thinner slug.

3) The structure of the truncated-liner matched with the additional body can effectively increase the head speed of the jet. After optimization, the velocity of the jet head can reach 10000m/s or more. The structure can also reduce the diameter of the slug while increasing the jet length.

4) This verification is mainly aimed at whether the hyper-cumulation effect can be generated under the truncated-liner matched with the additional body, and the mass of the jet formed by it is not fully optimized. At present, the diameter of the jet formed by this structure is relatively small. Next, an in-depth structural optimization and matching design should be carried out. In order to increase the jet velocity, the diameter of the jet can be increased too, so that the damage capability of the jet can be enhanced.

Acknowledgments
This work was supported in part by the Jiangsu Province Graduate Research and Practice Innovation Program (No.KY CX18_0470) and the China Scholarship Council (201906840011).

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