Numerical study on the matching law between charge caliber and delay time of the rod-shaped explosively formed projectile

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Abstract. To study the application of multi-point initiation technology on shaped charge warhead, numerically simulated the influence of initiating delay time of different charge caliber on detonation wave and performance forming of penetrator. The study found that as charge caliber increased, the allowable initiating delay time also increased. For the commonly used small and medium-charge caliber shaped charge warhead, the charge caliber \(D_k\) and the delay time \(\sigma\) presented a linear relationship \(\sigma = -12.79 + 1.25D_k\). As charge caliber continue increasing, the initiating allowable delay time started to increase exponentially. The study reveals the matching law between charge caliber, initiating delay time and performance forming of penetrator, and it offers guidance for the design of multi-point initiation network for shaped charge.

1 Introduction
Multi-point initiation technology, which can significantly improve the power of warhead, has been widely used in shaped charge warhead or fragment warhead [1-6]. With delay time as its key factor, multipoint initiation network is the most direct and effective method to achieve multi-point initiation. Therefore, many scholars have researched into this field [7-10]. Previous works on the design of the initiation network are generally goal-oriented, aiming at designing an initiation network for specific charge caliber. However, with the shaped charge warhead being widely used in the modern battlefield, charge caliber varies to meet different demand. Thus it is time-consuming and energy-consuming to redesign the multi-point initiation network every time the charge caliber of the warhead changes. Therefore, it is of great value to find a universal design formula for multi-point initiation network.

The key to multi-point initiation network design is the matching law of charge caliber, initiation points and initiating delay time. Designing an initiation network for warhead, firstly is to determine the diameter of the initiation network that corresponds with the charge caliber of the warhead. Then, the number of initiating points of multi-point initiation replacing annulus initiation is decided according to the diameter of the initiation network. The last step is to determine the allowable initiating delay time that meets the requirements of projectile formation. B.Bourne and W.B Li had researched into the rule of multi-point initiation replacing annulus initiation under different charge caliber [11-12]. They studied the relationship between charge caliber and initiation points, and concluded that for cylindrical charge structure, four or eight initiating points could replace annulus initiation.

This paper studies the relation of charge caliber and initiating delay time of cylindrical shaped charge, and provides reference for the research and design of multi-point initiation network.
2 Numerical simulation and result analysis

2.1 Numerical Model
In order to study the influence of different charge caliber and initiating delay time on the interaction process of detonation wave in the main charge as well as on the projectile parameters, finite element code LS-DYNA-3D [13] was used to simulate the forming process of Rod-Shaped EFP by multi-point initiation. The charge was cylindrical, with arc-cone combination liner, cone Angle $\alpha = 145^\circ$, arc Radius $R = 45\text{mm}$, Charge Height $H = 0.9D_k$ ($D_k$ for the charge caliber). Initiation points were evenly distributed at the largest radius of the charge end face. Therefore, initiating diameter was the same as the charge caliber. It can be known from W.B Li et al.[8] that when delay time occurs at multi-point initiation network, if the delayed initiation points are all on one side and larger in number, it will generate greater impact on the formation of the projectile, and in particular, on lateral displacement. In order to ensure the reliability of engineering application of this paper, the following research adopted the initiating deviation method that positioned the delay points all on one side and that had the most delay points.

Charge structure and finite element model is shown in figure 1. The forming process of shaped charge was a large deformation elastoplasticity fluid dynamics problem, So the ALE algorithm was used to deal with the problem involving large deformation of grid and material flow. ALE algorithm was used to deal with explosives, liner and the air, while Lagrange algorithm was used to deal with the shell. Algorithm of fluid-solid interaction was used to cope with the interaction between them, and for multi-material ALE method, air grid covering the entire projectile flying process must be established. In order to avoid the pressure reflection in the air boundary, setting the pressure outflow boundary conditions on the boundary nodes. The material parameters, material models and equation of state of the numerical simulation are shown in table 1 [13].

![Figure 1. Charge structure and finite element model.](image)

### Table 1. Material parameters.

| Name     | Material  | Density ($\text{kg/m}^3$) | Material Model       |
|----------|-----------|---------------------------|----------------------|
| Liner    | Copper    | 8960                      | JOHNSON_COOK         |
| Explosive| 8701      | 1713                      | HIGH_EXPLOSIVE_BURN  |
| Shell    | Steel 45# | 7830                      | JOHNSON_COOK         |
| Air      | /         | 2.93                      | NULL                 |

2.2 Project Design and Result Analysis
Focusing on the finite element model, simulated the formation of projectiles under different charge caliber and initiating delay time. Charge caliber $D_k = 50, 100, 200, 300, 500$ and $1000\text{mm}$. While initiating
delay time $\sigma = 50, 100, 200$ and 500ns. The conditions of projectile formation are shown in table 2. In order to facilitate comparison, choose the projectiles at the height of burst that 3.6-time charge caliber ($3.6D_k$) of each project representative for comparison and due to limited space, only a few selected numerical simulation results are listed in table 2.

Table 2. The penetrator shaped.

| $D_k$ | $\sigma$ | 50ns | 100ns | 200ns | 500ns |
|-------|---------|------|-------|-------|-------|
| 50mm  | 50ns    | ![image](image1.png) | ![image](image2.png) | ![image](image3.png) | ![image](image4.png) |
| 100mm | 100ns   | ![image](image5.png) | ![image](image6.png) | ![image](image7.png) | ![image](image8.png) |
| 200mm | 200ns   | ![image](image9.png) | ![image](image10.png) | ![image](image11.png) | ![image](image12.png) |
| 500mm | 500ns   | ![image](image13.png) | ![image](image14.png) | ![image](image15.png) | ![image](image16.png) |

It was shown in table 2 that when the delay time increased, the shape of projectile gradually bends. In the case of charge caliber 50 mm, when the delay time was within 100ns, the projectile shaping (lateral displacement, head speed $v$, length to diameter ratio $L/D$) was good. When the delay time was larger than 100ns, the projectile began to bend. In particular, when the delay time reached 500ns, heavy bending occurred to the projectile, and the flight stability and penetration capability decreased greatly. If the delay time was same, it had a greater impact on the projectile shape of small-caliber charges than the larger ones. For example, when the delay time was kept at 500ns, to 50mm charge caliber, the projectile was completely deformed, even no longer remaining the shape of a solid and dense rod; when the charge caliber was 100 mm or 200 mm, projectile did kept the shape but had certain degree of bending deformation; however, when the charge caliber increased to 500 mm, the projectile shape formed well and bending deformation was practically unnoticeable.

The influence of multi-point initiation on projectile formation was mainly manifested by its control over detonation wave of the main charge. Initiating delay time caused the asymmetric structure of detonation wave of the main charge, as is shown in table 3. Then the asymmetry detonation wave transmitted as a detonation velocity in the main charge. If the charge caliber was small, the asymmetrical detonation wave was directly applied to the liner immediately after it was formed or shortly after its propagation, the liner collapsed by asymmetry detonation wave caused bending deformation of the projectile. But when the charge height increased as the charge caliber increased, it took a period of time for the asymmetry detonation wave to propagate in explosive before it was applied to the liner. Although the steel shell had suppressed scatter of explosive in the process of propagation, there was still lateral rarefaction wave transmitted into the explosive, which resulted in the decrease of pressure and speed of detonation wave front, it means the detonation wave front which initiating by the delayed initiation points gradually caught up with wave front which initiating by the un-delayed initiation points, so the waveform deviation continuously decreased, the detonation wave tended to be symmetrical, as the liner being collapsed by the symmetry detonation wave, the lateral displacement was
small, and bending deformation decreased, therefore the initiating delay time had a greater impact on the projectile shape of small-caliber charges than the larger ones. Meanwhile, known from the similarity theory and dimensionless analysis, the waveform deviation in the axial location for smaller charge caliber was more obvious than for larger charge caliber.

Table 3. The detonation wave.

| $D_k$ | 50ns | 100ns | 200ns | 500ns |
|-------|------|-------|-------|-------|
| 50mm  | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) |
| 100mm | ![Image](image5.png) | ![Image](image6.png) | ![Image](image7.png) | ![Image](image8.png) |
| 200mm | ![Image](image9.png) | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |
| 500mm | ![Image](image13.png) | ![Image](image14.png) | ![Image](image15.png) | ![Image](image16.png) |

2.3 Relation between Charge Caliber and Delay Time

The influence of delay time on projectile formation was mainly manifested by the lateral displacement of the projectile [8]. The relation curve of lateral displacement ($\Delta X$) of projectile with different charge caliber and delay time ($\sigma$) obtained from table 2 is presented in figure 2, from which we can see that as the delay time increased, lateral displacement of the projectile also increased. However, even with the same delay time, lateral displacement still changed under different charge caliber. For example, when the charge caliber was 50mm, the delay time was 500ns, the lateral displacement of projectile was 15.8mm, and the percentage of the lateral displacement was 63.2% relative to the charge radius ($2\Delta X/D_k$). But when the charge caliber was 500mm, lateral displacement of the projectile was only 5.5mm, and relative displacement was 2.2%. If the delay time of multi-point initiation network was 500ns, it was obviously too large for 50mm-caliber charge, but it met the requirements of the projectile formation of 500mm caliber charge. In order to find suitable delay time that can match different charge caliber for the shaped charge, the ratio of lateral displacement to charge radius ($2\Delta X/D_k$) can be taken as a standard to measure the lateral displacement of the projectile. If the ratio is larger than 5%, the displacement is too big to meet the requirement of projectile formation. On the contrary, if the ratio is less than 5%, it meets the requirements of projectile formation. Specific data of the ratio of lateral displacement to charge radius ($2\Delta X/D_k$) under different charge diameter and delay time are shown in table 4.
Figure 2. Across displacements of penetrator changes with initiation deviation

Table 4. The ratio of across displacement and charge radius ($2\Delta X/D_k$) under different charge caliber and initiation deviation.

| $D_k$    | 0ns  | 50ns | 100ns | 200ns | 300ns | 500ns | 1000ns | 4000ns |
|----------|------|------|-------|-------|-------|-------|--------|--------|
| 50mm     | 0    | 4.8% | 14%   | 24.4% | 34.4% | 63.2% | \     | \      |
| 100mm    | 0    | 2%   | 3.8%  | 9.8%  | 14.5% | 30.1% | 61.7%  | \      |
| 200mm    | 0    | 0.5% | 1.5%  | 4.1%  | 6.6%  | 12.7% | 26.9%  | \      |
| 300mm    | 0    | 0.3% | 1.0%  | 2.7%  | 3.6%  | 6.4%  | 15.1%  | \      |
| 500mm    | 0    | 0    | 0     | 0     | 1%    | 2.2%  | 5.4%   | 22.2%  |
| 1000mm   | 0    | 0    | 0     | 0     | 0     | 0     | 0      | ≈5%    |

To deal with the data in table 4, it was necessary to find the relation curve between delay time and $(2\Delta X/D_k)$ by fitting the data points. As was shown in figure 3(a-e), the delay time ($\sigma$) had a linear relation with the ratio of the lateral displacement to charge radius $(2\Delta X/D_k)$ under the condition of the same charge caliber. And the delay time that met the ratio of the lateral displacement to charge radius $(2\Delta X/D_k)$ of less than 5% under different charge caliber were respectively 44.3ns, 107.6ns, 221.3ns, 375.4ns, 966.7ns, and ≈4000ns. By plotting the data of delay time with $2\Delta X/D_k$ of less than 5% corresponding with different charge caliber obtained from figure 3, and by carrying on data fitting processing, the relation between charge caliber and delay time was obtained, as is shown in figure 4. As the charge caliber increased, the allowable delay time maximum values also increased. The delay time increased smoothly when charge caliber was less than 300mm, and when it was larger than 300mm, delay time raised quickly. This was because when charge caliber increased, the charge height increased too. Then the travel-time of the detonation wave in the main charge got longer, and when the charge height exceeded certain value, detonation wave would have the tendency of becoming plane wave eventually, so after the charge caliber increased, the influence of delay time on projectile formation showed a trend of decrease.
After analyzing the data points in the figure, found that when charge caliber $D_k \leq 300\text{mm}$, charge caliber and delay time formed a linear relation. Abscissa represents the charge caliber, and ordinate represents the allowable delay time, fitted the curve showed in figure 4, the researcher obtained a relation equation between charge diameter and delay time:

\[
\sigma = -12.79 + 1.25 D_k (0 < D_k \leq 300\text{mm}) \quad (1)
\]

\[
\sigma = -481.31 + 460.7 e^{D_k/439.46} (D_k \geq 300\text{mm}) \quad (2)
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Figure 3. The relationship between deviation $\sigma$ and $2\Delta X/CD$ under different charge caliber.

3 Conclusion

Used LS-DYNA 3D finite element code to numerical simulate the Rod-shaped EFP formation process and based on detonation waveform theory to analysis the influence law of projectile formability under different charge calibers and different initiating delay times, can draw some conclusion:

1. When charge caliber increased, allowable initiating delay time also increased. And charge caliber $D_k \leq 300\text{mm}$, charge diameter and delay time had a linear relationship; charge diameter $D_k > 300\text{mm}$, the allowable delay time increased exponentially. In engineering applications, small and medium caliber...
shaped charge warhead use multi-point initiation network need small initiating delay time to guarantee projectile formability. For large charge caliber shaped charge warhead, the accuracy of initiating delay time of the initiation network may be loosened up appropriately.

2. The formula of this study, combined with the conclusion of four or eight-point initiation replacing annulus initiation [8-9] can be used as the reference or guideline for the design of multi-point initiation network.

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