Effects of Detonation Waves Asymmetric Collision

Tao Fang*, Xiangyu Li*

College of Science and Arts, National University of Defense Technology, Changsha, China

*Corresponding author e-mail: tomsonfang@163.com, *770205042@qq.com

Abstract. In this article, Effects of detonation waves asymmetric collision was studied. Through theoretical calculation, the position of detonation waves collision was shown. And it is found by numerical simulation that the pressure of detonation waves interaction decreases wave-likely following the initiation delay time increasing, but still exceed the pressure of the place where there is no interaction of detonation waves. The pressure-enhancing effects of detonation wave interaction can be used to achieve the energy accumulation.

1. Introduction

Since the discovery of detonation in explosives, the propagation and interaction of detonation waves in explosives have been the focus of scholars in related fields. In the article of Miu Yusong [1], the detonation wave normal collision, oblique collision and Mach reflection is analyzed. And the process of detonation wave head-on interaction was experimentally studied by Botors [2] et al. The pressure of the interaction zone will increase exponentially after the collision of detonation waves. By utilizing the collision effect of detonation waves, directional energy convergence can be generated to achieve the energy accumulation effect. The fragmentation behavior of metal liner under the superposition of detonation wave, and analyzed the influence of the number of initiation points were studied by Yu Qingbo [3] et al. Shen Huiming et al. The effect of convergent detonation waves on the penetration capability gain of EFP by using finite element program was analyzed by Shen Huiming [4] et al. W. Anold [5] proposed a new mode-adjustable warhead technology based on detonation wave superposition effect. Studied the fragmentation mechanism of metal disc under the interaction of detonation wave, and analyzed the influence of explosive parameters on the fragmentation of liner under multi-point initiation were studied by Zhang Kefan [6, 7] et al.

Although there have been some studies on the collision process and effect of detonation wave interaction, most of them are based on the symmetric collision. The study on the asymmetric collision of detonation wave with initiation delay time has not been reported. It is usually difficult to achieve strict simultaneous initiation of two or more points in practical operation, so it is necessary to study the asymmetric impact of detonation wave.

2. Physical Model

When multi-point detonation network is used to achieve the goal of multi-point synchronous detonation, there will be a delay between secondary detonation points due to the difference of charge density, and the detonation wave after multi-point detonation is no longer symmetrical collision. To facilitate analysis, a simplified physical model is established. As shown in Fig.1, O1 and O2 are two...
initiation points, and $l$ is the separate distance of them. After detonation, the detonation wave propagates along the path $O_1 M$ and $O_2 M$ and collides at point $M$. The angles between $O_1 M$ and $O_2 M$ and explosive-witness target interface are $\theta$ and $\phi$. $O_1$ was detonated earlier than $O_2$, and the time interval is $\Delta t$ and the detonation velocity of explosive is $v$.

![Diagram](image1)

**Figure 1.** Detonation waves asymmetric collision.

In order to facilitate analysis, the detonation process of explosive is not considered, and it is considered that the explosive will enter a stable detonation stage immediately after initiation. According to the geometric relationship,

$$|O_1 M| - |O_2 M| = v \Delta t$$  \hspace{1cm} (1)

If the plane rectangular coordinate system is established with $O_2$ as the origin and $O_2 O_1$ as the x-axis, the coordinates of $O_1$ and $O_2$ are $(0,0)$ and $(l,0)$, as shown in Fig.1. If the coordinates of point $M$ are $(x,y)$, then

$$\sqrt{x^2 + y^2} - \sqrt{(l-x)^2 + y^2} = v \Delta t$$  \hspace{1cm} (2)

To solve it, we get

$$x = \frac{l}{2} \pm \frac{v \Delta t}{2} \sqrt{1 + \frac{4y^2}{l^2 - (v \Delta t)^2}}$$  \hspace{1cm} (3)

According to the geometric relationship,

$$\theta = \arctan \frac{y}{x} = \arctan \frac{2y}{\pm v \Delta t \sqrt{1 + \frac{4y^2}{l^2 - (v \Delta t)^2}}}$$  \hspace{1cm} (4)

$$\phi = \arctan \frac{y}{l-x} = \arctan \frac{2y}{v \Delta t \sqrt{1 + \frac{4y^2}{(l-x)^2}}}$$  \hspace{1cm} (5)

So we get the collision point position, and in order to ensure that it is between the initiation points, the coordinates of point $M$ should satisfy the following condition,

$$x < l$$  \hspace{1cm} (6)
3. Numerical simulation

3.1. Finite element model
In order to analyze the enhancement effect of detonation wave asymmetric collision, the finite element program ANSYS/AUTODYN was used to simulate the force acting on the witness target of different initiation delay time. The two-dimensional symmetric finite element model is shown in Fig.2. The picture includes three parts: air, explosive and witness target. Explosives and air were analyzed in multi-material Euler algorithm. The air area is 120 mm long and 60 mm high. It is divided into 125,000 elements. And the length of TNT explosives is 100 mm and height is 30 mm. The material of witness target is 1006 steel, using Lagrange algorithm, of which the length is 100 mm, and the width is 3 mm. Main material parameters are shown in Table 1 and Table 2.

![Figure 2. Finite element model.](image)

Two initiation points $O_1$ and $O_2$ are set on the upper end face of the charge, with an interval of 30 mm. A series of observation points are set on the witness target to record the pressure on different locations of the witness target.

| Table 1. Main parameters of TNT. |
|----------------------------------|
| Material | $\rho$ g·cm⁻³ | $A$/GPa | $B$/GPa | $R_1$ | $R_2$ | $\omega$ |
| TNT      | 1.63            | 371     | 3.23     | 4.15  | 0.95  | 0.3      |

| Table 2. Main parameters of 1006 Steel. |
|----------------------------------------|
| Material     | $\rho$ g·cm⁻³ | c/km·s⁻¹ | $S_1$ | $S_2$ | $S_3$ | $\gamma_0$ |
| 1006 Steel   | 2.73            | 3.08     | 1.34  | 0     | 0     | 1.97      |

3.2. Analysis of pressure on the witness target
Fig.3 shows the axial distribution of the pressure on the witness target when the initiation delay is 0 µs and 1 µs. When the initiation delay is 0 µs, that is, when the two initiation points are synchronized, the pressure distribution of the target is symmetrical. In the area where without detonation wave superimposition occurs, the pressure on the witness target is smaller, about 29 GPa. The detonation wave below the initiation point is normal incidence, and the other positions are obliquely incident at a certain angle. However, due to the small incident angle, the pressure at different locations of the target is basically the same. After the detonation wave collides on the central symmetry line of the initiation point, it is incident on the witness target. And the pressure on the witness target is about 54.3 GPa. Thus, the superposition of detonation wave can increase the detonation pressure in the superposition area by several times.

When one of the initiation points is delayed by 1 µs, the force distribution of the witness target is no longer symmetrical, and the area of pressure rise shifts towards the delayed initiation point with an offset of 8 mm, which is consistent with the theoretical calculation value. At this time, the superimposed detonation wave is no longer normal incident on the witness target, but obliquely...
incident on the witness target at a certain angle, the incident angle is 12 degrees, and the incident pressure is 54.6 GPa. Thus, although the detonation delay changes the position of detonation superposition and the angle of incident to the witness target, the difference of incident pressure is not significant. The pressure at the position where the detonation wave is not superimposed on the target is still the same as that when the detonation wave collides symmetrically.

![Figure 3. The axial distribution of the pressure on the witness target.](image)

From the above analysis, it is known that the initiation delay changes the impact angle of detonation wave and the incident angle at the explosive-witness target interface, so the initial pressure of the shock wave incident on the witness target varies with the delay time. For a detonation wave without collision superposition, the delay time does not change its incident angle, so it has no effect on its incident pressure.

### 3.3. Effects of detonation delay time

From the analysis in Section 3.2, it can be seen that the detonation delay time only affects the incident pressure of the superimposed detonation wave, but does not affect the reflection and incidence of the non-superimposed detonation wave at the explosive-witness target interface. Therefore, in this section, the effects of detonation delay time on different charge thickness and detonation spacing is specifically analyzed for the max pressure on the target after detonation wave superposition.

The effects of delay time on the pressure and position of detonation wave after impact is shown in Fig.4, when the detonation distance is 30 mm and the charge thickness is 25 mm, 30 mm and 35 mm. It can be seen from the picture that when the initiation delay time is zero, the superposition position of detonation wave is on the central line of the initiation points. With the increase of the delay time, the distance from the center line of the collision position increases approximately linearly. When the delay time is 0.1 μs, the stacking pressure of detonation wave increases. With the increase of delay time, the superimposed pressure of detonation waves decreases wave-likely, but the pressure is still above 48 GPa, which is obviously higher than the position where there is no superimposed detonation wave. With the increase of charge thickness, the fluctuation of superimposed pressure of detonation wave tends to be gentle, but the superimposed pressure decreases slightly. When the detonation delay is 0.1 μs with the charge thickness of 25 mm, the incident pressure of detonation wave superimposed on the witness target is about 57 GPa, and for the charge thickness of 35 mm, the incident pressure is about 53.5 GPa.
When the charge thickness is 30 mm and the initiation spacing is 25 mm, 30 mm and 35 mm, the influence of delay time on the pressure and the position of the pressure after the impact of detonation wave is shown in Fig.4. With the increase of detonation points separate distance, the offset of collision point decreases and the linearity of change trend becomes worse with the same delay time. The fluctuation of superimposed pressure becomes stronger and stronger, but the magnitude of superimposed pressure increases slightly.

Analysis of the impact of detonation delay under different charge thickness and detonation spacing shows that when the charge thickness is less than the detonation spacing, the change of stacking pressure with the detonation delay shows stronger fluctuation. Because the detonation time is different, the detonation wave produced by the two detonation points reaches the witness target at different time, so the collision position of the two detonation waves on the interface between the detonation product and the witness target gradually deviates from the center line of the initiation point with the increase of the initiation delay. As the position of the collision point shifts gradually, the collision angle of the two detonation waves decreases gradually, resulting in the decrease of the collision pressure; the incident angle of the detonation wave on the witness target increases gradually after the collision superposition, resulting in the increase of the incident pressure. Two factors simultaneously affect the initial shock wave pressure incident on the witness target, so the wave-like change of the pressure on the witness target is observed.

4. Conclusion
In this article, Effects of detonation waves asymmetric collision was studied. A way to get the position of detonation wave collision point was proposed, and it fits the results of simulation well. With the software AUTODYN, pressure of detonation wave interaction was analysed. It is found that the pressure of the detonation wave interaction area is significantly higher than that without interaction. And the delay time of initiation results in the wave-like decrease of the interaction area’s pressure, although the decrease is very slight.
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