Simulation analysis of the effect of conical cap on the piercing performance of projectile

G J Niu, X H Shi, J C Li, L X Qian and C X Yu
Institute of Systems Engineering, China Academy of Engineering Physics, Mianyang 621999, Sichuan, China.

414niuji@caep.cn

Abstract. To study on the effect of conical cap on the piercing performance of projectile(Ø 150mm) when penetrating three-interval-layer steel target (target thickness: 20mm+20mm+20mm, the center of distance between adjacent targets is 1.5m), the FEA model of penetrating performance of the projectile with conical cap was built by using Ls-dyna, and the attitude change law, velocity change law and impacting acceleration change law of projectile in the process of piercing the targets were analyzed under the different impact velocity(500m/s, 600m/s, 700m/s, 800m/s) and impact angle(0°, 25°, 50°) condition. The simulation results show that: with the increase of impact velocity and impact angle, the time of the conical cap separating from the head of projectile and breaking is earlier, and the breakage of the cap is also more severity. Under the same impact angle and different impact velocity condition, the maximum axial acceleration variation of projectile penetrating into each target is inconsistent, which is closely related to the separation of the cap from the projectile and the breaking of the cap. After the cap separating from the head of projectile, the cap will impact on the target firstly, which can reduce the axial acceleration when the projectile penetrates the target. Under the same impact velocity condition, the residual velocity of the projectile decreased with the increase of impact angle; and under the same impact angle condition, the velocity change after the projectile penetrates the target gradually decreases with the increase of the impact velocity of projectile. The amount of kinetic energy change of projectile increases with the increase of impact velocity of the projectile, that is to say, the higher of the impact velocity, the more of the kinetic energy loss in process of projectile penetrating target.

1. Introduction
Multiple impact loads will be loaded on the head of semi-armour-piercing warhead when penetrating multi-layer steel targets, which is one of the important factors that affect the strength of projectile and functional reliability of fuze. In order to reduce the impact load, one effective method is to add a cap to the head of the projectile body, it can not only protect the head of the projectile body, but also effectively reduce the impact load when the projectile body penetrates the steel target, providing favorable conditions for the functional reliability of the fuze [1].

Take 150mm semi-armour-piercing projectile, for example, a conical cap was design, and the simulation analysis of projectile piercing under different impact angles and velocities was carried out for penetrating three-layer interval target, and the erosion of projectile head, attitude change and impact overload of projectile body were studied, which can provide references for design of warhead.
2. Warhead and conical cap
The warhead is mainly composed of conical cap, shell, charge and tail cover, as shown in figure 1. The diameter of warhead is 150 mm, and the diameter and length of warhead is 560mm, and the mass of the warhead is about 40kg, the materials of parts are shown in table 1.

![Figure 1. Schematic diagram of warhead with conical cap.](image)

Table 1. Materials and quality of each part of the warhead.

| number | part          | material       | density g/cm³ | mass kg |
|--------|---------------|----------------|---------------|---------|
| 1      | Cover tail    | G50            | 7.8           | 1.46    |
| 2      | Charge        | Substitute material | 1.9        | 8.91    |
| 3      | Shell         | G50            | 7.8           | 22.68   |
| 4      | Conical cap   | G50            | 7.8           | 5.94    |

3. Targets and FEA model
3.1. Targets
There were three types three-layer interval targets, as shown in figure 2. The material of target is 921A, and the size of each target is 1.2mm×0.8m×0.02m. The horizontal distance between the center of the adjacent targets is 1.5m.

![Figure 2. Schematic diagram of targets and FEA model.](image)

(a) $\theta=0^\circ$, normal penetration.
3.2. FEA model
The LS-Dyna software is used for finite element simulation analysis. The PLASTIC_KINEMATIC material model is used for the conical cap, shell and tail cover, and the JOHNSON_HOLMQUIST_CONCRETE material model is used for the charge, and JOHNSON_COOK material model is used for targets. The mesh division results of warhead and targets are shown in figure 3. Free contact algorithm is adopted between the cap and the shell, and the tail cover and the projectile body have common nodes [2].

3.3. Calculation conditions
In the simulation, the impact angles of projectile are 0°, 25° and 50°, and the velocities of projectile are 500m/s, 600m/s, 700m/s and 800m/s, there are 12 calculation conditions, as shown in table 2.
Table 2. Calculation conditions.

| Serial number | Impact angle $\theta^\circ$ | Impact velocity $V$ m/s |
|---------------|-----------------------------|-------------------------|
| 1             | 0                           | 500                     |
| 2             |                             | 600                     |
| 3             |                             | 700                     |
| 4             |                             | 800                     |
| 5             |                             | 500                     |
| 6             |                             | 600                     |
| 7             |                             | 700                     |
| 8             |                             | 800                     |
| 9             |                             | 500                     |
| 10            |                             | 600                     |
| 11            |                             | 700                     |
| 12            |                             | 800                     |

4. Analysis of simulation results

4.1. The attitude change of projectile body penetrating target

The attitude change process of projectiles body penetrating the targets are shown in figure 4~figure 6. When $\theta = 0^\circ$, the projectile basically remained horizontal during penetrating the targets at different impact velocities; and when $V=500\text{m/s}$ and $V=600\text{m/s}$, the conical cap completely broke when passing through the third-layer target; when $V=700\text{m/s}$ and $V=800\text{m/s}$, the conical cap completely broke after passing through the second-layer target, as shown in figure 4.

When $\theta = 25^\circ$, the projectile body slightly deflects in the course of penetrating the targets at different impact velocities. The higher the impact velocity of projectile, the earlier the conical cap falls off the projectile body, and the conical cap was broken during the projectile body penetrating the second-layer target, as shown in figure 5.

![Figure 4](image-url)  
*Figure 4. Attitude change of projectile body during penetrating targets ($\theta=0^\circ$).*
When $\theta = 50^\circ$ and $V=700\text{m/s}$, the projectile body deflects downward obviously in the process of penetrating the targets. When $V=500\text{m/s}$ and $V=600\text{m/s}$, the conical cap starts to fall off after passing through the first-layer target, and completely breaks in the process of penetrating the second-layer target, and when $V=700\text{m/s}$ and $V=800\text{m/s}$, the conical cap breaks during the projectile body penetrating the first-layer target, as shown in figure 6.

4.2. Erosion of shell’s head
The erosions of shell’s head are shown in figure 7~figure 10. It can be seen that with the increase of impact velocity and impact angle of projectile body, the erosion of projectile body head is increasingly intensified.
Figure 8. The erosion of shell’s head when $V=600\text{m/s}$.

Figure 9. The erosion of shell’s head when $V=700\text{m/s}$.

Figure 10. The erosion of shell’s head when $V=800\text{m/s}$.

4.3. Velocity change

The velocity change process of projectile body is shown in figure 11. The changes of velocity and kinetic energy of the projectile body before and after penetrating the targets are shown in table 3, where, $V_\text{s}$ is the residual velocity of the projectile body; $\Delta V_1$ is absolute velocity variation, $\Delta V_1 = V - V_\text{s}$; $\Delta V_2$ is the relative velocity variation, $\Delta V_2 = \Delta V_1/V \times 100\%$; $\Delta E_1$ is kinetic energy variation; $\Delta E_2$ is relative kinetic energy variation.
The 2020 Spring International Conference on Defence Technology  
Journal of Physics: Conference Series 1507 (2020) 032027  
doi:10.1088/1742-6596/1507/3/032027

(c) $V = 700 \text{m/s}$  
(d) $V = 800 \text{m/s}$

Figure 11. Curve of projectile velocity.

Table 3. Velocity change and kinetic energy change of warhead.

| Serial number | $\theta$ | $V$ (m/s) | $V_s$ (m/s) | $\Delta V_1$ (m/s) | $\Delta V_2$ (%) | $\Delta E_1$ (MJ) | $\Delta E_2$ (%) |
|---------------|---------|-----------|-------------|-------------------|------------------|------------------|------------------|
| 1             | 0       | 500       | 368         | -132              | -26.4            | -1.893           | -45.83           |
| 2             | 25      | 600       | 485         | -115              | -19.17           | -2.062           | -34.66           |
| 3             | 0       | 700       | 592         | -108              | -15.43           | -2.306           | -28.48           |
| 4             | 25      | 800       | 705         | -95               | -11.88           | -2.363           | -22.34           |
| 5             | 0       | 500       | 370         | -130              | -26.00           | -1.869           | -45.24           |
| 6             | 25      | 600       | 477         | -123              | -20.5            | -2.189           | -36.80           |
| 7             | 0       | 700       | 587         | -113              | -16.14           | -2.403           | -29.68           |
| 8             | 25      | 800       | 692         | -108              | -13.5            | -2.663           | -25.18           |
| 9             | 0       | 500       | 338         | -162              | -32.4            | -2.243           | -54.30           |
| 10            | 25      | 600       | 447         | -153              | -25.5            | -2.647           | -44.50           |
| 11            | 0       | 700       | 544         | -156              | -22.29           | -3.207           | -39.61           |
| 12            | 25      | 800       | 636         | -164              | -20.5            | -3.892           | -36.80           |

At the same velocity, $V_s$ decreases with the increase of $\theta$, when $\theta=0^\circ$ and $\theta=25^\circ$, $\Delta V_1$ decreases gradually with the increase of $V$; when $\theta=50^\circ$ and $V$ in the 500 m/s ~ 800 m/s, $\Delta V_1$ doesn't change too much.

In terms of kinetic energy loss, $\Delta E_1$ changes with impact velocity of projectile increases, when $\theta=0^\circ$, $\Delta E_1$ range in 1.893 MJ to 2.306 MJ, when $\theta=25^\circ$, $\Delta E_1$ range in 1.869 MJ to 2.663 MJ, when $\theta=50^\circ$, $\Delta E_1$ range in 2.243 MJ to 3.892 MJ. When the projectile hits the target at a large angle, the kinetic energy loss of the projectile is relatively large. When the projectile penetrates the target at a large angle, the kinetic energy loss of the projectile is also large.

4.4. Acceleration change

The change process of the shell's axial acceleration, $A_x$ is shown in figure 12 ~ figure 14 at different impact angles, and the statistical results of the axial acceleration peak of shell, $A_{x_{\text{max}}}$ is shown in table 4 when the projectile penetrates each target under different conditions.
**Figure 12.** Curve of axial acceleration of shell at $\theta=0^\circ$. 

(a) $V=500\text{m/s}$  
(b) $V=600\text{m/s}$  
(c) $V=700\text{m/s}$  
(d) $V=800\text{m/s}$
Figures 13 and 14. Curves of axial acceleration of shell at θ=25° and θ=50°.
Table 4. Statistical results of the axial acceleration peak of shell.

| number | $\theta$ | $V$ (m/s) | $A_{X\text{max}}\times10^4$g |
|--------|---------|----------|------------------|
|        |         |          | Target 1 | Target 2 | Target 3 |
| 1      | 0       | 500      | -2.094   | -3.867   | -3.143   |
| 2      | 0       | 600      | -2.535   | -3.636   | -1.633   |
| 3      | 0       | 700      | -3.076   | -3.011   | -2.644   |
| 4      | 0       | 800      | -3.335   | -2.147   | -2.619   |
| 5      | 25      | 500      | -1.954   | -2.697   | -1.364   |
| 6      | 25      | 600      | -2.575   | -2.597   | -2.166   |
| 7      | 25      | 700      | -2.957   | -1.493   | -2.627   |
| 8      | 25      | 800      | -3.075   | -1.558   | -2.989   |
| 9      | 25      | 500      | -1.623   | -0.878   | -1.407   |
| 10     | 50      | 600      | -1.979   | -1.030   | -1.831   |
| 11     | 50      | 700      | -2.230   | -1.691   | -2.302   |
| 12     | 50      | 800      | -2.244   | -2.783   | -2.985   |

When $\theta=25^\circ$, the maximum and minimum axial overload peaks of the projectile occurred during the penetration of target 2 and target 3 under the conditions of $V=500\text{m/s}$ and $V=600\text{m/s}$, and the maximum and minimum axial overload peaks occurred during the penetration of target 1 and target 2 under the conditions of $V=700\text{m/s}$ and $V=800\text{m/s}$.

When $\theta=50^\circ$, the maximum and minimum axial overload peaks of the projectile under the conditions of $V=500\text{m/s}$, $600\text{m/s}$, $700\text{m/s}$ and $800\text{m/s}$ occurred in the process of penetrating 1 target and 3 targets, 1 target and 2 targets, 3 target and target 1, respectively. Combined with figure 4~figure 6 and figure 12, it shows that the conical cap penetrates and destroys the target after separating from the projectile body head, which helps to reduce the axial overload of the projectile body.

The change of vertical acceleration of shell, $A_y$ is shown in figure 15 and figure 16 when $\theta=25^\circ$ and $\theta=50^\circ$, respectively. The statistical results of vertical overload peak, $A_{Y\text{max}}$ is shown in table 5 when the projectile penetrates each target under different working conditions. It can be see that the vertical overload is first positive and then negative in the process of penetrating each target.
Figure 15. Curve of vertical acceleration of shell at $\theta=25^\circ$.

Figure 16. Curve of vertical acceleration of shell at $\theta=50^\circ$. 
Table 5. Statistical results of the vertical acceleration peak of shell.

| Serial number | \(\theta\) ° | \(V\) m/s | \(Ay_{\text{max}}\) \(\times 10^4\) g |
|---------------|-------------|------------|-----------------------------------|
|               |             |            | Target 1                          | Target 2                          | Target 3                          |
| 5             | 25          | 500        | Positive 0.451                     | Negative -0.414                    | Positive 0.887                     | Negative -0.649                    | Positive 0.283                     | Negative -0.235                    |
| 6             |             | 600        | Positive 0.850                     | Negative -0.550                    | Positive 0.925                     | Negative -0.675                    | Positive 1.029                     | Negative -0.688                    |
| 7             |             | 700        | Positive 0.591                     | Negative -0.695                    | Positive 0.723                     | Negative -0.397                    | Positive 0.595                     | Negative -1.038                    |
| 8             |             | 800        | Positive 0.604                     | Negative -0.785                    | Positive 0.729                     | Negative -0.403                    | Positive 0.633                     | Negative -1.137                    |
| 9             |             | 500        | Positive 0.716                     | Negative -0.938                    | Positive 0.783                     | Negative -0.306                    | Positive 0.870                     | Negative -0.746                    |
| 10            | 50          | 600        | Positive 0.850                     | Negative -0.886                    | Positive 0.925                     | Negative -0.453                    | Positive 1.029                     | Negative -1.053                    |
| 11            |             | 700        | Positive 0.945                     | Negative -0.925                    | Positive 0.494                     | Negative -1.072                    | Positive 1.169                     | Negative -0.990                    |
| 12            |             | 800        | Positive 1.053                     | Negative -0.895                    | Positive 1.277                     | Negative -1.372                    | Positive 1.376                     | Negative -1.139                    |

5. Conclusion

Through the establishment of finite element simulation analysis model of projectile body armor piercing with conical cap, the projectile body attitude change process, velocity change and overload change rule were analyzed in the process of projectile body armor piercing three-layer interval target at different impact angles and velocities. The main conclusions were as follows:

(a) In the process of penetrating the target, with the increase of the impact velocity and impact angle of the projectile body, the earlier the time of the conical cap falling off and breaking from the projectile body.

(b) The maximum axial overload of projectile body is closely related to the separation from projectile head and broken of the conical cap, and when the conical cap was separated from the projectile head appropriately, the conical cap would penetrated the target firstly, which helps to reduce the axial overload of projectile body.

(c) At the same impact velocity, the residual velocity after the projectile penetrates the target decreases with the increase of the impact angle; and at the same impact angle, the variation of projectile velocity after penetrating the target gradually decreases with the increase of impact velocity.

(d) The change of kinetic energy after the projectile penetrates the target increases with the increase of the projectile’s impact velocity, that is to say, the higher the projectile's impact velocity, the greater the kinetic energy loss after penetrating the target.

References

[1] Jun-cheng Li, Gong-jie Niu and Feng-lei Huang 2017 proceedings of 30th International Symposium on Ballistics pp 2179-89

[2] Gong-jie Niu, Jun-cheng Li and Chun-xiang Yu 2016 proceedings of 29th International Symposium on Ballistics pp 1993-2003