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Numerical Calculation and Experimental Study on Penetration into Multi-Layer Spaced Steel Targets

Xiangli Cheng*, Hui Zhao, Bo Liu and Jun Liu
Institute of Electronic Engineering, China Academy of Engineering Physics, Mianyang 621999, Sichuan, China
*Corresponding author

***Abstract*—To provide exact mechanics input for anti-high-overload optimal design of penetration projectile, a projectile-target response model was built. On the basis of force analysis for penetration process, the rigid body motion model for projectile was established by adopting Newton's second law. Then, numerical integration calculation was carried out, and the trend of each physical quantity in penetration process was obtained. To verify the credibility of the model, artillery test was carried out, and the complete penetration process was recorded by high-speed camera. Based on the result that the values of calculation agreed well with that of tests, it could be concluded that the model was more suitable to analyze force conditions, which could be applied to guide the optimal design of the projectile.**

***Keywords*—penetration; rigid body motion model; numerical integration; artillery test**

I. INTRODUCTION

In modern warfare, more and more high-speed penetration projectiles are used to destroy high-strength hard targets such as defensive fortifications, surface warships, airport runways, ground buildings and aircraft shelters [1]. In the penetration process, projectile-target response mechanism is very complex, which brings great difficulties to the optimization design of projectile [2-3]. It has become a mechanical problem with great military needs.

An effective solution is to obtain the acceleration in the penetration process by establishing a reasonable, effective and simplified projectile-target response model [4-5]. Firstly, force analysis for penetration process was conducted and the rigid body motion model was built according to Newton's second law. Then, numerical integration calculation was carried out, and the trend of each physical quantity in penetration process was obtained. Lastly, artillery test was carried out to verify the credibility of the model.

II. THEORETICAL MODEL

A. Cavity Expansion Model

The cavity expansion theory [6-7] was an approximate method to analyze the penetration process. The principle was to build the relationship between the normal stress and the cavity expansion velocity according to the law of conservation of mass and momentum. And the projectile-target response force was obtained by integrating the surface of the projectile.

The normal stress σ_n at the surface element of projectile was closely related to the cavity expansion velocity V_n and the characteristic parameters A and B of target material, as in (1). The expressions of parameters A and B were as in (2) and (3). In the equation, η^* was the lock variable volume constant, ρ_0 was the initial density, λ was the strengthening modulus parameter, E was the elastic modulus, τ_0 was the lateral shear strength, σ_0 was the compressive strength.

$$\sigma_n = A + BV_n^2 \tag{1}$$

$$A = \frac{2\tau_0}{3}\left(1 - \ln\eta^*\right) \tag{2}$$

$$B = \frac{\rho_0}{A_1^2}\left[\frac{3\tau_0}{E} + \eta^*\left(1 - \frac{3\tau_0}{2E}\right)^2 + \frac{3\left(\eta^*\right)^{\frac{2}{3}} - \eta^*\left(4 - \eta^*\right)}{2\left(1 - \eta^*\right)}\right] \tag{3}$$

$$A_1 = \left[\left(1 + \frac{\tau_0}{2E}\right)^2 - \left(1 - \eta^*\right)\right]^{\frac{1}{3}} \tag{4}$$

$$\tau_0 = \left(1 - \frac{\lambda}{3}\right)\sigma_0 \tag{5}$$

The tangential stress σ_τ at the surface element of projectile was obtained, as in (6). Among them, μ was the dynamic friction coefficient.

$$\sigma_\tau = \mu\sigma_n \tag{6}$$

B. Differential Panel Method

Assuming that the angle of attack was always zero during the penetration process, there was no attitude deflection for the projectile. At this time, the projectile was mainly subjected to the penetration resistance of the target, that was, the projectile-target response force F_x, as shown in Figure 1. In the figure, H

was the target thickness, x was the penetration depth, V was the penetration velocity and LS was the length of the oval warhead.

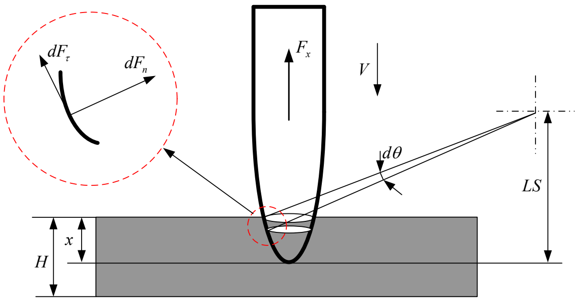

FIGURE I. FORCE DIAGRAM IN PENETRATION PROCESS.

The force acting on the target could be solved by differential panel method. For the penetration process, the circular cross section perpendicular to the axis of the projectile was taken as a micro-panel, which was denoted as dS, as in (7). Among them, CRH was bullet coefficient, D was the diameter, and θ was the center angle.

$$dS = 2\pi CRH^2 D^2 \left(\sin\theta - \frac{CRH - 0.5}{CRH} \right) d\theta \tag{7}$$

The normal force dF_n and tangential force dF_τ of the micro-panel dS could be obtained, as in (8).

$$\begin{cases} dF_n = \sigma_n dS \\ dF_\tau = \sigma_\tau dS \end{cases} \tag{8}$$

By projecting the normal and tangential forces of the micro-panel dS to the elastic axis, the axial force dF_x of the micro-panel dS could be obtained, as in (9).

$$\begin{aligned} dF_x &= dF_n \cos\theta + dF_\tau \sin\theta \\ &= 2\pi CRH^2 D^2 \sigma_n \left(\sin\theta - \frac{CRH - 0.5}{CRH} \right) (\cos\theta + \mu \sin\theta) d\theta \end{aligned} \tag{9}$$

By integrating the axial force dF_x of micro-panel dS along the projectile surface, the projectile-target response force could be obtained, as in (10).

$$F_x = \int_{\theta_1}^{\theta_2} dF_x \tag{10}$$

C. Rigid Body Motion Model

In the penetration process, the projectile would be decelerated acutely under penetration resistance. Assuming that there was no deformation, the penetration process could be simplified as rigid body motion of the center of mass. According to Newton's second law, the differential equation describing the penetration process was built, as in (11). Among them, t was the penetration time and M was the mass of projectile.

$$\begin{cases} M \dfrac{dV}{dt} = -F_x \\ \dfrac{dx}{dt} = V \end{cases} \tag{11}$$

It could be seen that the projectile-target response force determined the rigid body motion characteristics. When the projectile, the target and the initial velocity were known, the model was solved adopting numerical integration calculation, and the trend of each physical quantity in penetration process was obtained. Firstly, compute the penetration resistance adopting the cavity expansion model and differential panel method. Then, solve the differential equation, and the end condition of the program was judged. If not, compute the value next moment until the end condition was satisfied.

The detailed flow diagram programming was shown in Figure 2.

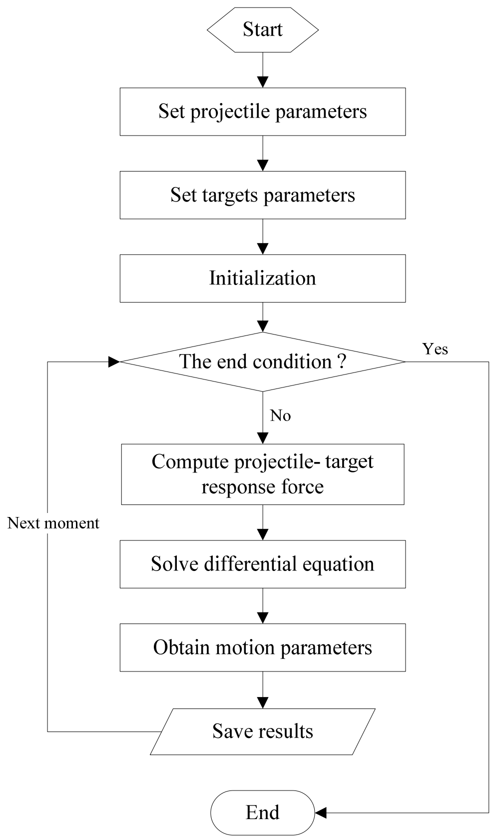

FIGURE II. FLOW DIAGRAM FOR PROGRAMMING.

III. RESULTS AND DISCUSSION

The process of an artillery test projectile penetrating into six-layer spaced steel targets was selected as an example. Detailed parameters were as follows:

The test projectile shown in Figure 3 had a diameter of 0.155 m, a length of 0.89m, a projectile coefficient of 3.0, and a weight of about 90 kg. The projectile was made of high strength alloy steel with elastic modulus 210 GPa and density 7800 kg/m^3.

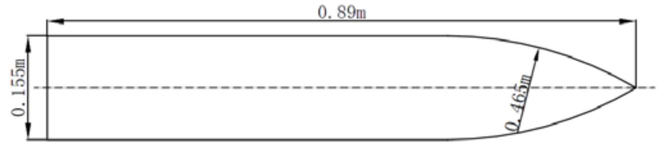

FIGURE III. SCHEMATIC DIAGRAM OF PROJECTILE.

The targets were six-layer spaced steel. The elastic modulus was 210 GPa and the density was 7800 kg/m^3. The dynamic friction coefficient was 0.02, the lock-in volume constant was 0.1, and the strengthening modulus parameter was 0.65.

The fourth-order runge-kutta algorithm was used for numerical integration. When calculating, the time step was 1μs and the calculation results were output every 1μs.

A. Numerical Calculation Results

When penetrating into six-layer spaced steel targets with the penetration velocity 780 m/s, the duration was about 13 ms and the residual velocity was about 698 m/s.

The velocity and acceleration curve in the penetration process were shown in Figure 4 and Figure 5 respectively.

It could be seen that there were six peak values. When penetrating into steel target, the projectile decelerated acutely, and the max value of the acceleration was 9350g (1g = 9.81 m/s^2). And when the projectile was freedom, the velocity was invariable, and the corresponding acceleration was zero.

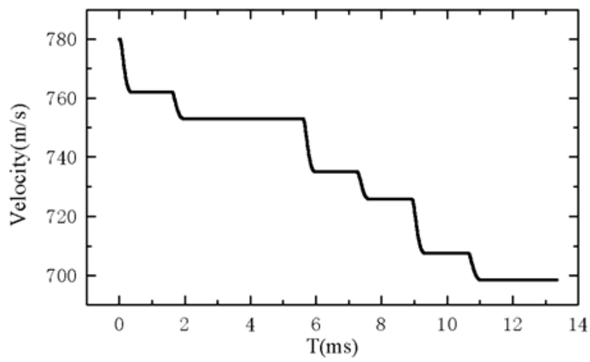

FIGURE IV. VELOCITY CURVE IN PENETRATION PROCESS.

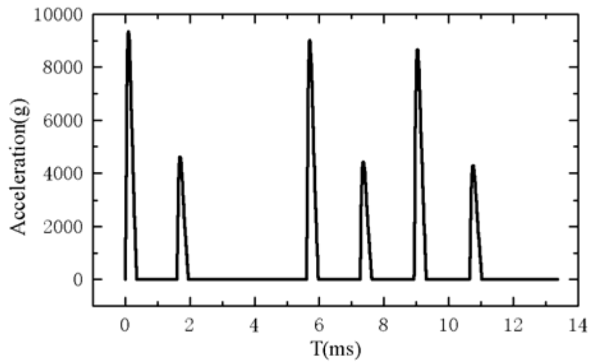

FIGURE V. ACCELERATION CURVE IN PENETRATION PROCESS.

B. Artillery Test Results

To verify the credibility of the model, the artillery test was carried out. During the test, the complete penetration process was recorded by high-speed camera, and the penetration velocity was 780 m/s. Define the moment penetrating the first layer target was zero moment. The penetration moment of each layer target were listed in Table 1, concluding numerical calculation results and high speed camera test results.

TABLE I. PENETRATION MOMENT OF EVERY LAYER TARGET

Layer	*Numerical calculation results (ms)*	*High speed camera test results (ms)*	*The absolute error (ms)*	*The relative error*
1	0.0	0.0	0.0	
2	1.604	1.6	0.004	0.25%
3	5.595	5.6	0.005	0.09%
4	7.252	7.4	0.148	2.00%
5	8.915	9.1	0.185	2.03%
6	10.638	10.7	0.062	0.58%

In the table, the absolute error was equal to the numerical calculation results minus the high speed camera test results, and the relative error was equal to the absolute error divided by the high speed camera test results. It could be seen that the maximum absolute error was only 0.185 ms, and the maximum relative error was only 2.03% when penetrating the fifth layer target.

The above analysis indicated that the numerical calculation results of the rigid body motion model were consistent with the experimental results, and could meet the needs of engineering estimation.

IV. CONCLUSION

The projectile-target response force was calculated adopting the cavity expansion theory and the differential panel method.

The rigid body motion model of the projectile penetrating into multi-layer spaced steel targets was built according to Newton's second law.

The numerical integration calculation was carried out, and the trend of each physical quantity in penetration process was obtained.

The artillery test penetrating six-layer spaced steel targets was carried out, and the complete penetration process was recorded by high-speed camera.

The comparison between the numerical calculation results and the high speed camera test results shown that the projectile-target response model could more accurately predict the law of overload change in the penetration process, and could provide a clearer mechanical input for the optimization design of anti-overload of projectile.

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