11th International Symposium on Plasticity and Impact Mechanics, Implast 2016

Penetration research of dual-mode penetrator formed by shaped charge with wave shaper

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Abstract

The objective is to match the penetration capability of dual-mode penetrator. Finite element software LS-DYNA is used to acquire four types of dual-mode penetrators EFP (Explosively Formed Projectile) and JPC (Jetting Projectile Charge). Considering the process of dual-mode penetrator flight and penetration, including the effects of velocity attenuation for stand-off and length change of EFP & JPC, also the differences between mechanisms of EFP into armor steel and JPC into concrete, an analytical model for predicting the final penetration of dual-mode penetrator is presented. We use the analytic model, to estimate the penetration of dissimilar modes and then a series of field tests are provided to demonstrate the reliability of the approach. Moreover, in application of the analytic method, along with the penetration restrictions of different modes, the work in this paper describes the optimal matching zone and extreme points of penetration capability of dual-mode penetrator.

Keywords: Shaped charge; EFP(Explosively Formed Projectile); JPC(Jetting Projectile Charge); penetration; penetration capability matching

1. Introduction

Tracking the development of intelligent and other new types of ammunition, multi-mode warhead has attracted more and more attention in explosive mechanics researches recently. W. Arnold\textsuperscript{[1-2]}, Graswald.M\textsuperscript{[3]}, Robert J.Lawther\textsuperscript{[4]}, David Bender\textsuperscript{[5]} et al had designed many kinds of multi-mode warhead by changing the initiation ways and structure of warhead, which formed the penetrators in good ways. Jiang j.w. \textsuperscript{[6]}, Li w.b. \textsuperscript{[7]} et al had did a lot of researches on the converting mechanism of multi-mode warheads, and got the penetrators by controlling the

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detonation of single-point and annular position. However, when match the penetration capability of multi-mode warhead, it is a certain result that destroys the penetration capability of each mode. Finding the matching methods to achieve a final penetration capability of multi-mode penetrator is an urgent problem.

The current study design a dual-mode penetrator (EFP & JPC) by controlling the initiation position of single-point which based on the shaped charge with wave shaper, and achieves an analytical model of final penetration with different stand-off of EFP into armor steel and JPC into concrete. A series of experiments are performed to demonstrate the accuracy of analytic model. In application of the model, some key factors of penetrator that impact the effect of penetration capability are analyzed, and effecting laws of penetration capability of dual-mode penetrator are proposed.

2. Research models

Our team has done a lot of researches on the forming mechanism and structural optimization of multi-mode warhead [8-10], and achieved a shaped charge structure with wave shaper shown in Fig. 1. Initiation point A is the detonation position that forms JPC penetrator whereas initiation point B is the detonation position to form EFP penetrator. Changing the value of curvature radius and eccentric coordinate of eccentric sub-hemisphere liner, the structure can form different types of dual-mode penetrators with different performance parameters in Table 1, which are the subjects for the later researches about the penetration capability of dual-mode penetrators.

Fig. 1. Simulation model of dual-mode Shaped charge structure.

Table 1. The forming shape and condition of dual-mode penetrator.

<table>
<thead>
<tr>
<th>Mode</th>
<th>States</th>
<th>A</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFP</td>
<td>Shape</td>
<td>71.12</td>
<td>56.96</td>
<td>70.45</td>
<td>55.46</td>
</tr>
<tr>
<td></td>
<td>$L_F$</td>
<td>27.50</td>
<td>31.43</td>
<td>47.77</td>
<td>23.57</td>
</tr>
<tr>
<td></td>
<td>$V_F$</td>
<td>2127</td>
<td>1925</td>
<td>1958</td>
<td>2271</td>
</tr>
<tr>
<td>JPC</td>
<td>Shape</td>
<td>0.252</td>
<td>0.215</td>
<td>0.187</td>
<td>0.264</td>
</tr>
<tr>
<td></td>
<td>$L_J$</td>
<td>3591</td>
<td>3474</td>
<td>3278</td>
<td>4069</td>
</tr>
<tr>
<td></td>
<td>$V_J$</td>
<td>3000</td>
<td>2812</td>
<td>2719</td>
<td>3155</td>
</tr>
</tbody>
</table>

3. Basic formulation

Simplifying the shape of dual-mode penetrators in Table 1, the objective is to achieve an analytical model of final penetration of the simplified EFP and JPC considering the effect of separate stand-off.
3.1. Effects of stand-off

Since the EFP always attacking a target in a long distance, the velocity of EFP which is one mode of dual-mode penetrators will decay with the distance. Simplify the shape of EFPs at 300μs moment which are shown in Table 1 a. For the flight speed of EFP penetrator reaching 6.8 Mach, the shock wave appears at the fireside, initial point of separation region and secondary attachment point. Vortex is formed for the attachment layer condition and converging or gyration of the shock wave. The correlation is a nonlinear function to geometry of penetrator. Considering EFP’s velocity attenuation caused by air resistance, the empirical formula of velocity is obtained by using resistance law:

$$V_f = V_0 e^{-ax}$$  \hspace{1cm} (1)

Where $V_0$ is the initial velocity, $x$ is the flight distance, and $a$ is the coefficient of velocity attenuation. Measure more than three group velocity data in unique position of EFP’s flight profile, the axial resistance ratio is fitted by the least square method, and then, the velocity of EFP that reaches target is confirmed. However, considering the large velocity gradient, the JPC penetrator will stretch constantly. It is necessary to find out the axial distribution function of JPC’s velocity which is the foundation of analysis of infinitesimals kinematic relations. Aim to seek effects of stand-off to the length of JPC reaching target, the distribution function of $V_h(x)$ and $V_t(x)$ of shaped JPC is calculated through numerical simulation. Assuming the JPC is coherent and not broken before reaching target, the length $L_z$ of JPC is shown bellow with the top velocity of JPC $V_h(x)$, tail velocity $V_t(x)$, initial length $l_0$ and stand-off $h_0$ known:

$$L_z = \int_0^{\Delta h_0} (V_h(x) - V_t(x))dx + l_0$$  \hspace{1cm} (2)

Where $\Delta h_0$ is the value of distance between the target and foreside of JPC. Then, the length of penetrator meeting the target is calculated. In consideration of mutual force of unit elements, it is extremely difficult to obtain an exact distribution function $V_h(x)$ or $V_t(x)$ by calculation. However, the smaller the $\Delta h_0$, the smaller effect of $V_h(x)$ and $V_t(x)$ to the length of JPC reaching target, if conditions warrant it, the value of $\Delta h_0$ should be zero to simplify the analysis process. The current study obtained the length of JPC in Table 1 with $\Delta h_0=0$ and stand-off of 10$D_k$.

3.2. Penetration mechanism

The dual-mode penetrators in Table 1, the EFP penetrate armor steel target different from JPC penetration into concrete. As distinct targets for each mode, two kinds of analytical model are presented.

3.2.1. A two-step mechanism for EFP penetrate armor steel

Analyzing the penetration mechanism of EFP into finite thickness armor steel, material density has great influence on penetration when the penetrator in high speed, and with the velocity attenuation, there is a secondary penetration due to the remainder impact stress and material strength when the penetrator in low speed. An analytic model of final penetration is framed in two-step based on high speed penetration and low speed penetration. Simplifying the problem, all process of penetration are regarded as unidimensional problem, and the following assumptions are made:

- The EFP penetrate target as plastic fluid and it's free to the back of the target during the high speed period
- The remainder energy of EFP is consumed completely in material deformation and plugging perforation during low speed period
During the high speed penetration, according to the conclusion of hypothetic a, the target can be regarded as semiinfinite thickness. Applying the theories of momentum conservation laws, mass conservation and kinematic relations, the penetration depth\(^{(11)}\) of EFP penetrator into armor steel is shown in the following formula:

\[
L_b = L_{b0} \left[ \exp \left( \frac{\rho_b}{2\delta_b} U^2 - \frac{\rho_b}{2\delta_b} U_0^2 \right) \right]
\]

Where \(L_{b0}, L_{bth}, U, U_0, \rho_b, \delta_b\) are penetration depth, target thickness, penetration velocity, the initial penetration velocity, target material density and tensile strength.

Using conservation of energy during the low speed penetration, while \([(M_cV_c^2E)/(\pi L_cR_c^2)]^{0.5} \leq \delta_b\), in other words the impact stress of penetrator is less than material strength of target, the energy of penetrator is consumed in its material deformation and its influence to penetration can be ignore\(^{(12)}\). Otherwise, penetrator with a certified quality \(M_c\) penetrating the target with a velocity \(V_c\), the energy of EFP converts to material deformation energy and plug kinetic energy. The formula is expressed as:

\[
\begin{align*}
\frac{1}{2} M_c V_c^2 & = W_p + W_t & V_c \leq V_k \\
\frac{1}{2} M_c V_c^2 & = \frac{1}{2} (M_c + M_t) W_f^2 + W_p + W_t & V_c > V_k
\end{align*}
\]

Where \(V_k\) is critical velocity of the plug formed, \(V_f\) is the velocity of the plug, \(W_p\) and \(W_t\) are material deformation energy and shear deformation energy of the target. The formula of \(W_p\) and \(W_t\) is expressed as:

\[
\begin{align*}
W_p & = \pi R_c h^2 \delta_s \\
W_t & = \frac{1}{2} \pi h \delta \left( R_c^2 - R_s^2 - 2R_s^2 \ln \frac{R_c}{R_s} \right)
\end{align*}
\]

Where \(\delta_s\), \(\delta_s\), \(R_c\), \(R_s\), \(h\) are the shear strength of material, the yield strength, the radius of the plug, the radius of EFP penetrator, the material spatial displacement. If the plug is created in the penetration of EFP into armor steel, \(h\) is the remainder thickness of target, and then the velocity of the plug is obtained; if not, \(h\) is the penetration depth in low speed period. Finally, final penetration depth of EFP into armor steel is obtained.

3.2.2. Revision of JPC penetrate concrete

Simplifying the process to analyze the final penetration of JPC into concrete, the following assumptions are made:

- The JPC is coherent during the penetration, and the velocity gradient and radius of JPC is one dimensional equation along its axis length
- All parameters of JPC and target in shock-wave-range are available for the Bernoulli equation in the process of penetration
- Regard as the area of mushroom head is thin enough to ignore its mass and momentum compared the whole JPC

With a derivative process as ref\(^{(13)}\), the relation between penetration depth \(X\) of JPC into semiinfinite concrete target and initial velocity \(v_0\) is shown in the following formula:

\[
X = \int \frac{u(v)f(v)}{f(v)} dv
\]

\[
f(v) = \frac{\alpha v}{\rho_v} + [v - u(v)]^{(\alpha - 1)}
\]
Where $u(v)$, $l(v)$, $\alpha$, $Y_p$, $\rho_p$ and $v$ are the penetration velocity, the length of the penetrator, the coefficient of mushroom head, the penetrator strength, the penetrator density and the velocity of penetrator reaches target. While the JPC with extraordinary speed run into the surface of a concrete target, there is tremendous pressure on the top of JPC penetrator. The foreshide shape of JPC can be approximated to cylindrical, at the moment of JPC run into the surface of concrete target in a velocity $v$, the pressure $P$ affect the whole interface, the duration depends on the time for unloading wave spreading from contour to axis of cylindrical underside[14](see Fig. 2). The pressure rises to $P$ at the collision moment, only the liquid around border involves lateral flush freely, while one near the axis is compressed until the rarefaction wave around the contour arriving. After the rarefaction wave arriving, the pressure of the surface between JPC and concrete drop to steady-state flow.

Fig.2. The illustration of JPC run into concrete surface

Although the surface pressure between JPC and concrete force the concrete target to form stress wave which cause it the broken, the ratio of mushroom head formed in penetration of JPC into concrete is interrelated with the lateral flush of JPC, based on the spreading time of rarefaction wave $t=r_h/C_w$, the ratio of mushroom head can be approximated to the formula as:

$$\alpha = \sqrt{V_v/3000}$$

4. Experiments and calculations

Field test demonstrates the reliability of final penetration analytic model of dual-mode penetrators into armor steel and concrete. The experiment is designed, whose general arrangement is illustrated in Fig. 3. The EFP of dual-mode penetrators into armor steel with stand-off $200D_k$ and the JPC penetrator into concrete with stand-off $10D_k$. A protector is installed behind the target.

Each mode of the dual-mode penetrators which are listed in Table 1 is tested twice independently. The predictable results of penetration show in Fig. 3.

According to the $300\mu s$ performance parameter of the four dual-mode penetrators in Table 1, the coefficient $a$ of velocity attenuation in flight is fitted, and the hit velocity $V_{z}$ (see Table 2) is calculated based on initial velocity $V_0$. The density of the penetrator is $8.96\text{g/cm}^3$, the penetrator strength is $230\text{Mpa}$, concrete density is $7.85\text{g/cm}^3$, concrete strength is $1200\text{Mpa}$. Theoretical calculation achieves the velocity of the plug while the EFPs overmatch armor steel, or obtains the final penetration with bulges at back of the target due to material deformation. For the initial length $L_p$, top velocity $V_{h}$, tail velocity $V_{t}$ of JPC listed in Table 1, with the penetrator density $8.96\text{g/cm}^3$, strength $900\text{Mpa}$, and concrete density $2.4\text{g/cm}^3$, in application of the analytical model of JPC into concrete, the calculation results and experiments are listed in Table 2.
Comparing the results of theories and experiments of each type dual-mode penetrators, the computation error of EFP is lower than 6.5%, and the error of JPC is less than 5%. Analyzing the consequences of theories and experiments about all kinds of dual-mode penetrators, theoretical calculation achieve all kinds of consequences such as penetration depth, bulges on back of target and overmatching the target which are tally with experiments results very well. The calculation indicates that the analytical model can obtain an accurate result of penetration depth of EFP into armor steel and JPC into concrete, considering the forming condition and flight process of dual-mode penetrators.

### Table 2. Results of experiment and calculation.

<table>
<thead>
<tr>
<th>Penetrator</th>
<th>Parameter</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
</tr>
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<tbody>
<tr>
<td>EFP</td>
<td>a</td>
<td>0.00389</td>
<td>0.00196</td>
<td>0.001751</td>
<td>0.006452</td>
</tr>
<tr>
<td></td>
<td>$V_0$</td>
<td>2136</td>
<td>1928</td>
<td>1955</td>
<td>2280</td>
</tr>
<tr>
<td></td>
<td>$V_z$</td>
<td>1976</td>
<td>1853</td>
<td>1800</td>
<td>2004</td>
</tr>
<tr>
<td>Test 1</td>
<td></td>
<td>47.025</td>
<td>45.79</td>
<td>47.56</td>
<td>46.14</td>
</tr>
<tr>
<td>Test 2</td>
<td></td>
<td>50 (Pierce)</td>
<td>51.88 (Swell)</td>
<td>50 (Swell)</td>
<td>50 (Pierce)</td>
</tr>
<tr>
<td>Theoretical penetration depth</td>
<td>Pierce</td>
<td>48.9</td>
<td>50.64 (Swell)</td>
<td>Pierce</td>
<td></td>
</tr>
<tr>
<td>Theoretical velocity ($m/s$)</td>
<td>271.7</td>
<td>/</td>
<td>/</td>
<td>171</td>
<td></td>
</tr>
<tr>
<td>JPC</td>
<td>Test 1</td>
<td>720</td>
<td>720</td>
<td>700</td>
<td>780</td>
</tr>
<tr>
<td>Test 2</td>
<td></td>
<td>700</td>
<td>800 (Pierce)</td>
<td>740</td>
<td>800 (Pierce)</td>
</tr>
<tr>
<td>Theoretical penetration depth</td>
<td>744</td>
<td>796</td>
<td>718</td>
<td>810 (Pierce)</td>
<td></td>
</tr>
</tbody>
</table>

### 5. Results and discussion

It is significant to match the penetration capability of dual-mode penetrators in design of dual-mode warhead. Firstly of all, the constraints of penetrators between two modes should be confirmed. According to hit length of JPC and hit velocity of relevant EFP which are the two modes of a dual-mode penetrator that shown in Table 1, the constraints curve is obtained as Fig. 4 (a); likewise, the constraints curve of hit velocity of JPC and relevant EFP is shown in Fig. 4 (b). It is clear that enhance a performance parameter of one mode, the relevant parameter of another mode will increase too, which show a monotonic trend.

![Fig. 4. (a) Hit length of JPC to hit velocity of EFP; (b) Hit velocity of JPC to EFP.](image)

Chose the type(c) in Table 1 as a subject of dual-mode penetrators, the length and hit velocity of EFP are 0.07m and 1800m/s, the tail velocity, foreside velocity and hit length of JPC are 2719m/s, 3278m/s and 0.187m. The current study analyzes the penetration capability in the application of controlling variable method in velocity and length of dual-mode penetrators. Fig. 5 is the curve of velocity $V$ and length $L_p$ of EFP penetrator to the penetration depth $Q$. With reference to Fig. 5 (a), along with the increasing of EFP velocity, the process of penetration should been divided into four period: in P1, the low speed penetration can be ignored for which Equation (4) is unsolvable; in P2 and lest period, the Equation (4) is solvable, and the target is penetrated with stretching due to low speed penetration; in P3, the target stretches enough while the tensile strain is less than fracture strain, forming bulges back of target, and the target isn’t overmatched; in P4, EFP penetrates the target without obvious tensile strain. The first
breakpoint velocity is at point of P1 to P2, value of which is the Equation (4) with only one numerical solution as
discriminant of Equation (4) is zero: \( \Delta = 0 \); the second breakpoint is transition point of P2 and P3, where the fracture
strain less than tensile strain. It is easy to see that zones of P2 and P4 and the range of two breakpoints are the
maximum penetration capability zones. Comparing the Fig. 5(a) with Fig. 5 (b), the velocity of EFP has greater
influence on penetration than its length, and only when the velocity is sufficient that the length of EFP will affect the
penetration results obviously. The calculation curve of velocity \( V_h \) and length \( L_p \) of JPC to the penetration depth \( Q \) is
shown in Fig. 6. It is obvious that both the velocity and length have a great impact on the penetration depth. With
reference to Fig. 6 (a), when the tail velocity is definitely, there is optimum velocity of JPC which make the
penetration depth up to a maximum value. As the slope of \( V-Q \) curve is quite different in current mode, the
penetration process should been divided into four period: in S1, the slop of \( V-Q \) curve is large obviously; in S2, the
slop slowdown; in S3 , the penetration depth is maximum; in S4 ,the penetration depth descend. With reference to
Fig. 6 (b) about the length of JPC to penetration depth in different periods, though the penetration depth increases
linearly with the length increasing of JPC , the slop is different obviously, and it is obvious that the slop in S3 period
is larger than the others. Thus, matching the penetration capability of the dual-mode penetrators, first of all, it should
optimize the JPC penetrator into S3 zone which is in S1, S2, and S4 zone at the beginning.

![Fig. 5. (a) Hit velocity of EFP; (b) initial length of EFP.](image)

![Fig. 6. (a) Hit velocity of JPC; (b) initial length of JPC.](image)

Matching penetration capability of the dual-mode penetrators designed currently, considering the length of dual-
mode penetrators has less influence on penetration depth than its velocity which is a constraint to velocity at the
same time. It is necessary to match the velocity of dual-mode penetrators firstly. With reference to the \( V-Q \) curve in
Fig. 5 and Fig. 6, the penetration process of each mode is divided into four zones, as a result, there are \( 4 \times 4 \)
combinations of dual-mode penetrators, and the best constraints are S3-P2 and S3-P4. Considering the constraints
shown in Fig.4 (b) of the dual-mode penetrators, rule out the extra zones but the S3-P2 is the optimum
combination of penetration for dual-mode penetrators. Moreover, the final penetration depth of EFP into armor steel and JPC into
concrete appears at the \( \Delta = 0 \) and \( u(v)l(v)/f(v)=0 \) point respectively. However, it is extremely hard to design a dual-
mode warhead which will form dual-mode penetrators just at the maximum point, as a result , if the velocity of dual-
mode penetrators has been optimize into the optimum combination zone, it is necessary to improve the length of
penetrator which will improve the penetration capability further.
6. Conclusions

Based on a dual-model shaped charge with wave shaper, obtain four types of dual-mode penetrators by simulation. Analyze the influence of different stand-off to the velocity attenuation and hit length changing of dual-mode penetrators EFP and JPC theoretically.

In application of the conservation of energy and impact wave theories, achieve the two-step analytical model of EFP penetrate armor steel and a modified model of final penetration for JPC into concrete with an empirical formula of the mushroom head ratio ; the error of theoretical calculation and experimental data is less than 6.3%.

Analyze the curve of final penetration with the hit condition of dual-mode penetrators to different types of target. Find the optimum matching combination is S3-P2 for the dual-mode penetrators designed in the paper, and obtain the final penetration depth of EFP into armor steel and JPC into concrete appears at $\Delta=0$ and $u(v)/f(v)=0$ point respectively. Before the point appears, improve the velocity of dual-mode penetrators is benefit for the penetration of each mode; if the point appears, there is a primary and secondary order to optimize the velocity and length of different mode penetrators for improving penetration capability.

Acknowledgement

The work presented in this paper has been funded by the National Natural Science Foundation of China under No. 11202103 and Innovation project of Jiangsu Province under No. KYZZ16_0199.

References