Criteria for intermittent and continuous disturbance transition of ERA interaction with shaped charge jet

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Abstract: There are two interaction mechanisms between shaped charge jet and thin flying plate driven by explosion, that is, the intermittent and continuous disturbance. Determination of the transition criteria for the intermittent and continuous disturbance is of importance for the penetration calculation of the escaping jet and the design of ERA (explosive reactive armour). In this paper a new criteria was presented based on the analysis of interaction process, and the effects of NATO angle and thickness of flying plate on the disturbance frequency were discussed. It is shown that the critical shaped charge jet velocity increases with the plate thickness and NATO angle, especially increases drastically between 45° and 60°.

Key words: explosion mechanics; intermittent disturbance; continuous disturbance; explosive reactive armor; shaped charge jet

1 Introduction

Reactive armors are broadly used to protect the main tanks and military vehicles from the attack of the shaped charge jets because of the merits of light weight, small volume, convenient detachment, low cost and high safety. Extensive papers were published on the interaction mechanism between the flying plates and the shaped charge jets after thirty years' working on this high efficiency armor system[1,2]. M. Held has done much work on this interesting topic[3-5]. N. Barenea, N. Sela and M. Ravid[6] presented an analytical model based on the assumption that the interaction of the jet with many flying plates. M. Maysless[7] studied the interaction process and proposed the underlying mechanisms called "pebble-stone" interaction by which a shaped charge jet was defeated.

ERA cassettes are sandwiches basically consisting of an explosive layer contained in two metal plates. The explosive will be initiated when the shaped charge passing through it, the plates driven by the detonation products will fly at very high speed along each normal direction, interacting with the passing jets and making the rods changing the moving direction during this process and losing the original penetration ability. There are three different mechanisms[4]: increased dynamic plate thickness, jet deflection by the inclined flying plates, shock wave and the reaction products.

Commonly there are two regimes of interaction between the fast jets and inclined moving plates, the first is non-stable interaction of wavy character called the intermittent interaction and the second, is a smooth deflection of the jet indicting steady state interaction, called sustained interaction. The intermittent interaction means that after detonation, the metal plates driven by the high pressure move in the opposite direction along each normal direction, during this process the coupling of the flying plates and the crater of the fast jets in the plates makes the interaction at intervals. Otherwise, if the impact pressure is not strong enough, that is, below a certain velocity, called the critical jet velocity, the cycle may be too short, the disruption amplitude will be small and the jet elements will be a smoothly deflected. The criteria between intermittent and continuous interaction is important for the residual penetration calculation of the escaping jets and the design of the ERA.

2 N. Barenea's criteria

In his analytical model[6], N. Barenea proposed a simple criterion to distinguish between the two interaction regimes:

$$\frac{(D_c\cos\theta - d_j)}{U_y t_e} \leqslant \varepsilon \tag{1}$$

Here, ε is a small positive empiric constant taken to be 0.2, U_y is the plate velocity along the y direction, D_c is the Szendrei formula for the crater diameter

produced by a jet of velocity V in a semi-infinite target.

$$D_c = \frac{\sqrt{\rho_p \rho_j}}{\sqrt{2}\sigma_p \left[\sqrt{\rho_p} + \sqrt{\rho_j} \right]} \times d_j \times V \qquad (2)$$

ρ_p, ρ_j are the density of the plate and shaped charge jet respectively, d_j is the jet diameter and σ_p is the plate dynamic strength.

t_e is the effective crater time given as:

$$t_e = \frac{\alpha H_i}{U_p \cos\theta} \quad i = 1,2,3 \qquad (3)$$

α is an experimentally determined constant set to be 4.5. H is the thickness of the plate or explosive, U_p is the plate velocity.

The empiric constant in this criterion is difficult to be determined, and the physical meaning is not clear.

3　New criterion for the interaction regimes transition

3.1　Physical model of disturbance frequency calculation

Suppose a shaped charge jet produced at the virtual origin at a standoff distance S_0 at time $t = 0$, the jet radius is r_j and the jet head velocity is V_{j0} at the angle ε between the normal of the plates and the jet direction (NATO angle), the thickness of the front plate, back plate and explosive layer plate are T_f, T_b, T_e respectively. The explosive will be initiated when the shaped charge jet penetrates the ERA and the plates will fly at the speed of V, the physical model of interaction between flying plates and jet is shown in Fig.1.

To simplify the theoretical analysis of this problem, the basic assumptions have made as follows:

1) Lateral size of the plates is large enough to neglect the effect of the side rarefaction wave in the metal plate.

2) Shaped charge jet remains continuous during its interaction with metal plates and the effect of the reaction products is neglected. In fact the action of the detonation products and high pressure is very short and is secondary in anti-shaped charge jets penetration.

3) The explosive will be initiated after the jet penetrates through ERA. The first shock in the front of the jet head will desensitize the explosive and there is a delayed transition time.

4) Yield strength of the shaped charge jet is negligible, which will not make the adjacent jet element change.

Suppose the point B and point F locate at the edge of the back plate and front plate, coordinate system is shown as Fig.1, the crater velocity is:

$$r_c(t) = \sqrt{A/B - \left[\sqrt{A/B - r_j^2} - \sqrt{B}t \right]} \qquad (4)$$

$$A = r_j^2 \cdot V_{j0}^2 \left[1 + \sqrt{\rho_t/\rho_j} \right]^{-1} \qquad (5)$$

$$B = 2R_t/\rho_t \qquad (6)$$

r_c is the crater radius, R_t is the dynamic strength of the plate, ρ_t, ρ_j are the density of the plate and jet respectively.
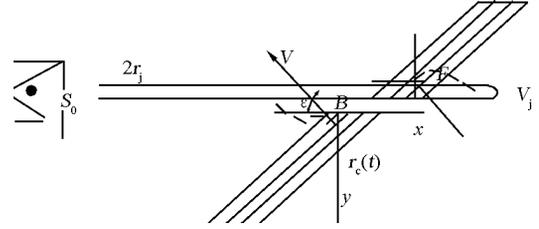

Fig.1　Physical model of interaction frequency between flying plates and jet

The equation of movement locus of point B is:

$$\begin{cases} x = Vt\cos\varepsilon \\ y = Vt\sin\varepsilon - r_c(t) \end{cases} \qquad (7)$$

Eliminate t, and with Eq.(3) we have

$$y = x\,\mathrm{tg}\varepsilon - \sqrt{\frac{A}{B} - \left[\sqrt{\frac{A}{B} - r_j^2} - \frac{\sqrt{B}x}{V\cos\varepsilon} \right]^2} \qquad (8)$$

Let $y = 0$, we can get the distance between the initial point to the next crossing point on the x axis, and with Eq.(5) and Eq.(6):

$$x = \frac{\left[\sqrt{A - Br_j^2} \pm \sqrt{A + V^2 r_j^2 \sin^2\varepsilon} \right] V\cos\varepsilon}{B + V^2 \sin^2\varepsilon} \qquad (9)$$

Taking the real interaction process and the plate thickness, that is, x and V must be in the same direction, choose " $+$ ".

3.2　New criterion determination

When the distance between the two points is no more than the plate thickness the process can be regarded as continuous interaction. The transition criteria for the two regimes can be written as:

$$\frac{\left[\sqrt{A - Br_j^2} + \sqrt{A + V^2 r_j^2 \sin^2\varepsilon} \right] V\cos\varepsilon}{B + V^2 \sin^2\varepsilon} \leqslant \frac{T_p}{\cos\varepsilon} \qquad (10)$$

For example, suppose a jet parameters: $V_{j0} = 8.0 \times 10^3$ m/s, $r_j = 1.0 \times 10^{-3}$ m, $\rho_j = 8.9$ g/cm³, $S_0 = 0.025$ m; and the plate parameters: $\rho_t = 7.85$ g/cm³, $R_t = 500$ MPa, $V = 800$ m/s, $\varepsilon = 60°$, $T_p = 2$ mm. From Eq.(10), the when the jet velocity $V_j = 5\,800$ m/s, the interaction regime will change, that is, below this velocity, the shaped charge jet elements will be disturbed continuously.

4　Results and discussion

1) Plate thickness effect on the disturbance transition

Change the plate thickness only while keep others constant, the relation between the critical velocity and plate thickness is shown as Fig.2. The critical velocity

increases with the plate thickness, when the plate thickness is 3 mm and velocity is 800 m/s, the jet critical velocity can get to 8.6 km/s.
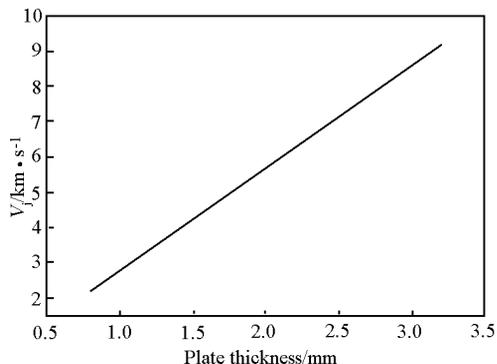

Fig. 2   Relation between the plate thickness and the critical jet velocity

2) Effect of the NATO angle

Other parameters kept constant, only the NATO angle is changed, the relation between the jet critical velocity and NATO angle is shown as Fig. 3. The critical jet velocity increases with the NATO angle. The critical velocity increase slowly when the NATO angle is below 45°, while between 45° and 60°, it increases drastically, when the NATO angle is 65°, for this system the interaction transition can occur at the shaped charge jet velocity 8 800 m/s. Obviously, the equivalent plate thickness increases with the NATO angle.
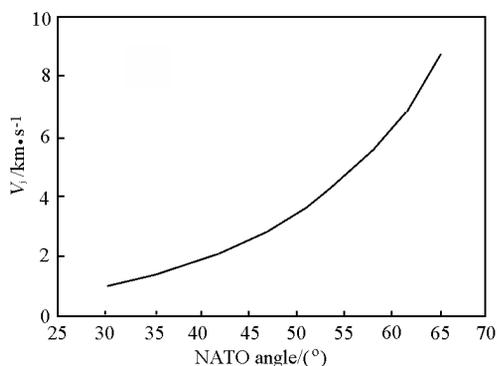

Fig. 3   Relation between the NATO angle and critical jet velocity

Generally, in the continuous disturbance style, the shaped charge jet will be disturbed more seriously, and the residual penetration will be less, that is, the disturbance effectiveness is higher, so the residual penetration can be used to represent the disturbance effect. Here, some experiments have been done by Held with 96 mm shaped charge under different NATO-angles at 2 caliber standoff. The experiments results are given in Table 1.

Table 1   Residual penetrations in the steel at the NATO-angles of 30o, 40°, 60°[8]

No.	NATO-angles/(°)	Penetration/mm
1	30	461
2	40	294
3	60	140

Test results are given in Fig. 4, from it, we can see that the residual penetration depth become less with the larger NATO-angle, that is, the critical jet velocity become larger.
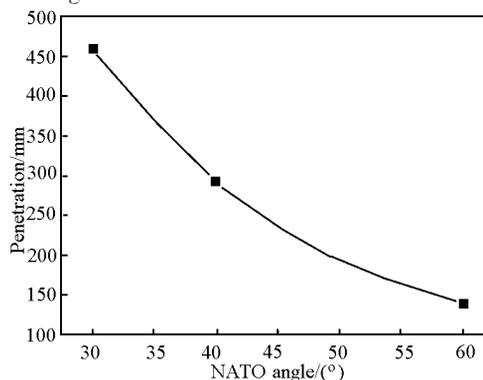

Fig. 4   Residual pentration at NATO-angle of 30°,40°,60°

5   Conclusions

From the present investigation, it can be concluded as follows:

1) Criteria presented for the disturbance regimes between ERA and shaped charge jet here include the parameters of the jet and ERA, compared with the N. Barenea's criteria.

2) The critical shaped charge jet velocity increases with the plate thickness.

3) The critical jet velocity increases with the NATO angle, especially increases drastically between 45° and 60°.

References

[1]　Held M. Invertor[P]. British Patent: 1581125, 1974.

[2]　Zhu Dingbo, Li Jingyun, Li Dejun. Disturbance on an armour-piecing jet caused by an explosive armour[J]. Acta Armamentar, 1991, 2(1): 46-52.

[3]　Held M. Verification of the equation for radial crater growth by shaped charge jet penetration[J]. Int. J. Impact Engng. 1995, 17: 387-398.

[4]　Held M. Momentum theory of explosive reactive armours[J]. Propellants, Explosives, Pyrotechnics, 2001, 26:91-96.

[5]　Held M. Disturbance of shaped charge jets by bulging armour[J]. Propellants, Explosives, Pyrotechnics, 2001, 26:191-195.

[6]　Barenea N, Sela N, Ravid M. An analytical model for shaped charge jet interaction with reactive armour and residual penetration [A]. 14th ISB[C]. Canada,1993:651-660.