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A COMPUTATIONAL METHOD OF FAST SIMULATING FULL-PHYSICS PROCESS OF SHAPED CHARGE

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A computation method of fast simulating full-physics process of shaped charge is advanced, which is an Eulerian numerical method combined with the VMO theory of jet element penetration and the model of Thomas' quasi-steady crater formation during the quasi-steady penetration stage. The comparisons of its computational results of examples with pure numerical solution of MEPH code and experimental ones are given.

INTRODUCTION

The jet formation in shaped charge and the jet penetration to the target is a complicated dynamic process, which is made by a strong blast load of short duration. At present, only depending on numerical method, can it be well investigated. Because the pure numerical solutions require very advanced computer, therefore, it does not suit for 2-D engineering optimization design of shaped charge. Recently, a kind of computational method has been developed in which numerical simulations are combined with analytical solution in different stages, such as AUTODYN, etc. Most of them are based on Lagrangian method and are combined with PER analytical theory during liner collapse. It can speed up the computation of the process of the jet formation, but it cannot speed up the computation of the process of the jet penetration to thick target, which spends enormous CPU time.

This paper is based on Eulerian computational method and is combined with the VMO theory[1] of the jet element penetration and model[2] of Thomas' quasi-steady crater formation during the quasi-steady penetration stage. This computational method can exactly simulate the full-physics process for various shaped charges, and can solve the contradiction between the computation accuracy and CPU speed. It can be extended and applied to 2-D engineering optimization design of various shaped charges.

1 NUMERICAL METHOD

Except special explanation, all signs are in accord with general recognition.

By using the finite difference method, the following 2-D non-steady elasto-plastic hydrodynamic conservation equations in Eulerian cylindrical coordinate system are solved discretely.

$$\rho \frac{d(F1)}{dt} = \frac{1}{r}\frac{\partial(F2)}{\partial r} + \frac{\partial(F3)}{\partial z} + F \tag{1}$$

$$F1=\begin{bmatrix} 1/\rho \\ u_r \\ u_z \\ e+(u_r^2+u_z^2)/2 \end{bmatrix}, F2=\begin{bmatrix} ru_r \\ r(\sigma_{rr}-q_r) \\ r\sigma_{rz} \\ r(\sigma_{rr}u_r+\sigma_{zr}u_z-q_r u_r) \end{bmatrix}, F3=\begin{bmatrix} u_z \\ \sigma_{rz} \\ \sigma_{zz}-q_z \\ \sigma_{zz}u_z+\sigma_{zr}u_r-q_z u_z \end{bmatrix}, F=\begin{bmatrix} 0 \\ (\sigma_{rr}+\sigma_{zz}+3p+q_r)/r \\ 0 \\ 0 \end{bmatrix} \tag{2}$$

Where

$$\sigma_{ij} = -p\delta_{ij} + s_{ij}, \quad \delta_{ij} = \begin{cases} 0 & i \neq j \\ 1 & i = j \end{cases} \tag{3}$$

$$p = \left[c_0^2(\rho-\rho_0) + (K-1)\rho e\right]\left[1-2y/(3c_p)\right], \quad y = \begin{cases} y_0(1-e/e_m) & e < e_m \\ 0 & e \geq e_m \end{cases} \tag{4}$$

$$\dot{s}_{ij} = 2\mu\left[\dot{\varepsilon}_{ij} + \delta\,\dot{\rho}/(3\rho)\right] - \omega_{ij} \tag{5}$$

$$\dot{\varepsilon}_{rr} = \partial u_r/\partial r, \quad \dot{\varepsilon}_{rz} = (\partial u_r/\partial z + \partial u_z/\partial r)/2, \quad \dot{\varepsilon}_{zz} = \partial u_z/\partial z \tag{6}$$

$$\omega_{rr} = -\omega_{zz} = -(\partial u_r/\partial z - \partial u_z/\partial r)s_{rz}, \quad \omega_{rz} = (\partial u_r/\partial z - \partial u_z/\partial r)(s_{rr} - s_{zz})/2 \tag{7}$$

$$q_k = \rho(f_k)(a_k^2 f_k + a_c c), \; f_k = |\partial u_k/\partial k| - \partial u_k/\partial k, \; k = (r,z) \tag{8}$$

If equivalent stress satisfies Mises, R. von yield condition, the computation for S_{ij} should be corrected; if $e \geq e_m$, then set $S_{ij}=0$ and $y_0=0$; the reaction process of energetic material is described by Wilkins reaction speed function.

2 ANALYTICAL MODEL

2.1 Virtual Multi-Origin Jet element Penetration Theory

Virtual Single-Origin (VSO) element jet penetration theory can only be applied to estimate the penetration problems of continuous jet with linear speed distribution.

For the jet with arbitrary energy distribution, it can be treated as L jet segments; the speed distribution in each segment is linear approximately. If the influence of the jet strength being considered simultaneously and assuming that:

A. the penetration of the broken jet element starts at T_b from the m (n)-th element with speed $V_{mn}=V_b$ in the n-th segment,

B. the influence of the gaps among broken jet segments on the DOP is offset by the opposite influence of the segments stretches during the time from T_b to itself joining penetration on the DOP,
then, we can easily extend from VSO theory to VMO theory including the broken jet penetration by the recursive method, and obtain total DOP as

$$P = P_c + P_b \tag{9}$$

$$P_c = \sum_{N=1}^{n} P_{N-1} + \left(h_n + \sum_{N=1}^{n} P_{N-1}\right)\left[(V_{1n}/V_b)^{1/\gamma} - 1\right] \tag{10}$$

$$P_b = Z_{bcr} + \left\{\sum_{N=1}^{n} T_{N-1} + \left(h_n + \sum_{N=1}^{n} P_{N-1}\right)\left[(V_{1n}/V_b)^{(\gamma+1)/\gamma} - 1\right]\Big/ V_{1n}\right\}(V_b - V_{cr}) \tag{11}$$

$$\gamma = (\rho_t/\rho_j)^{0.5} \tag{12}$$

Where, V_{cr} is the jet critical penetration velocity; Zbcr is the distance between Vb jet element and V_{cr} jet element at the moment when head jet impacting target. For the L-th jet segment, we have

$$P_l = \left[h_l + \sum_{L=1}^{l} P_{L-1}\right]\left[(V_{1l}/V_{ml})^{1/\gamma} - 1\right] \tag{13}$$

$$T_l = \left[h_l + \sum_{L=1}^{l} P_{L-1}\right]\left[(V_{1l}/V_{ml})^{(1+\gamma)/\gamma} - 1\right]\Big/ V_{1l} \tag{14}$$

$$h_l = h - z_l \tag{15}$$

$$z_l = m^{-1}(l)\sum_{M=1}^{m}(z_{Ml} + V_{Ml} t_l) \tag{16}$$

$$t_l = \left[m^{-1}(l)\sum_{M=1}^{m} V_{Ml}\sum_{M=1}^{m} z_{Ml} - \sum_{M=1}^{m} V_{Ml} z_{Ml}\right]\Big/\left\{\sum_{M=1}^{m} V_{Ml}^2 - m^{-1}(l)\left(\sum_{M=1}^{m} V_{Ml}\right)^2\right\} \tag{17}$$

Where, (z_l, t_l) and h_l are the VO-coordinate and the Virtual Standoff. $m(l)$ is the number of jet elements. z_{Ml} and V_{Ml} are the axial coordinate and speed of each jet element. V_{1l} and V_{ml} are speeds of head and end elements respectively. $P_l(P_0=0)$ and T_l are the total DOP and penetration time.

2.2 Model of Quasi-Steady Crater Formation

We adopt the efficiency model of Thomas' quasi-steady crater formation[2]. After the distribution of kinetic energy of jet is computed by 2-D Eulerian code, and the DOP of jet element be calculated by 1-D VMO theory, then according to the Thomas' model, we can obtain the corresponding diametrical radius rt of penetrated hole as

$$(r_t/r_j)^2 = \rho_j V_j^2 / [2R(1 + C_l/\gamma)]^2 \tag{18}$$

Where, the resistance R of target and the dynamic stretch coefficient C_l of jet can be determined by experimental and analytical methods[2].

3 LINKAGES AND STAGNATION CRITERION OF PENETRATION COMPUTATION

When the motion characteristic of the fluid space-time distribution that is described by numerical solution satisfies those physical assumptions in VMO and Thomas' analytical models: i.e. there is no momentum exchange among jet elements, and they are all approximately in quasi-steady motion, satisfy $dV_j/dt \ll \varepsilon_v \ll 1$, simultaneously, if the axial variation of the diameter near the bottom of the penetrated hole satisfied $\partial r_t/\partial z \ll \varepsilon_r \ll 1$, also is in accord with the characteristic of quasi-steady penetration, then, the results of numerical solution of 2-D non-steady can be transformed equivalently into the initiation and boundary condition of two-direction 1-D non-steady analytical solution. Meantime, the transition from numerical solution to analytical solution can be performed timely.

When the speed of jet element is equal to or less than the critical penetration speed, or the whole jet mass has already depleted, then, the stagnation of penetration can be determined.

4 EXAMPLES

Example B1 computes the process made by the short standoff, in which the collapse of the liner of shaped charge and the penetration of jet to multi-layer composite target composed of steel, water and concrete are concurrent (table 1). Example B2 computes the penetration of broken jet to semi-infinite steel target under the condition of the long standoff (Table 1). The results of fast computational method (FC) are shown in Figure 1 and Table 2, and are compared with results of MEPH[3] code and experiment.

Compared with experiment, the errors of the jet head speed, DOP to target and the diameter of hole are all less than 10%. Compared with pure numerical solution of MEPH code, FC method reduces CPU time by 80% (personal computer).

Table 1: The computational examples

Example	Shaped charge		Explosive mass/kg	Liner mass/kg	Standoff/mm
	Length/mm	Calibre/mm			
B1	52	41	0.0246	0.0413	18
B2	243	150	4.6100	0.7500	710

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Table 2: The comparisons of computational results with results of meph code and experiments.

Example	Jet		Penetration				Expending CPU time/s	
	Head speed/(km/s)		Last-layer DOP/mm		Quasi-steady stage average hole diameter/mm		FC	MEPH
	FC	Exp.	FC	Exp.	FC	Exp.		
B1	5.22		494	468	9.1	8.6	12182	60965
B2	7.76	7.16	1100	1035	26.8	28.6	48628	374061

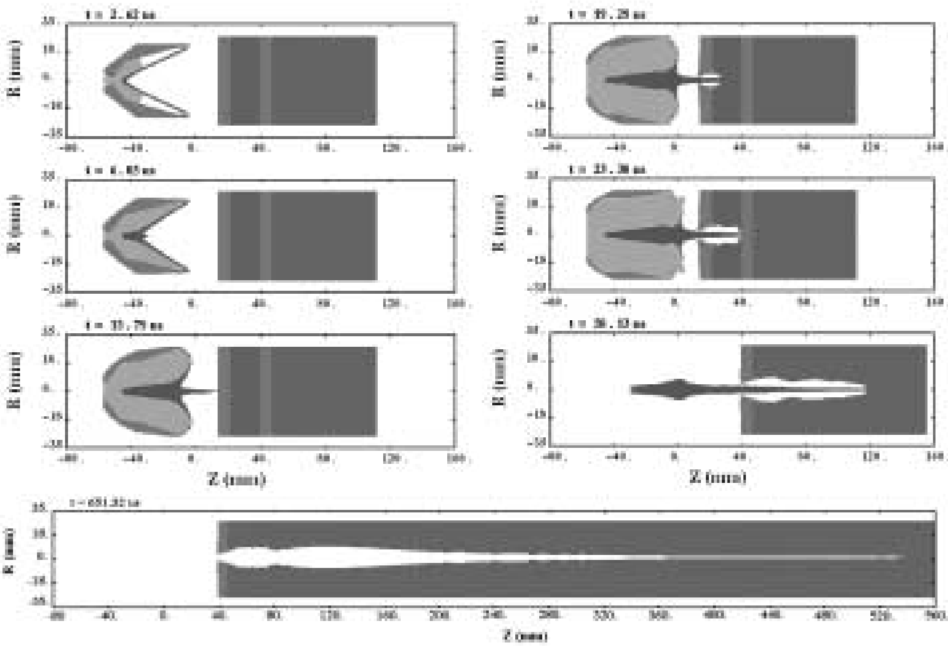

Figure 1: The fast simulating results of full-physics process for shaped charge.

5 CONCLUSION

The fast computation method not only can exactly simulate the full-physics process for various shaped charges (short or long standoff, multi-layer composite or semi-infinite thick target, homogeneous or non-homogeneous material), but also can solve the contradiction between the computational accuracy and CPU speed. Thus, it can be extended and applied to 2-D engineering optimization designs of various shaped charges accurately and economically.

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