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多级炸药装置驱动高速飞片研究

HIGH VELOCITY FLYERS ACCELERATED BY MULTISTAGE EXPLOSIVE SLABS

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多级炸药装置驱动高速飞片研究

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摘　要

讨论了初级飞片撞击起爆炸药块，使之发生强爆轰并驱动次级飞片达到高速度的理论问题。解析分析表明，初级飞片作用下炸药块中形成强爆轰逐渐衰减成为正常爆轰，波后产物具有较宽的压力平台，可以有效地使次级飞片加速到 6～7 km/s，再经过阻抗匹配的组合飞片增速，得到 10 km/s 以上速度的完整末级飞片。这种装置结构简单，操作简便，成本较低，作为高速碰撞和动高压加载的撞击器，具有重要的应用前景。

High Velocity Flyers Accelerated by Multi Stage Explosive Slabs

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ABSTRACT

The problem of accelerating metallic flyers to ultra high speed with strong detonating explosive slabs has been analyzed and numerically simulated in the paper, where the next stage explosive slab is impacted by the flyer of previous stage and accelerates the another next stage flyer to a higher speed. There is a high plateau in the detonation products pressure profile of the slab, to which the effective acceleration is attributed. A combination of impedance matched flyers of the final stage is impacted by the strong detonating explosive driven flyer at speed 6～7 km/s, and could be sped up over 10 km/s. This kind of high speed impactors have the advantages of simple structure, lower cost, smart design and promising in many applications of high dynamic pressure loading and high velocity impact.

INTRODUCTION

In order to study dynamic behaviors of materials under very high pressure ($10^2 \sim 10^3$ GPa), and high velocity impact phenomena, many dynamic loading techniques, such as light gas gun, high power laser and underground nuclear explosion, have been developed. But these devices are expensive, bulky, and with many limitations in use. By means of several stages of the explosive slab-flyer combinations the final stage flyer could be sped to a very high velocity over 10 km/s. This test set-up is simple and useful as a dynamic loading method[1~3].

In this paper, the strong detonation propagation in the explosive slab impacted by the previous stage flyer and the acceleration of this stage flyer by the strong detonation products have been analyzed with one dimensional gas dynamics theory and the Gurney model. Furthermore, the complete dynamic process in a three stage device has been numerically simulated with the one dimensional reactive hydrodynamic elastic and plastic code SSS. The calculation indicates that the velocity of the last molybdenum flyer can be over 14 km/s. This prediction should be verified and improved by the experiments to be conducted.

1 STRONG DETONATION PROPAGATION IN EXPLOSIVE SLAB

1.1 Steady Strong Detonation

Let D_J denote the normal steady detonation speed and γ the isentropic index of detonation products of the explosive slab which is impacted by a planar rigid piston at a constant velocity u_0. A strong detonation will form in the slab if u_0 is greater than the CJ particle velocity $u_J = D_J/(\gamma+1)$. Behind the detonation front the products flow field is uniform and with a particle velocity u_0. If the initial pressure p_0 ahead of the front is neglected, the steady strong detonation speed D can be deduced as[4]

$$D = \frac{D_J^2 + (\gamma+1)^2 u_0^2}{2(\gamma+1)u_0} \tag{1}$$

The strength of a strong detonation can be characterized by the parameter z defined as

$$z = [1-(D_J/D)^2]^{1/2} \tag{2}$$

Obviously, $0 \leqslant z \leqslant 1$, $z = 0$ or 1 denotes CJ detonation or the extremely strong detonation respectively. With the parameter z, the flow variables just behind the strong detonation front are

$$u=\frac{D(1+z)}{\gamma+1},\ v=\frac{v_0(\gamma-z)}{\gamma+1},\ p=\frac{\rho_0 D^2(1+z)}{\gamma+1},\ c^2=\frac{\gamma D_J^2}{(\gamma+1)^2}(1+z)(\gamma-z) \tag{3}$$

Where the reaction zone thickness is neglected, u, v, p and c are particle velocity, specific volume, pressure and sound speed of detonation products respectively, $\rho_0 = 1/v_0$ is explosive density. In the following, we use above symbols to denote the corresponding dimensionless variables whose dimension factors are ρ_0, D_J and explosive slab thickness l. Then the Riemann invariants can be expressed as

$$\alpha=u+\frac{2c}{\gamma-1}=\frac{3\gamma-1}{\gamma^2-1}+\frac{2z}{\gamma+1}-\frac{(\gamma+1)z^2}{4\gamma(\gamma-1)}+O(z^3)$$

$$\beta=u-\frac{2c}{\gamma-1}=-\frac{1}{\gamma-1}+\frac{(\gamma+1)z^2}{4\gamma(\gamma-1)}+O(z^3) \tag{4}$$

1. 2 The Quasi-Steady Approximation of Strong Detonation Propagation

After the impactor flyer M_1 with initial velocity u_0 hits an explosive slab, a strong detonation is induced in the slab. Then the detonation products push the flyer backwards, therefore, the strong detonation front is sped down. The interaction between M_1 and the strong detonation front proceeds until the detonation front becomes a normal one. In order to uncouple this interaction, the quasi-steady approximation is assumed that the rigid flyer M_1 acts as a piston and moves under the pressure of uniform detonation products described by Eqs. (1) and (3), where u_0 should be replaced by the flyer's instant velocity U_1. The flyer acceleration can be described by

$$M_1\frac{dU_1}{dt}=-p=-DU_1 \tag{5}$$

where M_1, U_1 and t are flyer's dimensionless mass per unit area, velocity and time respectively. Denote x_D as the detonation front position, $dx_D/dt=D$ yields

$$dx_D/dU_1 = -M_1/U_1 \tag{6}$$

Under the initial conditions $t = 0$: $x_D = 0$, $U_1 = u_0$, we integrate Eq. (6) and get

$$U_1/u_J = \mathrm{tg}[\mathrm{arctg}(u_0/u_J)-t/2M_1]$$

$$x_D = M_1\ln(u_0/U_1) \tag{7}$$

U_1 decreases as t increases. At $t = t_J$, U_1 becomes u_J, then the strong detonation becomes the normal detonation or CJ detonation. The transition time is

$$t_J = 2M_2[\mathrm{arctg}(u_0/u_J)-\pi/4] \tag{8}$$

1.3 The Linear Approximation of Strong Detonation Propagation

If z is small and the terms of z^2 and higher order can be neglected, the Riemann invariant β is approximately equal to β_J, and the detonation front is controlled by the invariant α depending on the impactor flyer. The α family of characteristics will be a truncated fan with the center coordinates as[5]:

$$x_* = -\frac{1+4u_0}{\upsilon(1+2u_0)^2}, \quad t_* = -\frac{2}{\upsilon(1+2u_0)^2} \tag{9}$$

where $\upsilon = 16/27\ M_1$, the point for flyer M_1 to impact the explosive slab is taken to be the origin of (x, t) coordinate. The locus of strong detonation front is described by the following equations

$$\begin{aligned} &\mathrm{d}x_D/\mathrm{d}t = D(z) \\ &(x_D - x_*)/(t - t_*) = u + c = \alpha(z) \end{aligned} \tag{10}$$

and the initial condition $t = 0$: $x_D = 0$.

If we take the linear approximation

$$D(z) \approx 1 + z^2/2, \quad \alpha(z) \approx 1 + z/2$$

Then obtain

$$\begin{aligned} x_D - x_* &= \frac{(t-t_*)[3+C(t-t_*)]}{2+C(t-t_*)}, \\ D &= 1 + \frac{2}{[2+C(t-t_*)]^2} \end{aligned} \tag{11}$$

Where $C = 2\upsilon(1-2u_0)(1+2u_0)^2/(4u_0-1)$.

The approximate solution (11) is only valid for $1/4 \leqslant u_0 \leqslant 1/2$, where $u_0 \geqslant 1/4$ is the necessary condition for strong detonation, and for $u_0 = 1/2$ Eq. (11) yields $z = 1$, i. e., the extremely strong detonation. Obviously, this limitation is unreal due to the linear approximation, and hence Eq. (11) can be only employed near $u_0 = 1/4$.

2 ACCELERATION OF FLYER BY STRONG DETONATION PRODUCTS

2.1 1-D Unsteady Gas Dynamics Theory

Because of the interaction between the impactor flyer and the detonation front, there is not any exact solutions to the strong detonation propagation and to the resulting movement of the secondary flyer driven by it. But it is still possible to obtain some approximate solutions for the secondary flyer acceleration on the basis of the quasi-steady or the linear approximation mentioned above. It is easy to understand that the thickness of explosive slab is quite important. Under the action of the same impactor flyer, the detonation speed and pressure plateau in a thin explosive slab are higher, but the products flow is with less mass and affected by serious rarefactions. On the other hand, for thicker explosive slabs, the detonation may attenuate to a normal one soon and the products flow may become the Taylor wave before reaching the secondary flyer, so that the acceleration will degenerate.

For the quasi-steady approximation, the selection of explosive slab thickness is based on the principle that the detonation front just runs through the explosive slab at t_J. The secondary flyer M_2 moves under the truncated center rarefaction wave, and can be calculated by the one dimensional gas dynamics theory.

2. 2 Improved Gurney Model

In order to estimate the final velocities of $U_{1\infty}$ and $U_{2\infty}$ for M_1 and M_2, the Gurney model is a convenient approach. Assume that flyers M_1 and M_2 are both rigid, and the product particle velocity between them is of linear distribution. We improve the Gurney model with the modification of M_1 having an initial velocity $U_0 > 0$ and get

$$\begin{cases} U_{1\infty} = [2M_1U_0 - (1+2M_2)U_{2\infty}]/(1+2M_1) \\ U_{2\infty} = [-H + \sqrt{H^2+4FI}]/2F \end{cases} \tag{12}$$

where

$F = (1/3+M_2)+G/3+(1/3+M_1)G^2$

$G = -(1+2M_2)/(1+2M_1)$

$H = 2M_1U_0[1+6(1/3+M_1)G]/3(1+2M_1)$

$I = u_g^2 + M_1U_0^2(1+8M_1/3)/(1+2M_1)^2$

When $U_0 = 0$, $H = 0$, $I = u_g^2$, u_g is the scaled Gurney velocity, Eq. (12) becomes the standard Gurney model. For explosive JO-9159, the Gurney velocity is $u_gD_J = 0.286$ cm/μs. Eq. (12) gives $U_{1\infty}D_J$=0.0335 cm/μs, $U_{2\infty}D_J$=0.6762 cm/μs for U_0D_J=0.47 cm/μs, they are close to the numerical simulation and related test results. Therefore Eq. (12) can be used as a basic tool to optimize the test set-up design.

3 NUMERICAL SIMULATION

The numerical simulation model is illustrated in Fig. 1, where C_1, C_2 and C_3 are three vacuum cavities, and their widths are 10, 8 and 0.005 mm respectively. The thickness of slab 1, M_1, slab 2, M_2 and M_3 are 50, 2.5, 5, 1 and 0.1 mm respectively. The third stage of this system also adopts an inert flyer combination of impedance matching.

The calculation shows that the strong detonation speed reaches 11.1 km/s initially, but soon attenuates to the normal detonation state. The impact of flyer M_1 contributes a part of energy to the explosive slab 2 and results in a slowly increasing pressure profile in its products (see Fig. 2). Therefore flyer M_2 can reach a marked high velocity range close to the detonation speed. Fig. 3 shows the free surface velocity u_2 of flyer M_2. Its final velocity is about 6.7~7.0 km/s. If we use a single stage explosive set-up, the acceleration of a 2.5 mm thick steel flyer up to 7 km/s requires a 25 cm thick slab of JO-9159, whose diameter should be over 50 cm in order to maintain a planar area of detonation wave at its end. This comparison indicates the potential advantage of the multi-stage explosive device.

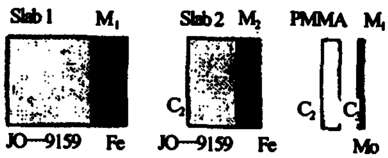

Fig. 1 A illustration of the numerical simulation model

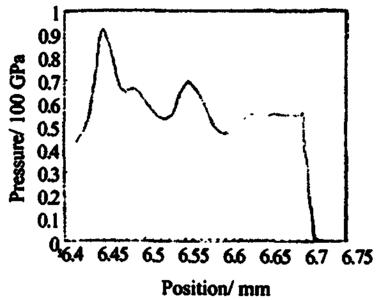

Fig. 2 Pressure in detonation products of explosive slab 2

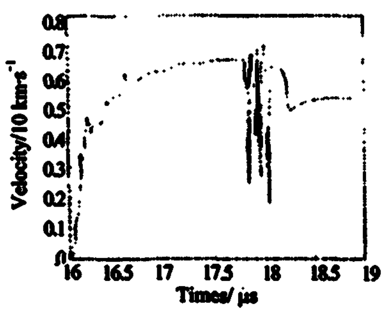

Fig. 3 Free surface velocity of flyer M_2

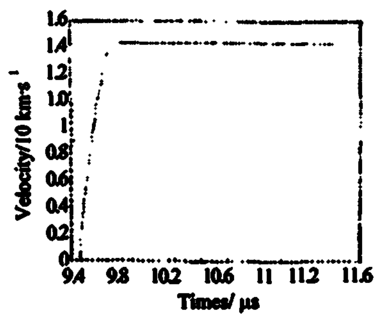

Fig. 4 Free surface velocity history of flyer M_3

As shown in Fig. 4 the free surface velocity u_3 of the last molybdenum flyer M_3 can be up to 14.4 km/s within a acceleration time 0.28 μs.

The precision of the numerical simulation depends not only on the calculation method but also on the thermodynamic constants of flyer materials as well as detonation products. Unfortunately there is no precise experimental data available yet for the strong detonation products. Hence, the last flyer's velocity calculated may be too high. But the possibility to obtain a very high velocity flyer using the strong detonation device is encouraging. It should be pointed out that the flatness of flyers at the impact moments, their stability and reliability in acceleration are quite important to the related experiments.

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