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A Numerical Analysis for Pressure in Mixed Fuel during Launching*

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Abstract: The launching safety of explosive charge drastically affecting the application of high explosive should be used with care. The researchers are interested in the low cost and high efficiency of FAE (fuel air explosive) charged warhead. However, few references about the launching safety of the mixed fuel, especially under high launching load, can be found. In this paper, the pressure and pressure-rate in the mixed fuel during launching was analyzed by the explosion mechanics programming Object MMIC. The analysis shows that the pressure and pressure rate are different from those obtained from the traditional launching safety theory. Therefore, it is necessary for FAE weapon to establish a new launching safety theory by means of the innovative method combining the pressure wave stage with the inertia stage.

Key words: FAE; launching safety; launching load; pressure; pressure rate

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1 Introduction

The launching safety of explosive charge, which affects interior ballistic performance and design of weapons including guns, projectiles, fuses and propellant charge, has been the sophisticated subject of extensive studies. With new warhead technologies being designed and developed to obtain high power, it is necessary to improve the interior ballistic performance. A high initial velocity can be achieved when the gun chamber pressure increases to 500～700 MPa. Furthermore, these high velocities add major concerns to what affect the warhead's design and intended performance. Therefore, the launching safety of explosive charge drastically affects the application of high explosive[1].

The launching safety depends on the property of explosive under impact loading. Conventional launching safety research concentrates on the stage of inertial loading action during launching of warhead. The launching of the explosive charged warhead is described as two stages[2]. The first is the stage of pressure wave action, in which the pressure wave transmits from the bottom to top of the warhead. The second is the stage of inertial loading action, in which the charge is under inertial loading for acceleration during launching of warhead. The first stage is the most dominant for the launching

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safety of charge. Few references on the first stage were reported, and the present studies on launching safety[3] mainly concentrate on the second stage.

FAE has been used in a variety of warheads to gain an excellent efficiency, so the increasing researches are interested in the low cost and high efficiency of FAE warhead. FAE, a mixed fuel, consists of metallic particle and liquid ingredient[4-5]. Thus a special phenomenon will occur during launching because of the liquid ingredient. The physical state of the fuel correlates with its initial physical state and launching load. Under low launching load, the physical state of the liquid ingredient is consistent with that of the solid ingredient and no risk will occur. However, under high launching load, the liquid ingredient may be separated with solid ingredient during launching, which introduces a safety risk. Therefore, it is urgent to study the launching safety of the mixed fuel especially under high launching load.

In this paper, the explosion mechanical programming Object MMIC[6] is used to study the dynamic mechanical properties of the mixed fuel during launching, including the influence of pressure and pressure rate at different positions. Studies in this domain have the potential for gaining information on the underlying behavior of the mixed fuel, leading to predictions for launching safety of the mixed fuel.

The software Object MMIC has used to analyze explosion action in rock, soil and air[7-9] extensively and successfully. It has been proven this code is reliable.

2 Computational Models

Object MMIC compiled by the C^{++} language is a Eulerian Multi-Materials numerical method based on objected-oriented. The programming is considered to be of high reliability and maintainability proved by many emergent engineering problems[7-9].

2.1 Solution Method

The Multi-Materials problem, which means that there are no less than three kinds of materials in the computational zone and in a cell, is always an important research content in the Eulerian numerical method. Rectangle discrete meshes in the axial symmetry or plane coordinates system are applied to treat with the interaction among two or more materials. All the physical properties are located at the center of a cell while the artificial viscosity is located at the center of the side of a cell. Through the pressure effect step and advection step, we can get the computing scheme to resolve the problem. The computing recycle is as following[10]:

(a) Calculating the partial stress of the cell according to the deformation geometry relationship and the stress-strain relationship.

(b) The pressure effect step, also called Lagrange's step, considering the effect of pressure gradient and partial stress to get the temporary velocity and internal energy.

(c) Advection step, also Euler step, remapping the mass, momentum and energy on the Euler mesh to gain the new cell velocity, mass, and energy of each materials in the cell.

(d) To the mixed cell advection, we use two methods.

An advanced method, which is the mixed cell including two kinds of materials, is presented based on the thought of Youngs[10] and Yu[11]. The volume ratios of eight cells around the donor cell are used to decide the interface in the mixed cell (Fig. 1). A approximately straight line in the mixed cell represents the interface of materials. The slope of the straight line is decided by the distribution of the volume ratios of eight cells around the donor cell A. After the slope is decided, the position of the straight line is decided by the volume ratio of materials in the donor cell. According to the reconstructed interface, the volume flow from the donor cell to the accept cell can be calculated, then the flow of mass,

momentum and energy can be calculated.

The SLIC (Simple line in cell) method is used when three materials in a cell. The distributing state of materials is decided by the state of the right and left cell. The interface is constructed through the straight lines that parallel or perpendicular to the advection direction. Finally the advection volume is calculated according to the distribution state in the cell.

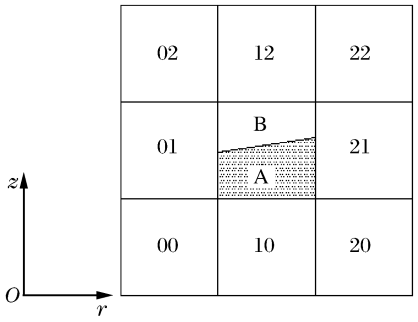


Fig. 1 The interface of materials in the cell

(e) Calculating the pressure of each cell based on the equation of state.

(f) Calculating the next time step according to the stable condition and starting a new recycle.

The new material interface method can describe the objects with complicated shape and improve the material transport precision.

The continuous computational domain is divided into 150×200 rectangular grid. To deal with the boundary condition[12], a row of cell is appended to the boundary cell of the computational domain. z-axis is a symmetry axis. The gun shell is an immovable boundary, and the rest boundaries are transmitting boundaries.

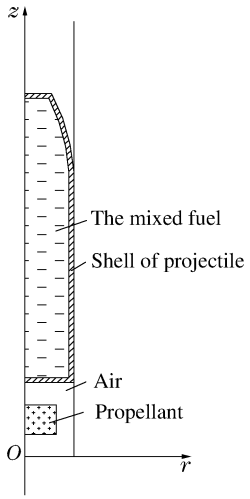


Fig. 2 Arrangement of initial field

2.2 Numerical Model

The physical model used to simulate the propellant field is simply depicted in Fig. 2.

2.3 Governing Equations

A non-conservation partial differential equation is defined as follows[6]

$$\begin{cases} \dfrac{\partial \rho}{\partial t}+u_z\dfrac{\partial \rho}{\partial z}+u_r\dfrac{\partial \rho}{\partial r}+\rho\left[\dfrac{\partial u_z}{\partial z}+\dfrac{\partial (r^\alpha u_r)}{r^\alpha \partial r}\right]=0 \\ \rho\left(\dfrac{\partial u_z}{\partial t}+u_z\dfrac{\partial u_z}{\partial z}+u_r\dfrac{\partial u_z}{\partial r}\right)=-\dfrac{\partial p}{\partial z}+\dfrac{\partial S_{zz}}{\partial z}+\dfrac{\partial (r^\alpha S_{rz})}{r^\alpha \partial r} \\ \rho\left(\dfrac{\partial u_r}{\partial t}+u_z\dfrac{\partial u_r}{\partial r}+u_r\dfrac{\partial u_r}{\partial r}\right)=-\dfrac{\partial p}{\partial r}+\dfrac{\partial S_{rz}}{\partial z}+\dfrac{\partial (r^\alpha S_{rr})}{r^\beta \partial r}-\alpha\dfrac{S_{\theta\theta}}{r} \\ \rho\left(\dfrac{\partial e}{\partial t}+u_z\dfrac{\partial e}{\partial z}+u_r\dfrac{\partial e}{\partial r}\right)=-p\left[\dfrac{\partial (r^\alpha u_r)}{r^\alpha \partial r}+\dfrac{\partial u_z}{\partial z}\right]+S_{zz}\dfrac{\partial u_z}{\partial z}+S_{rr}\dfrac{\partial u_r}{\partial r}+S_{rz}\left(\dfrac{\partial u_z}{\partial r}+\dfrac{\partial u_r}{\partial z}\right)+\alpha\dfrac{u_r S_{\theta\theta}}{r} \end{cases} \tag{1}$$

The above four independent equations are conservation equations of mass, momentum, energy, respectively. Where t, r, and z are variants of time and space; ρ is the density; u_r and u_z are radial and axial velocity of particle, respectively; p is the hydrostatic stress; S_{rr}, $S_{\theta\theta}$, S_{zz} are radial, circumferential and axial partial stress, respectively; S_{rz} is the radial/axial shear stress; and e, α, β are ratio energy, constant and modified coefficient of yield stress, respectively.

2.4 Equations of State

An ideal air law[13] is expressed as

$$p_i=(\gamma-1)\rho_i e_i \tag{2}$$

where γ is the polytropic index, ρ_i is the density of air, and e_i is the ratio internal energy.

The equation of state of the mixed fuel is needed in the simulation. However, no equation of state of the fuel can be gained at present. Because the mixed fuel consists of solid, liquid and air ingredients,

so the equation of state[14] is described as

$$\rho_{\mathrm{f}}=\rho_0\left\{\alpha_{10}\left[\frac{k_1(p_{\mathrm{f}}-p_{\mathrm{f0}})}{\rho_{10}c_{10}^2}+1\right]^{-1/k_1}+\alpha_{20}\left[\frac{k_2(p_{\mathrm{f}}-p_{\mathrm{f0}})}{\rho_{20}c_{20}^2}+1\right]^{-1/k_2}+\alpha_{30}\left(\frac{p_{\mathrm{f}}}{p_{\mathrm{f0}}}\right)^{-1/k_3}\right\}^{-1} \tag{3}$$

where ρ_0 is the initial density of the mixed fuel, α_{i0}, ρ_{i0}, c_{i0} ($i=1,2,3$) are the relative volume, density and sound speed of solid, liquid and air at $p_f=p_{f0}$, respectively; and k_1, k_2, k_3 are adiabatic coefficients of solid, liquid and air, respectively. For the mixed fuel, $\rho_0=1.49$ g/cm^3, $\rho_{10}=2.2$ g/cm^3, $\rho_{20}=1.0$ g/cm^3, $\rho_{30}=1.2\times10^{-3}$ g/cm^3, $c_{10}=4\,500$ m/s, $c_{20}=1\,500$ m/s, $c_{30}=340$ m/s, $k_1=3$, $k_2=3$, $k_3=1.4$.

The shell of the projectile is made of metal, so the state equation of the shell can be calculated by the Mie Grüneisen equation, as follows

$$p_{\mathrm{s}}=p_{\mathrm{H}}(1-\Gamma\mu/2)+\Gamma\rho_{\mathrm{s}}(e_{\mathrm{s}}-e_{\mathrm{s0}}) \tag{4}$$

with

$$p_{\mathrm{H}}=k'_1\mu+k'_2\mu^2+k'_3\mu^3 \qquad \mu\geqslant 0 \tag{5}$$

$$p_{\mathrm{H}}=k'_1\mu \qquad \mu<0 \tag{6}$$

The subscript "H" refers to the Hugoniot curve, while $\mu=\rho_{\mathrm{s}}/\rho_{\mathrm{s0}}-1$ represents the compressed degree and Γ is the Grüneisen parameter. e_{s0} is the initial ratio internal energy per unit mass and e_{s} is the ratio internal energy per unit mass. ρ_{s0} is the initial density and ρ_{s} is the density. k'_1, k'_2, k'_3 are the material constants, respectively.

Although the acting time of propellants and TNT are different, there are some approximations between them considering whether to satisfy the initial stage of launching. The initial stage of launching is studied in the paper, and the duration is less than 100 μs. Hence, it is appropriate for propellant product to use the JWL equation of state[14-15].

2.5 Initial Condition

For a FAE warhead, the mass $m=10$ kg, the outside shell diameter $d_1=100$ mm, the shell thickness is 5 mm, the mass of the mixed fuel $m_1=4$ kg, the inside shell diameter $d_2=90$ mm, the propellant length $h=410$ mm. The pressure and pressure rate of the mixed fuel during launching at the acceleration $a_1=10^4g$ and $a_2=2\times10^4g$ are successfully simulated by Object MMIC, respectively.

The computation is reported as follows. The principal objective is to calculate the over-loading force as well as the pressure of the mixed fuel based on the acceleration. The second approach, the parameters of the propellant chamber are obtained by means of the coupling volume ratio of the propellant, calculated by the formula (7)[3] as follows

$$p=p_0(V_0/V)^{\gamma}=\begin{cases}\dfrac{1}{4}\rho_0D^2(V_0/V)^{\gamma_1} & p>p_{\mathrm{k}}\\ p_{\mathrm{k}}(V_{\mathrm{k}}/V)^{\gamma_2} & p<p_{\mathrm{k}}\end{cases} \tag{7}$$

where p is the pressure in gun, p_0 is the initial pressure in gun, ρ_0 is the initial density of the propellant, D is the detonation velocity, V is the volume of the propellant when the pressure is p, V_0 is the initial volume of the propellant. $p_{\mathrm{k}}=0.2$ GPa is the pressure at separation point, V_{k} is the volume of the propellant at $p=p_{\mathrm{k}}$, γ_1 and γ_2 are the polytropic indexes, of which $\gamma_1=3$ at $p>p_{\mathrm{k}}$, $\gamma_2=1.4$ at $p<p_{\mathrm{k}}$.

The over-loading force is derived to be

$$F_1=m_1a_1=10^6\ \mathrm{N} \tag{8}$$

Then the over-loading pressure of the mixed fuel is equal to

$$p_1=F_1/S=F_1/(\pi d^2/4)=0.127\ \mathrm{GPa} \tag{9}$$

From Eq. (7), V_0/V_{k} is solved

$$V_0/V_{\mathrm{k}}=0.234 \tag{10}$$

The equation for p_1 now is

$$p_1 = 1.27 \times 10^8 (V_0/V)^{1.4} \tag{11}$$

Inserting Eq. (9) into Eq. (11), yields the coupling volume ratio of the propellant chamber $V_0/V \approx 0.17$.

For the propellant, the diameter $d'_1 = 58$ mm, and the height $h_1 = 50$ mm, while for the propellant chamber, the diameter $d'_2 = 100$ mm, and the height $h_2 = 100$ mm.

By means of the same method the actual over-loading of the fuel $p_2 = 0.254$ GPa, the pressure $p_2 = 1.55 \times 10^{10} (V_0/V)^3$, and the coupling volume ratio of the propellant $V_0/V \approx 0.25$. For the propellant, the diameter $d''_1 = 70$ mm, and the height $h'_1 = 50$ mm, while for the propellant chamber, the diameter $d''_2 = 100$ mm, and height $h'_2 = 100$ mm.

3 Results and Discussion

3.1 The Pressure Distribution in the Fuel Medium

The mass ratio of the solid ingredient to the liquid ingredient in mixed fuel is 3 : 2, and the density of fuel $\rho = 1.47$ g/cm^3. "L" is the vertical distance between the position of the fuel and the bottom of the fuel. "R" is the horizontal distance between the position of the fuel and the symmetry axis, where R is 5 mm.

The pressure history of the fuel at $10^4 g$ and $2 \times 10^4 g$ are shown in Fig. 3. The figures show that the pressure calculated at $2 \times 10^4 g$ is greater than that at $10^4 g$ at the same distance. The pressure wave produced by the propellant energy travels in the mixed fuel. There is a drastic release of the propellant energy and a rapid expansion of the propellant gas product. On the pressure-time plot, the pressure rises at a constant rate to a peak value, then drastically decreases to a stable state.

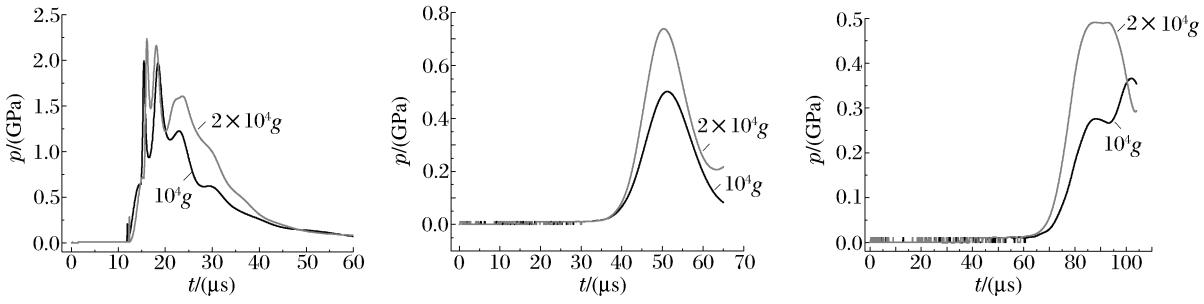


Fig. 3 The pressure distribution of the fuel versus time at different distances at $10^4 g$ and $2 \times 10^4 g$

The momentum developed by the propellant energy is transformed to an impulse delivered to the mixed fuel filled in an artillery projectile during launch. The warhead shell may then rebound and strike the fuel again delivering a second impulse. In the impact mode, i. e. the stage of pressure wave, the pressure in the mixed fuel rises more rapidly to a higher peak due to the inertia effect. The mechanical properties of the mixed fuel depend on its inertia effect and relevant effects. When the pressure wave travels forward until it impacts the top of the mixed fuel, the mixed fuel is assumed to be rigid, and the pressure and pressure rate can be inferred from the breech pressure, called as the stage of traditional inertial over-loading, while in the impact mode, the pressure and pressure rate depend on the total run. The release of the propellant energy and the mechanical properties of the mixed fuel, in this mode, are originally obtained from the rapid release of the propellant energy.

It is revealed that the pressure-time curve in the mixed fuel is different from the traditional pressure-time curve. It should be noted that the difference between the stage of pressure wave and the stage of inertial over-loading cannot be ignored, where the pressure in both conditions is distinct.

Therefore, an important conclusion drawn here is that the traditional launching safety theory is not appropriate to the evaluation of FAE warhead's launching safety.

The plots of the peak pressure p_{max} against the distance L at $10^4 g$ and $2\times10^4 g$ are produced, as shown in Fig. 4. The figure shows that the pressure initially decreases rapidly with increasing distance and then levels off to a sable state. The solution shows that the simulated pressure at the bottom of the fuel has the maximum value.

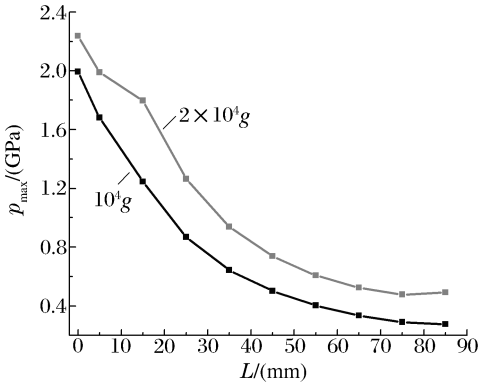
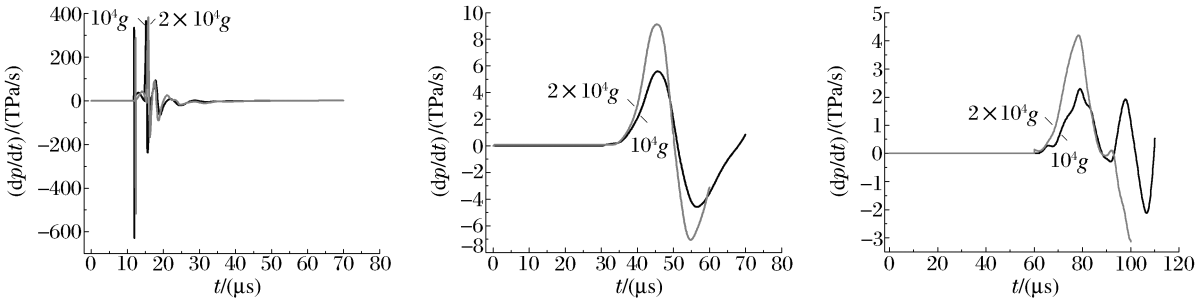


Fig. 4　The peak pressure of the fuel versus distance at $10^4 g$ and $2\times10^4 g$

3.2　Effect of the Stress Rate in Mixed Fuel

During the initial launching of the projectile, the longitudinal over-loading of the projectile leads to impact on the fuel and the shell boundary as well as the occurrence of pressure wave in fuel, where the pressure rate and deforming energy of the charge are main factors. Hence, it is necessary for FAE fuel to analyze the pressure rate during launching. Pressure rate-time curves of the fuel during launching at $10^4 g$ and $2\times10^4 g$ are shown in Fig. 5, thereinto the pressure rate is approximately instantaneous loading and unloading, furthermore, the peak value rises to 100 TPa/s.



L=0　　L=45 mm　　L=85 mm

Fig. 5　The pressure rate distribution of the fuel versus time at different distances at $10^4 g$ and $2\times10^4 g$

The pressure rate rises to a peak value before the maximum pressure. FAE fuel exhibits viscoplasticity[16] when the pressure rate reaches 100 TPa/s. FAE fuel consists of solid particles, liquid ingredient and gas ingredient, so the fuel have the properties of compression and volumetric deformation not being resumed[17]. The pressure rate is the principal parameter governing the deformation of the mixed fuel because the dynamic response of the mixed fuel is sensitive to the pressure rate.

The plots of the peak pressure rate $\dot{p}_{max}$ versus the distance L at $10^4 g$ and $2\times10^4 g$ are shown in Fig. 6. The pressure rate of $2\times10^4 g$ is greater than

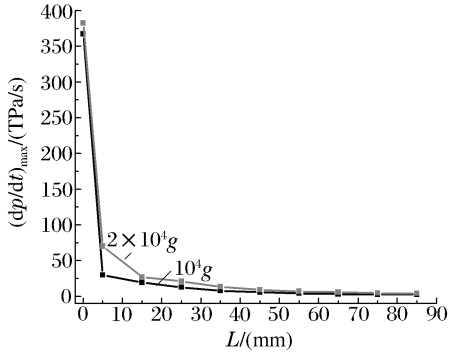


Fig. 6　The peak pressure rate of the fuel versus distance at $10^4 g$ and $2\times10^4 g$

that of 10^4 g at the same distance.

4 Analytical Results Compared with Experimental Data

To compare the numerical compute results with experiments, the stress in the FAE charge is measured with dynamic pressure storage measurement system, as shown in Fig. 7. The experimental configuration is shown in Fig. 8.

For a FAE warhead, the outer shell diameter is 90 mm, and the inner shell diameter is 85 mm. The height of the mixed fuel is 100 mm, 110 mm, 120 mm, 130 mm and 140 mm, respectively.

The dimension of the propellant is ∅30 mm×25 mm. The pressure of the mixed fuel is measured by the piezoelectric pressure-sensor.

The difference between the simulation and the experiment results is shown in Table 1. Seen from Table 1, the simulation provides good results with the highest deviation of 7.8%.

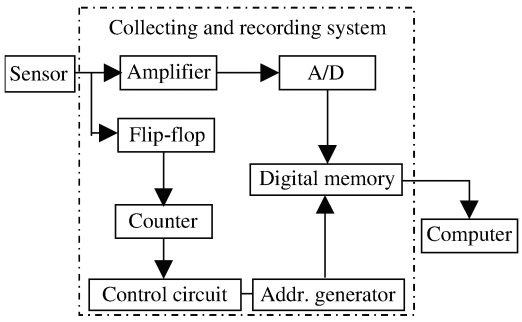


Fig. 7 Dynamic pressure storage measurement system

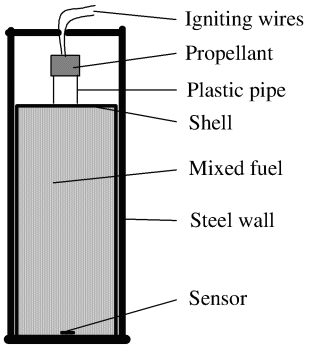


Fig. 8 Experimental configuration

Table 1 Comparison between simulation and experiment data

H/(mm)	Analytical result/(MPa)	Experimental data/(MPa)	Deviation/(%)
100	36.27	34.64	4.5
110	30.94	30.13	2.6
120	28.13	25.94	7.8
130	25.23	25.07	0.6
140	21.74	20.76	4.5

5 Conclusions

The explosion mechanical programming Object MMIC is used to study the pressure and pressure rate in the mixed fuel during launching. In the stage of pressure wave, the pressure and pressure rate are obviously greater than those calculated by the traditional launching safety theory. The results of the analyses indicate that the pressure wave stage and the inertia stage are different. The pressure wave stage is a special stage for the mixed fuel, which cannot occur in the solid charge. Also, it is needed to establish the launching safety theory of FAE warhead by means of the new and innovative method combining the pressure wave stage with the inertia stage.

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发射过程中混合燃料应力状态的数值分析

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摘要: 炸药装药在发射条件下的安全性问题已成为高能量炸药应用的一个技术障碍,引起了各国的广泛重视。燃料空气炸药(FAE)战斗部是近年来倍受国内外关注的新概念武器。目前关于FAE装药的发射安全性特别是高过载环境下的发射安全性研究还不系统、不够深入,也没有给予足够的重视。运用爆炸力学程序Object MMIC程序分析了FAE战斗部发射过程中的应力和应力率变化规律。分析结果表明,FAE战斗部发射过程中受到的应力和应力率不同于传统的发射过程,因此,有必要建立适用于FAE武器的全新的发射安全性理论。这些研究对提高FAE战斗部发射安全性提供了依据。

关键词: 燃料空气炸药;发射安全性;发射过载;应力;应力率

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