Original Research Article

Study on the characteristics of micro pressure control metal diaphragm based on double chamber firing technology

Xin Zhang

Jiangsu Institute of Automation, Lianyungang, Jiangsu, 222000, China

Abstract:This paper examines a micro pressure-controlled metal diaphragm for parallel double chamber firing. The diaphragm, featuring a positive arch and double X-grooves, bursts under pressure without detachment. The convex side bears more pressure. Key parameters, including rupture pressure and diameter, were calculated using design theory. CEL simulations analyzed pressure capacity and rupture deformation. Experiments verified simulations: concave max pressure was 5 MPa, convex 7 MPa, a 40% difference. This design informs multi-chamber weapons and high-pressure devices.

Keywords: Micro pressure control metal diaphragm; Double chamber firing charge; CEL method; Double X-shaped cross groove; CEL

1. Introduction

Sun Shaodong et al[4] found that toroidal notched diaphragm has lowest control thresholds, while cross notched has highest. Mohebbi Morteza et al[5] established an analytical relation to predict rupture thresholds. Chu Zhang et al[6] predicted fatigue life of diaphragm using ABAQUS-SAFE co-simulation. Yu Xiaozhe et al[7] conducted bursting tests, discussing stress-strain relationship of 316L material. Pressure bulge height increases linearly with pressure, and pressure rise rate affects deformation. The face I pulse defect groove controls small opening pressure and rupture size, with an insulating layer[9-10]. CEL method excels in fluid structure coupling problems[11-14]. Li Chengde[15] and Zhou Qingwen[16] used coupled Euler Lagrangian analysis to simulate rock mass impacting water and ship grounding. Quan Xiaobo[17] studied breaking process after buffer head cap collision. Positive arch control diaphragm has cross-grooving for fast response and enhanced rupture, preventing debris splash. Its convex surface serves pressure relief and prevents powder gas flow. Fracture pressure and diameter were determined through numerical analysis and validated by impact test platform.

2. Theoretical research on pressure control metal diaphragm

2.1. Principle analysis of pressure control metal diaphragm in double chamber firing technology

In parallel double chamber firing, the propellant chamber pressure is controlled by a metal diaphragm with equal arcs and a groove. This design eases rupture. At preset pressure, stress focuses at the center, causing fracture and crack propagation. The diaphragm splits into eight lobes. When one chamber fires, powder gas breaches the concave surface, flows to the low-pressure chamber, and impacts the convex surface of the other diaphragm. The convex surface design prevents gas flow into the adjacent chamber, preventing firing phenomena.

2.2. Technical objective of pressure control metal diaphragm in the parallel double chamber firing technology

In the parallel double chamber firing technology, the preset burst pressure and radius of the burst port are closely related to the chamber pressure and instantaneous flow in the trajectory equation of the double chamber. The trajectory equation of the double chamber is as follows:

$$\frac{\mathrm{d}z}{\mathrm{d}t} = \frac{u_1}{e_1} P_g^n \tag{1}$$

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = \chi \frac{\mathrm{d}z}{\mathrm{d}t} + 2\chi\lambda z \frac{\mathrm{d}z}{\mathrm{d}t} + 3\chi\mu z^2 \frac{\mathrm{d}z}{\mathrm{d}t} \tag{2}$$

$$\frac{\mathrm{d}v}{\mathrm{d}t} = \frac{s}{\varphi m} P_q \tag{3}$$

$$\frac{\mathrm{d}L}{\mathrm{d}t} = v \tag{4}$$

$$\frac{\mathrm{d}P_g}{\mathrm{d}t} = \frac{1}{s l_\psi}\left(f\omega \frac{\mathrm{d}\psi}{\mathrm{d}t} - f q_{mb} - s P_g \frac{\mathrm{d}l_\psi}{\mathrm{d}t} \right) \tag{5}$$

$$\frac{\mathrm{d}\eta}{\mathrm{d}t} = q_{mb} \tag{6}$$

$$\frac{\mathrm{d}P_q}{\mathrm{d}t} = \frac{1}{s\left(L_0 + L\right)}\left[f q_{mb} - (\theta+1) s v P q \right] \tag{7}$$

$$\rho_g = \frac{\omega\psi - \eta}{s l_\psi} \tag{8}$$

$$\rho_q = 1.293 + \frac{\eta}{V_0 + sL} \tag{9}$$

$$q_{mb} = \begin{cases} 0 & L \le l_x \\ \mu_b \mathrm{r}_b^2 \pi K_0 \sqrt{P_\mathrm{g}\rho_g} & L > l_x, P_q \le \xi P_\mathrm{g} \\ \mu_b \mathrm{r}_\mathrm{b}^2 \pi \sqrt{\frac{2\gamma}{\gamma-1} P_\mathrm{g}\rho_g \left[\left(\frac{P_q}{P_\mathrm{g}}\right)^{\frac{2}{\gamma}} - \left(\frac{P_q}{P_\mathrm{g}}\right)^{\frac{\gamma+1}{\gamma}} \right]} & L > l_x, \xi P_\mathrm{g} < P_q \le P_\mathrm{g} \\ -\mu_b \mathrm{r}_b^2 \pi \sqrt{\frac{2\gamma}{\gamma-1} P_q\rho_q \left[\left(\frac{P_\mathrm{g}}{P_q}\right)^{\frac{2}{\gamma}} - \left(\frac{P_\mathrm{g}}{P_q}\right)^{\frac{\gamma+1}{\gamma}} \right]} & L > l_x, \xi P_q < P_\mathrm{g} \le P_q \\ -\mu_b \mathrm{r}_b^2 \pi K_0 \sqrt{P_q\rho_q} & L > l_x, P_\mathrm{g} < \xi P_q \end{cases} \tag{10}$$

$$\xi = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \tag{11}$$

$$K_0 = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \tag{12}$$

Table 1. Parameter meaning of ballistic equation in double chamber.

symbol	meaning	symbol	meaning
n	Burning rate index (0.845 in this paper)	P_g	Propellant chamber pressure
z	Burned relative thickness	χ、λ、μ	Drug shape coefficient
u_1	Burning rate per unit pressur	φ	Secondary work factor
e_1	1/2 powder thickness	m	Projectile mass
	Burned relative mass	P_q	Low chamber pressure
v	Velocity of the projectile inside the body	s	Body tube cross section
l_ψ	Chamber volume reduced diameter length	L	Projectile motion travel
q_{mb}	instantaneous flow rate	f	gunpowder impetus
⊔	Powder loading density	V	Chamber volume
p	Powder density	α	Powder gas allowance
η	Powder gas flow rate between propellant chamber and low pressure chamber	r_b	The radius of the pressure control diaphragm between the medicine chamber and the low pressure chamber
L_0	Initial length of low pressure chamber	θ	adiabatic exponent
g	Density of gunpowder gas in the chamber	l_x	0
$_q$	Density of gunpowder gas in low pressure chamber	b	flow coefficient
ω	explosive payload	γ	constant

2.3. Theoretical formula for pressure control metal diaphragm

The relationship between the radius of curvature and the arc height and the diameter of the blasting hole is as follows[18]:

$$R=\frac{4H^2+(2\alpha)^2}{8H} \tag{13}$$

R is the radius of curvature of the arch; H is the arch height of the control diaphragm; α is the radius of the blasting opening for controlling the pressure plate

Without considering the influence of groove width, groove number and groove length, the relationship between the bursting pressure of positive arch groove control diaphragm and the dimension parameter is as follows [19]:

$$P=\frac{0.433}{\mathrm{n}+0.277}\left(\frac{2}{\sqrt{3}}\frac{\mathrm{e}}{\mathrm{n}}\right)^{\mathrm{n}}\sigma_{\mathrm{b}}\frac{S}{\mathrm{R}} \tag{14}$$

P is bursting pressure; n is the strain hardening index (0.42); σ_{b} is the tensile strength of the pressure control sheet material (210MPa); S is the original thickness of the control diaphragm

2.4. Theoretical calculation results of pressure control metal diaphragm

Figure 4 displays internal trajectory analysis of double chamber, showing muzzle velocity and chamber pressure with 2.5mm rupture radius and 5 MPa preset pressure. Barrel movement is 3.338ms, max muzzle velocity 196.146 m/s, max bore pressure 1.7728 MPa at 0.486ms. Studies on charge, diaphragm channel diameter, and chamber volume effects on initial velocity were done. Figures 5(a), 5(b), 5(c) show chamber pressure, charge weight, and chamber volume impact initial velocity. Diaphragm size was calculated using a theoretical formula

(**Table 2**, Figure 6). A Double X-shaped cross groove structure with 4mm length was designed to enhance breaking ability.

Table 2. Bursting disc structure parameters.

H	*h*	*α*	*R*	*S*	*P*
0.5mm	0.05mm	2.5mm	6.5mm	0.1mm	5MPa

3. Analysis based on CEL technology

3.1. Numerical calculation model

This paper utilized the CEL method to simulate the pressure bearing and fracture of a micro pressure control diaphragm under fluid impact, validating its theoretical design. A Euler-Lagrange coupling model was constructed, with Euler domain simulated by linear Us-Up Hugoniot EOS. Constraints were applied to the diaphragm and fluid pipeline with frictionless contact. Fluid impact was simulated by adjusting surface directions, as shown in Fig. 7.

Us-Up Hugoniot equation of state :

$$P=\frac{\rho_0 c_0^2\eta}{\left(1-s\eta\right)^2}\left(1-\frac{\Gamma_0\eta}{2}\right)+\Gamma_0\rho_0 E_m \tag{15}$$

$$\eta=1-\frac{\rho_0}{\rho} \tag{16}$$

$$U_s=c_0+sU_p \tag{17}$$

Newton's viscous shear model:

$$S=2\mu\dot{e}=\mu\dot{\gamma} \tag{18}$$

$$\dot{\gamma}=2\dot{e} \tag{19}$$

In the formula: ρ_0 is the reference density; P Is compressive stress; E_m Is the specific energy; Γ_0 Is the material constant; η Is the nominal volume compression strain; U_s Is linear impact velocity; U_p Is Linear particle velocity; c_0 and s define the linear relationship between U_s and U_p; S Is the deviation of stress; μ Is the dynamic viscosity $\dot{e}$ is the strain rate deviation; $\dot{\gamma}$ Is the engineering partial strain rate.

The specific parameters are:

$c_0=4.22\times10^2\,\mathrm{m/s}$, $s=0$, $\Gamma_0=0$, $\rho=1.25\times10^3\,kg\cdot m^{-3}$, $\mu=1\times10^{-3}\,Pa\cdot s$.

3.2. Material model

Micro pressure control diaphragm made of copper, fluid pipe of structural steel, Euler domain fluid of nitrogen. Controlled pressure diaphragm undergoes elastoplastic deformation and damage under fluid impact, plastic fracture occurs at yield limit. Johnson-Cook plastic fracture failure model used for copper material, parameters in **Table 3.**

Expressions of yield stress, strain rate and temperature in Johnson-Cook plastic constitutive model

$$\bar{\sigma}=\left(A+B\left(\bar{\varepsilon}^{pl}\right)^n\right)\left[1+C\ln\dot{\varepsilon}^*\right]\left(1-\hat{\theta}^m\right) \tag{20}$$

$$\hat{\theta} = (\theta - \theta_{\mathrm{transition}}) / (\theta_{\mathrm{melt}} - \theta_{\mathrm{transition}}) \tag{21}$$

$$\dot{\varepsilon}^{*} = \frac{\dot{\bar{\varepsilon}}^{\mathrm{pl}}}{\dot{\varepsilon}_0} \tag{22}$$

In the formula, A, B, C, n and m are the material parameters measured at the transition temperature $\theta_{\mathrm{transition}}$ less than or equal to; $\hat{\theta}$ Is dimensionless temperature; $\dot{\bar{\varepsilon}}^{\mathrm{pl}}$ Is the equivalent plastic strain rate; $\dot{\varepsilon}_0$ Is the reference strain rate; θ Is the current room temperature; θ_{melt} Is the melting temperature; $\bar{\sigma}$ Is non-zero strain rate yield stress.

Johnson-Cook dynamic failure model expression:

$$\bar{\varepsilon}_{\mathrm{f}}^{\mathrm{pl}} = \left[\mathrm{d}_1 + \mathrm{d}_2 \exp\left(\mathrm{d}_3 \frac{\mathrm{p}}{\mathrm{q}}\right)\right]\left[1 + \mathrm{d}_4 \ln\left(\frac{\dot{\bar{\varepsilon}}^{\mathrm{pl}}}{\dot{\varepsilon}_0}\right)\right]\left(1 + \mathrm{d}_5 \hat{\theta}\right) \tag{23}$$

In the formula, p is compressive stress; q is Mises stress; $\bar{\varepsilon}_{\mathrm{f}}^{\mathrm{pl}}$ Is the strain at failure; d1 ~d5, is the failure parameter measured at the transition temperature $\theta_{\mathrm{transition}}$ or less.

Tab.3 Johnson Cook constitutive model for bursting discs.

r/(kg·m-3)	*E/GPa*	*n*	*A/MPa*	*B/MPa*	*n*
8800	115	0.31	90	292	0.42
m	*m/℃*	*r/℃*	d_1	d_2	d_3
1.68	1058	25	0.54	4.89	-3.03
d_4	d_5	*c*			
0.014	1.12	0.24			

3.3. Grid generation

In the Euler-Lagrange coupling model, grid quality is high. Euler domain uses EC3D8R grids of 0.2mm. Pressure plate and fluid pipeline use C3D8R grids of 0.1mm and 0.4mm, respectively. Grid count affects accuracy and time. Smaller hexahedral grids are used for the micro diaphragm and Euler domain, with encryption at stress concentration. Thicker hexahedral grids are used for the fluid pipeline, as shown in Figure 7.

3.4. Analysis of simulation results

The CEL method simulated pressure rupture of the micro pressure control diaphragm. Initial fluid loading was 5MPa, 6MPa, and 7MPa in the Euler domain, impacting concave and convex surfaces. It simulated fracture states at pressure limits and verified convex surface's pressure relief ability. Fluid distribution in the Euler domain is shown in Figure 8. Stress, strain, and displacement distributions at rupture are in Figures 9-11. These distributions under impact load are also shown in Figures 9-11. Simulations prove structural design rationality and provide experimental verification reference.

Figs. 8 & 9 display stress concentration at groove intersections on concave diaphragm under 5MPa fluid impact. At 0.12ms, diaphragm expands and fractures, exceeding fracture strain. Failed elements are removed. Minimal stress, strain, and displacement near circumferential support. Simulation results indicate complete cracking within 0.12ms, releasing fluid without crushing, aligning with Fig. 2(a)'s theoretical calculations and rupture state assumption.

Figures 8 and 10 show the diaphragm's convex surface compresses towards the concave side under 2ms and 6MPa fluid impact. Stress and strain around the Double X-shaped cross groove and concave surface are high but safe. Numerical analysis confirms that the maximum chamber pressure, 1.7728 MPa within 1ms, is far below the convex surface's capacity, verifying its pressure relief ability.

Fig. 8 & 11 show 0.06ms diaphragm's convex surface compresses under 7MPa fluid, causing stress. 0.12ms diaphragm's convex surface compresses to concave, causing reverse fracture, allowing fluid escape. Double X-shaped element fails due to fracture strain, with stress, strain, & displacement decreasing from center to support. Support remains intact. Simulations show convex surface's strength & pressure relief. Fig. 4 shows max pressure flowing into low pressure chamber is 1.7728MPa, preventing fire.

4. Experimental verification

4.1. Test device and arrangement

Test device includes HP nitrogen cylinder, pressure sensor, data computer, gas pipe, test equipment, and 24V power. HP nitrogen cylinder connects to test equipment via gas pipe to power micro diaphragm burst. 24V power powers pressure sensor, which sends signal to data computer for processing. Pressure curve shown on computer screen in real-time. Experimental and on-site layouts in Figures 12 and 13.

The micro pressure control diaphragm dimensions are listed in Table 2. Given its size and need to simulate dual chamber launch conditions, specialized equipment is designed, as seen in Figure 14. The diaphragm is compacted via a plug. During testing, high-pressure nitrogen enters the diaphragm from an air inlet, impacting it. A pressure sensor measures chamber pressure.

4.2. Experimental result

Tested in 5 groups, Figs. 15, 16, 17 show concave and convex curves with rupture. Concave avg. pressure: 4.89MPa, avg. error 3.92%; Convex avg. pressure: 6.82MPa, avg. error 3.34%. Errors are close to target with avg. error <5%. Possible causes: tool lifespan, diaphragm material. Under 6MPa, convex pressure sustained 1.5s without rupture. Equipment has anti-debris design; rupture causes brief second peak.

Fig. 18 shows shear cracking on concave surface causing eight-lobed split, tight. No splintering. Convex surface shows no cracks at 6 MPa, indicating higher pressure tolerance. Positive arch reduces pressure, X-grooves enhance rupture. In dual-chamber, concave ruptures at preset pressure, convex prevents cracking. Capacities align with theory, confirming demands met and methods validated.

5. Conclusion

This paper introduces a micro pressure control metal diaphragm, analyzed with double chamber ballistics and diaphragm mechanics. Using the CEL method, we simulated its pressure tolerance and failure under gas impact, experimentally verifying the design. Key findings:

a) Stress concentration at double X-grooves led to crack propagation but avoided crushing.

b) The diaphragm withstood 5 MPa concave and 7 MPa convex pressure, showing superior pressure relief.

c) Actual pressure error was within 0.6 MPa, with a 5% average error, aligning with simulations. This research contributes to pressure regulation in multi-chamber weapons and high-pressure devices.

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