

Simulated artillery chamber pressure generator for special dynamic evaluation

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Original scientific paper

A simulated artillery chamber pressure generator (SACPG) was proposed for solving the dynamic evaluation in application environment of internal electronic pressure gauge. Strength autofrettage theory of SACPG was studied and simulated by ANSYS. Pressure waveforms, of which the amplitudes were up to 700MPa and the rise time was between 2 ms and 5 ms, had been obtained through controlling the diaphragm thickness and charge quantity. Simulation and test results show that the device can effectively simulate artillery chamber environment, which provides the feasibility evaluation of the internal electronic pressure gauge .

Key words: Simulated artillery chamber pressure generator, Autofrettage, ANSYS simulation, Application environment

Simulacijski model generatora tlaka artiljerijske komore za dinamičku evaluaciju. Simulacijski model generatora tlaka artiljerijske komore (engl. Simulated Artillery Chamber Pressure Generator, SACPG) predložen je za dinamičku evaluaciju internog elektroničkog manometra u aplikacijskom okruženju. U simulaciji SACPG-a korištena je teorija *autofrettage* snage. Valni oblici tlaka, s amplitudama do 700 MPa i vremenom porasta između 2 i 5 ms, dobiveni su promjenom debljine dijafragme i količinom punjenja. Simulacijski rezultati pokazuju kako model može učinkovito simulirati relevantne procese u artiljerijskoj komori, što omogućuje testiranje rada internog elektroničkog manometra.

Ključne riječi: Simulacijski model generatora tlaka artiljerijske komore, *Autofrettage*, ANSYS simulacija, aplikacijsko okruženje

1 INTRODUCTION

Chamber pressure is defined as the pressure generated by an explosion on per-unit area of the chamber wall when a gun is fired. It is an important parameter of the artillery system that must be tested and verified during development and product acceptance [1], [2] and [3]. The internal copper post (copper ball) gauge [4] and [5] can only obtain the maximum pressure by measuring its distortion quantity. Although convenient, it is incapable of recording the dynamic change of the chamber pressure with time. The internal electronic pressure gauge (IEPG) can obtain the pressure-time curves conveniently and accurately by putting the device into the gun chamber [1] [2], [6] and [7], therefore, it is used widely. In order to ensure the accuracy and reliability of the pressure measured by IEPG under the actual application, the comprehensive performance index of IEPG should be evaluated. The peak pressure of artillery firing can reach 700MPa, with a rise time range of 2 ~ 6 ms and pulse width range of 10 ~ 50ms. However, the product simulating the firing process of instantaneous high

pressure is lacking. Shock tube used for pressure calibration is usually under 100MPa which can not meet the amplitude requirements [8] and [9]. The rise time and pulse width for the closed bomb device [10] can not meet the requirement.

A dynamic evaluation apparatus which is called the simulated artillery chamber pressure generator (SACPG) was developed. The apparatus can simulate artillery firing process and produce single pulse pressure signal similar to chamber pressure. This paper utilizes autofrettage process to improve the strength of mechanical structure. Its reliability under the applied condition of high pressure was verified through theoretical calculation, ANSYS numerical simulation and tests. When the propellant types are known, the pressure rise time, peak value and pulse width could be realized by adjusting the charge quantity and the diaphragm thickness. The pressure produced by SACPG can meet the needs of IEPG evaluation.

2 SIMULATED ARTILLERY CHAMBER PRESSURE GENERATOR

2.1 Structure of SACPG

The structure of the SACPG is shown in Fig.1. It contains body, front and end cover, chamber, pressure sensor, ignition component, pressure limiting diaphragm, air scoop. The main body of the dynamic evaluation apparatus is a half closed empty cavity. Three standard pressure sensors are installed on one end of the empty cavity. The pressure relief diaphragm and air scoop are installed on the other end of the empty cavity. IEPG is put in the bottom of chamber, whose pressure sensitive side is opposite to standard pressure sensors sensitive sides. The inside radius a of the cylinder is 30 mm, the outside radius b is 90 mm, long L is 190 mm, air scoop diameter d is 18 mm. The body is made of PcrNi3MoVA, of which yield strength σ_s is 1050 MPa.

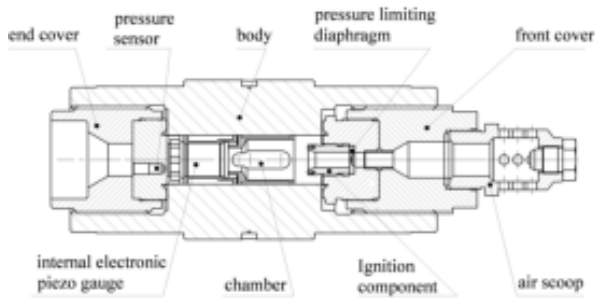


Fig. 1. Simulated chamber pressure generator structure

2.2 Theoretical Analysis and Calculation of the Structure Strength

In order to bear the instantaneous inner pressure of 700MPa, and ensure the reliability, stability and service life of SACPG, the autofrettage design [11] and [12] is used to improve its body yield strength.

The empty cavity can be simplified as a thick wall cylinder which is affected by internal pressure, as shown in Fig. 2. Chamber body appears plastic deformation when the cylinder inside pressure p_i is greater than the elastic limit pressure p_e . Radius ρ is the elastic-plastic distinguish border which divides the circular cross section into two parts. The inner occur plastic deformation and the outer part is still in the elastic state. The autofrettage processing has two steps. Firstly, exerting an internal pressure p_a to inner diameter and keeping a period time which making elastic-plastic interface at radius ρ . Secondly, adding internal pressure p_b again, p_b is less than p_a . Because residual stress in the body which against the new stress, so that the new plastic deformation of the cylinder will not occur. This method enhances the elastic limit pressure of the cylinder.

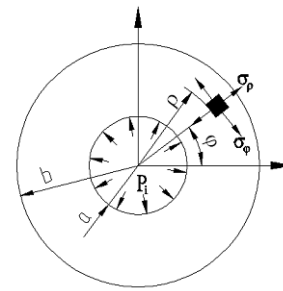


Fig. 2. Internal and external pressure distribution of the body

According to the von-Mises yield condition, without autofrettage processing, the elastic limit pressure is [13]:

$$p_e = \left(1 - \frac{a^2}{b^2}\right) \frac{\sigma_s}{\sqrt{3}} = 599 \text{ MPa} \quad (1)$$

After using autofrettage processing, the elastic limit pressure is

$$p_s = 1.08\sigma_s \left[\ln\left(\frac{\rho}{a}\right) + \frac{b^2 - \rho^2}{2b^2} \right] \quad (2)$$

In actual application, in order to ensure reverse yield does not occur after unloading, combining Manning empirical formula and cylinder size, radius ρ of elastic-plastic distinguish interface is selected. $(\rho - a)/(b - a)$ is defined as autofrettage degree. According to experience, autofrettage degree is equal to 30% ~ 50%, get

$$\rho = a + 0.3(b - a) \quad (3)$$

Plug shape parameters a , b into formula (3), $\rho = 48$ mm. Plug a , b , ρ and σ_s into formula (2), $p_s = 938$ MPa. Plastic deformation strength increases by 74% compared to no processing. The safety coefficient is 1.34 when the maximum working pressure is at 700 MPa.

2.3 ANSYS Simulation

In order to simplify analysis and shorten computing time, according to symmetry, a quarter model of the cylinder is established by ANSYS. The constraints imposed on radial displacement is zero, and the inside arc is imposed pressure.

The material properties are shown in Tab.1. The material type is homogeneous linear elastic isotropic. Finite element type is structural solid planes strain of 8 nodes 183. The model mesh size is 1 mm, element shape is mapped quad, and has 8520 elements and 25965 nodes.

Firstly, applying internal pressure $p_a = 900$ MPa, the diagram of Von-Mises stress distribution is shown in Fig.

Table 1. PcrNi3MoVA parameters

elasticity modulus [GPa]	Poisson's ratio	Density [kg/m ³]	yield strength [MPa]
200	0.3	8930	1050

3. Figure 4 shows the equivalent stress distribution on radius of 30 mm to 90 mm. Figure 3 illustrates that the radius of elastic-plastic interface is 42 mm, which in accordance with the theory design. Figure 4 states that the stress is rapidly decline.

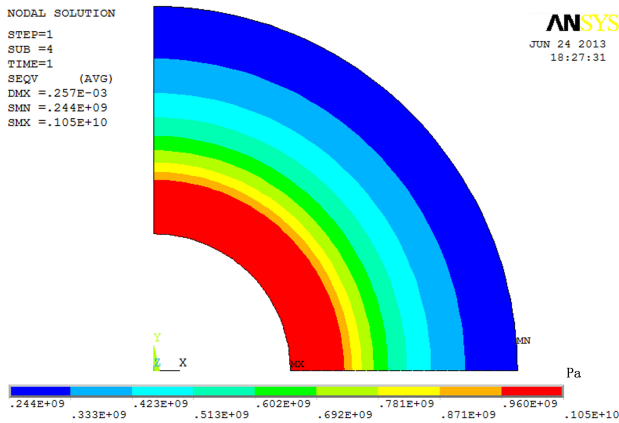


Fig. 3. Von-Mises stress diagram of 900MPa

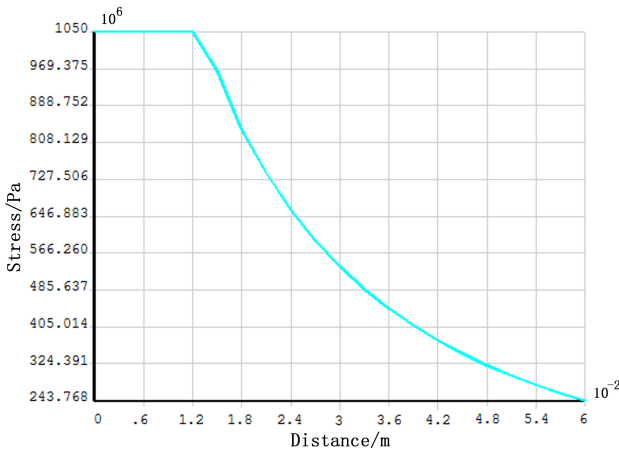


Fig. 4. Von-Mises equivalent stress distribution curve of 900MPa

After internal pressure of 900 MPa is unloaded, the autofrettage processing is completed. Figure 5 shows the Von-Mises stress diagram in the case of $p_b = 700$ MPa pressure loaded on internal wall. The maximum stress doesn't appear at the internal wall, but happen at the around elastic-plastic interface of autofrettage processing. The equivalent

stress distribution on radius of 30 mm to 90 mm is shown in Fig. 6. The internal wall stress is 680 MPa, and the biggest stress is 851 MPa occurring radius at 42 mm. The biggest stress is smaller than the material yield strength which is 1050 MPa, so the body plastic deformation will not happen. The biggest stress is 81% of the material yield strength under 700 MPa loaded on internal wall, so the body obtains significantly higher strength through autofrettage processing which ensures the work safety.

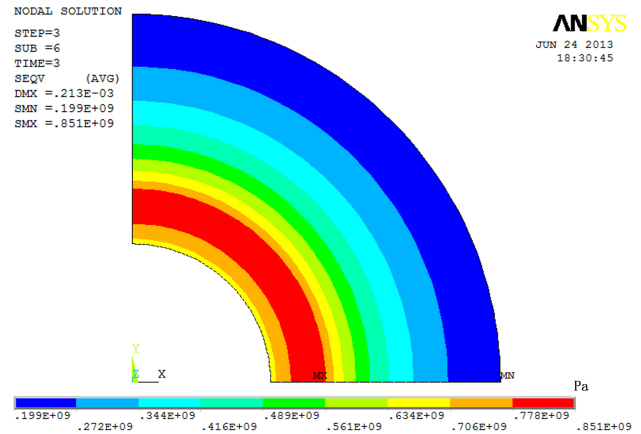


Fig. 5. 700MPa Von-Mises stress diagram

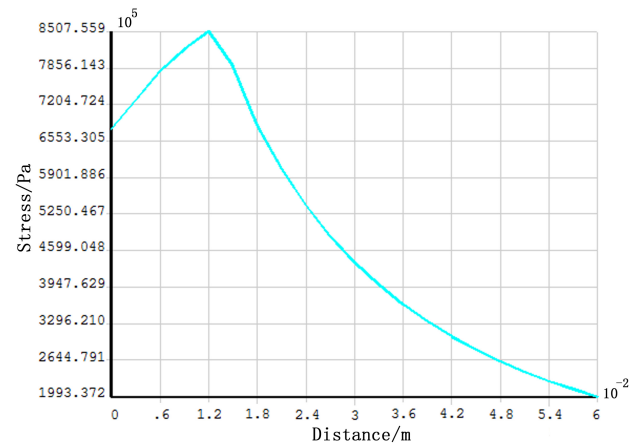


Fig. 6. Von-Mises stress equivalent stress distribution curve of 700MPa

3 THEORY OF SIMULATION CHAMBER PRESSURE CHANGES

SACPG is a half closed bomb, when the pressure of propellant combustion in the chamber increases to a critical pressure p_m , the pressure-relief metal diaphragm is ruptured and the high-pressure gas is suddenly released.

The gas flowed out from nozzle, gas flow rate and chamber pressure decline time are decided by air scoop area. Before the maximum pressure, the process is similar to the constant volume combustion theoretical $p = f(t)$ of ballistics gunpowder, the pressure rise time can be given by [14].

$$t_R = I_k / (p_m - p_B) \ln (p_m / p_B) \tag{4}$$

$$I_k = \int_0^{t_k} p dt \tag{5}$$

$$p_m = f \Delta / (1 - \alpha \Delta) \tag{6}$$

Where t_R is the rise time, I_k is gunpowder pressure impulse, p_m is the maximum pressure, p_B is ignition pressure, Δ is loading density, f is propellant force, α is gunpowder volume.

While the loading type, density and quantity are selected, the pressure rise time t_R can be estimated by insert specific numerical into formula (4), (5), (6). In the practical application, the peak value p_m and rise time t_R are not only ascertained by the law of constant volume combustion, but also affected by the rupture pressure of limiting diaphragm. For this, it is necessary to do some tests.

4 EXPERIMENTAL RESULTS AND ANALYSIS

4.1 Pressure influenced by charge quantity and pressure limiting diaphragm

The SACPG pressure measurement system consists of computer, three standard piezoelectric pressure sensors, three charge amplifiers and a multi-channel data acquisition system. Three charge amplifiers are one to one corresponding to three standard piezoelectric pressure sensors, then they are calibrated in the first class high pressure station of the national defense. The pressure sensors type are kistler 6123BK. The elementary error of each standard pressure measurement system is not more than 0.5% FS. The data acquisition system is 14-Bit and sampling frequency is 125 kHz.

The pressure limiting diaphragm diameter is 18 mm, and the material is steel C45E4. The propellant is 5/7 single-base granule of the bullets used for anti-aircraft.

In order to obtain the relationship among peak pressure, charge quantity M and diaphragm thickness h , the experiments with a fixed charge quantity M , changing diaphragm thickness h , and with a fixed diaphragm thickness h , changing charge quantity M were tested respectively. The parameters based on previous work of authors in reference [2]. The experiments in each condition have been carried out 5 times, the average peak pressures of experiments are shown in Tab. 2.

Table 2 shows that when M is fixed, with the increase of diaphragm thickness h , the maximum pressure p_m increases too, but the pressure increase ration is not equal to

thickness ration. Fixing diaphragm thickness h , increasing loading quantity M , although the maximum pressure p_m increases with the loading quantity, the peak pressure change is not in proportion to loading quantity.

Table 2. Comparison table of h , M and p_m

h [mm]	M [g]	p_m [MPa]	h [mm]	M [g]	p_m [MPa]
1.0	75	204	2.5	86	378
1.5	75	227	2.5	92	394
2.0	75	297	2.5	96	428
2.5	75	358	2.5	100	458

In formula (5), the gunpowder pressure impulse I_k is integral value from zero time to maximum pressure of the measured curve. In formula (6), the p_m is the maximum pressure that the gunpowder is completely burned in airtight environment. The p_m is determined by limiting diaphragm, so the measured maximum pressure value is adopted in formula (4). The ignition pressure p_B is an atmospheric pressure. The rise time t_R in theory could be computed by formula (4) and (5). The rise time t_R of theory and rise time t_R' of test at different p_m is shown in Tab. 3. The max relative error of theory rise time and testing rise time is less than 5.3%. So the pressure and rise time generated by SACPG are consistent with the theory value.

Table 3. Rise time comparison

p_m [MPa]	t_R [ms]	t_R' [ms]	relative error [%]
220	2.05	2.17	5.3
325	2.63	2.72	3.2
463	1.92	2.02	4.8
574	2.06	2.12	2.9

4.2 Comparison of SACPG pressure and the gun chamber pressure

For effective simulating the firing process, four typical artillery guns chamber bottom pressure-time curves were got by internal electronic pressure gauge. The internal electronic pressure gauge which has a volume of 22 cm³, resolution of 12-Bit, sampling frequency is 125 kHz, and measurement range reach to 600 MPa. The characteristics data of the pressure curves are shown in Tab. 4. The amplitude of the artillery chamber pressure signal is between 200 MPa and 600 MPa. The effective bandwidth f_v is less than 2.6 kHz.

Through comprehensive adjusting charge quantity and pressure limiting diaphragm thickness, the characteristic data produced by the SACPG are shown in Tab. 5. The amplitude of the simulation pressure signal is between

Table 4. Artillery chamber pressure waveform parameter

artillery type, charge type	p_m [MPa]	t_R [ms]	T_p [ms]	f_v [kHz]
105 mm siege gun, full charge	272	2.34	9.04	2.32
130 mm cannon, grenade full charge	322	5.81	21.43	0.96
100 mm smoothbore assault gun, grenade full charge	378	4.20	14.84	1.86
100 mm smoothbore piat, tungsten alloy wear armour bomb	529	2.14	12.15	2.56

T_p denotes pressure pulse width and f_v denotes effective bandwidth.

Table 5. Character parameters of simulation pressure

M [g]	h [mm]	p_m [MPa]	$t_{R'}$ [ms]	T_p [ms]	f_v [kHz]
75	1.0	220	2.17	11.40	2.93
75	2.2	325	2.72	26.86	2.76
105	2.5	463	2.02	19.42	3.07
125	2.5	574	2.12	18.82	2.99

200 MPa and 600 MPa. The effective bandwidth f_v is more than 2.76 kHz.

If the bandwidth generated by the SACPG wants to cover the bandwidth of gun pressure, the pressure rise time generated by the SACPG needs to be smaller than the rise time of gun pressure. For different guns and charging types, the gun chamber pressure rise time is different, about 2 ~ 6 ms. By adjusting the diaphragm thickness, the pressure rise time of SACPG is about 2 ~ 5 ms, which is less than the rise time of gun chamber pressure. It meets the requirement of dynamic calibration and evaluation for the calibration signal bandwidth. Gun chamber pressure pulse width is about 9 ~ 45ms. SACPG chamber pressure pulse width is 10 ~ 60 ms. The pulse width of SACPG chamber pressure is greater than the pulse width of gun chamber pressure. Because the diaphragm diameter of SACPG is smaller than the gun diameter, which used to release the pressure, so the pressure releases slowly. However, its effect on IEPG measurement precision can be ignored [15].

The pressure curves in Fig. 7 and Fig. 8 have been respectively obtained under the third experimental condi-

tions in Tab. 4 and Tab.5. After Fourier transform, the normalized spectrum of the gun chamber pressure curve and the simulation chamber pressure curve are shown respectively in Fig. 7 and Fig. 8. As can be seen from Fig. 7 and Fig. 8, the gun pressure magnitude is decayed to -40 dB at 0.28 kHz and -72 dB at 1.29 kHz, the simulated pressure magnitude is decayed to -40 dB at 0.57 kHz and -72 dB at 1.71 kHz. The SACPG simulated pressure frequency bandwidth is bigger than the gun pressure frequency bandwidth. So the pressure produced by SACPG which can be used for IEPG evaluating.

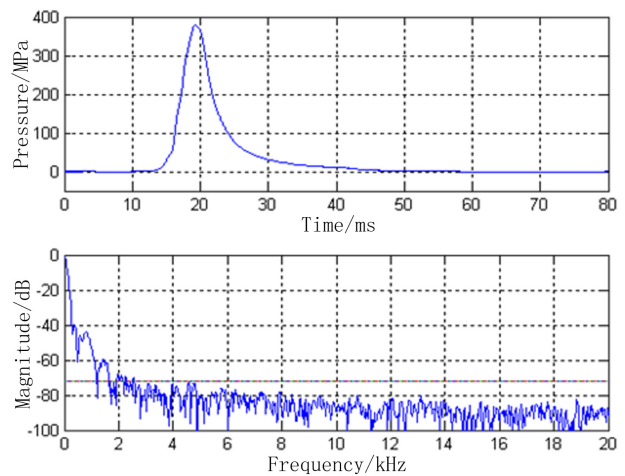


Fig. 7. Typical measured gun chamber pressure curve and spectral analysis

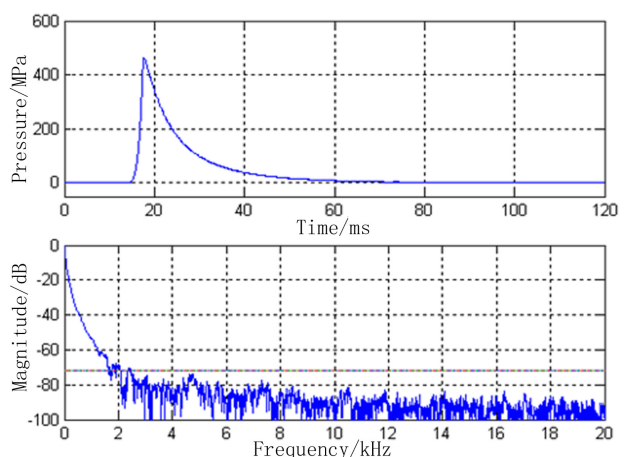


Fig. 8. Simulation chamber pressure curve and spectral analysis

5 CONCLUSIONS

SACPG is designed for evaluation of the internal electronic pressure gauge, by autofrettage treatment of body, which guarantees the safety under the condition of 700 MPa. Pressure rise time and peak satisfied the application environment has been realized by adjusting the charge quantity and diaphragm thickness. This device provides evaluation methods for high pressure testing instruments.

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