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Leakage Rate Calculation of O-Ring Seal Structure of SRM During Its Ignition and Pressure Setting-up

Jiazhao Chen [1, a], Xueren Wang [1, b], Tingjing Geng [1, c] and ZhaoJun Zhu [2, d]

[1] 206 Staff room, Xi 'an High-Tech Institute, Xi'an 710025, China;

[2] School of aero engine, Zhengzhou University of Aeronautics, Zhengzhou, 450046, China.

[a] jzzhch@sina.com, [b] 2454615668 @qq.com, [c] 1832994156@qq.com ,

[d] zhuzhaojun.2009@163.com

Abstract

Rubber-ring aging results in decrease of contact stress of the seal structure and decline of resilience of the seal ring, and then it influences the performance of the O-ring seal structure. By introducing time aging item to Roth leakage rate calculation model, contact stress and leakage rate of the O-ring seal structure are calculated during static work of SRM after its rubber-ring has been aged. Using the resilience speed of the seal ring and the gap opening speed of the seal flange, those are determined by experiment, the dynamic compression ratio of the seal ring is calculated during SRM ignition and pressure setting-up. And then the dynamic contact stress and leakage rate of O-ring seal structure are calculated, so as to assessment the influence of the rubber-ring aging on the performance of the O-ring seal structure under long-term storage of SRM.

Keywords

SRM, ignition and pressure setting-up, O-ring seal structure, leakage rate.

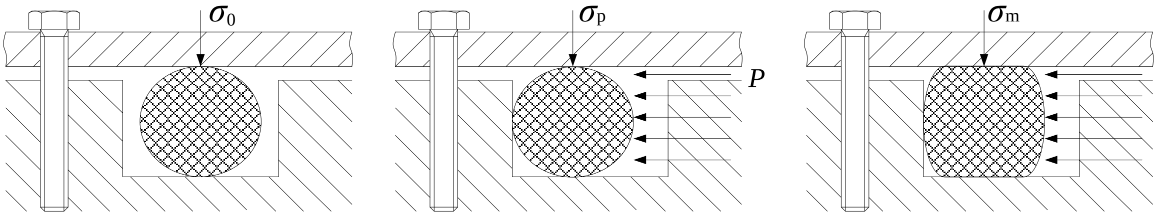
1. Introduction

Solid rocket motor is often used as the power unit of missile weapon system. Its storage reliability and service life are very important, which has attracted extensive attention of scholars at home and abroad [1,2]. Among them, whether the sealing structure of solid rocket motor can work normally after long-term storage is an important issue worthy of in-depth study. If the sealing structure has poor performance, it may lead to serious consequences such as deterioration of working performance, fire penetration, explosion and so on. Solid rocket motor usually adopts O-ring sealing structure [3]. Scholars at home and abroad have done a lot of research work on the sealing mechanism, contact stress, leakage analysis, sealing ring aging and life evaluation of O-ring sealing structure [3], but they mainly focus on the static working condition of the engine. In fact, in the process of ignition and pressure building of solid rocket motor, the pressure of combustion chamber changes sharply, and the sealing structure is subjected to a very severe test. There are few reports on whether the O-ring seal structure can adapt to the drastic change of pressure in the process of ignition and pressure building of solid rocket motor after long-term storage and natural aging of its rubber seal ring. Based on the contact stress and leakage rate, this paper studies how the aging of rubber ring affects the sealing of O-ring sealing structure in the process of ignition and pressure building of solid rocket motor.

2. Effect of compression ratio of O-ring on leakage rate

2.1. Compression ratio and contact stress of O-ring

The O-ring sealing structure is composed of sealing groove, O-ring rubber seal and bolt [5]. It is assumed that the groove depth is *h* and the section diameter of the O-ring is *d*. O-shaped rubber sealing ring is a kind of extrusion sealing element. Its sealing principle is to generate contact stress on the sealing contact surface through the extrusion deformation of elastic O-shaped element [5] σ_m. When the contact stress is greater than the pressure of the inner sealing medium, it can be sealed reliably, and when the contact stress is less than the pressure of the sealing medium, the seal fails [6].The contact stress comes from two aspects. On the one hand, after the O-ring is installed in the sealing groove, its section will produce elastic deformation due to the extrusion of the preload of the flange [7], the section height will change from *d* to *h*, and the contact stress will be generated on the sealing contact surface σ_0, as shown in Figure 1 (a);On the other hand, when there is a sealing medium, under the action of the medium pressure (internal pressure of the container) *P*, the O-ring will displace and move to the low-pressure or non pressure side, and the sealing ring will also produce elastic deformation [8] and contact stress σ_p (Figure 1 (b)).Therefore, the contact stress of O-ring sealing structure σ_m is produced by the joint action of preload and medium pressure, i.e $\sigma_m=\sigma_0+\sigma_p$ (Figure 1 (c)).



(a) contact stress caused by preload(b) contact stress caused by medium pressure

(c) contact stress caused by interaction

Figure 1:Seal principle of O-ring seal structure

The section height of the O-ring changes from *d* to *h*, and the compression ratio of the O-ring is defined as:

$$\varepsilon=\frac{d-h}{d}\quad g_t=g_0+\int_0^t v_g dt \tag{1}$$

The greater the shrinkage ε, the greater the deformation of the O-ring, the greater the contact stress σ_m, and the better the seal.

For O-shaped rubber sealing rings, the contact stress σ on the sealing interface is related to the material of the sealing ring, the interface shape, the compression amount ε and the internal pressure *p*, etc. Generally, there are:

$$\sigma=1.25(1+\frac{\mu^2K_\varepsilon}{1-\varepsilon})E\varepsilon+\frac{\gamma}{1-\gamma}p \tag{1}$$

In the formula: μ is the friction coefficient between the sealing ring and the flange; γ is the Poisson's ratio; K_ε is the ratio of the contact width b of the O-ring to the cross-sectional diameter d of the O-ring.

When the compression amount ε is in the range of 0.1 to 0.4, the contact width b of the compressed O-ring and the flange can be calculated by the following formula:

$$b=(4\varepsilon^2+0.34\varepsilon+0.31)d \tag{2}$$

Then there

$$K_\varepsilon=\frac{b}{d}=(4\varepsilon^2+0.34\varepsilon+0.31) \tag{3}$$

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2.2. Leakage rate of O-ring sealing structure

In fact, sealing is relative and leakage is absolute.When the leakage rate of the sealing structure is greater than a certain threshold, the structure can not work normally, that is, the sealing failure.On the contrary, the sealing is normal.According to Roth's sealing theory, the flange surface in contact with the O-ring seal is flat from the macro point of view, but there are some tiny leakage channels from the micro point of view.These leakage channels can be simplified as isosceles triangle. For the whole rubber O-ring sealing structure, the leakage holes are formed by several isosceles triangle micro leakage holes with constant cross-sectional area in parallel [9].The leakage rate of O-ring sealing structure is:

$$Q = 4\sqrt{\frac{T}{M}}\frac{Lh^2}{b}\exp(\frac{-3\sigma_m}{R_s})\Delta p \tag{4}$$

Where, t is the ambient temperature; M is the molecular weight of the gas; b is the width of the contact surface of the sealing surface; Δp is the pressure difference inside and outside the sealing structure; L is the length of the sealing surface of the rubber ring, which is approximately the circumference of the rubber ring; h is the initial height of the leakage triangle section, that is, the surface roughness of the metal material after machining; σ_m is the average contact stress on the sealing surface; R_S is the sealing performance coefficient of rubber material, which reflects the ability of soft sealing material to fill the leakage channel under a certain pressing force.

According to the above calculation formula, the compression rate of rubber O-ring directly affects the size of contact stress, and then affects the leakage rate of O-ring sealing structure.

3. Effect of rubber O-ring aging on leakage rate of sealing structure

The rubber O-ring will undergo natural aging during use. The aging of rubber will change part of its elastic strain into plastic strain when it is extruded for a long time [11], so as to reduce the contact stress, reduce the ability of filling uneven grooves on the metal processing surface, and reduce the sealing performance. In order to evaluate the influence of rubber ring aging on the structural performance of O-ring seal, the aging time factor [12] is introduced into the contact stress calculation model, that is:

$$\bar{\sigma}(t)/\bar{\sigma} = B\exp(-K_c t^{\alpha}) \tag{5}$$

Where, t is the natural aging time, σ is the contact stress of the rubber ring without aging, $\sigma(t)$ is the contact stress of the rubber ring after time-t aging, and B、 α is the aging model coefficient; K_c is the aging rate constant.

By introducing equation (6) into equation (5), the leakage rate model of O-ring sealing structure with time aging term can be obtained, that is, the leakage rate calculation model of rubber O-ring after aging:

$$Q = 4\sqrt{\frac{T}{M}}\frac{Lh^2}{b}\exp(\frac{-3\sigma_m B\exp(-K_c t^{\alpha})}{R_s})\Delta p \tag{6}$$

It can be seen that after long-term storage of solid rocket motor, the rubber O-ring will naturally age, which will affect the size of contact stress, then affect the leakage rate of O-ring sealing structure, and finally affect the sealing performance of solid rocket motor.

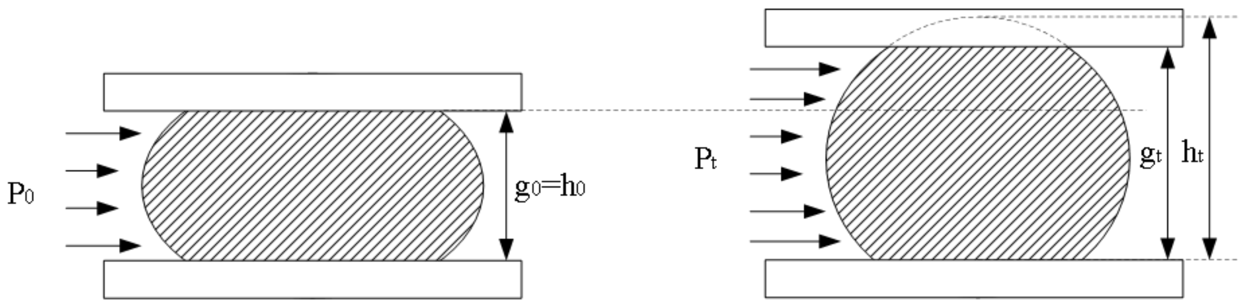
4. Calculation of dynamic leakage rate of rubber O-ring under ignition pressure build-up

The previous consideration is the impact of rubber aging on the sealing performance when the O-ring sealing structure works under static pressure.However, the working process of solid rocket motor is a dynamic process, especially in the process of ignition and pressure building of the engine, the pressure rises sharply. At this time, under the action of the pressure in the engine, the clearance of the sealing flange increases rapidly, resulting in the rapid decrease of the preload on the sealing ring, so as to reduce the stress on the contact surface.At this time, due to the hyperelasticity of the rubber material, the rubber O-ring will rebound rapidly to fill the enlarged flange gap and make up for the lost contact stress.If the rebound rate VH of rubber O-ring is greater than the increase rate VG of sealing flange clearance in this process, the reliable sealing of O-ring can be ensured, otherwise the sealing will fail [13], that is, the failure criterion of O-ring sealing structure in the process of ignition and pressure building is:

$$v_h \le v_g \tag{7}$$

The dynamic condition of ignition and pressure construction must be considered in the design of solid rocket engine, so that the O-ring seal structure can adapt to the drastic change of combustion chamber pressure and reliable sealing.However, the rebound performance of the sealing ring is decreased due to the aging of rubber [14] [15], which leads to the further decrease of contact stress and leakage rate, which further reduces the performance of O-ring sealing structure.After the solid rocket engine is stored for a long time, the rubber O-ring aging naturally. Can the sealing structure adapt to the drastic change of pressure during ignition and pressure construction, and reliable sealing?Here are some analysis.

4.1. Calculation of dynamic compression rate of rubber O-ring during ignition pressure construction



(a) Time when the internal pressure starts to rise (b) Time t during the rise of internal pressure

Figure 2: Deformation process of O-ring seal structure in engine ignition and pressure building

Figure 2 (a) shows the starting time of pressure rise in the combustion chamber, with the internal pressure of P_0, the initial cross-section diameter of the sealing ring being d and the compression rate of ε_0, flange clearance is g_0, seal ring height is $h_0 = (1-\varepsilon_0)\, d$, and $g_0 = h_0$.

Figure 2 (b) shows that the internal pressure rises to P_t, the rebound rate of sealing ring is V_h and the increase rate of seal flange clearance is V_g. Then the gap between the sealing flange is increased to:

$$g_t = g_0 + \int_0^t v_g dt \tag{8}$$

If the sealing ring is unrestricted, the spring back height of the sealing ring can reach at t time:

$$h_t = h_0 + \int_0^t v_h dt \tag{9}$$

But due to the flange constraints, the actual rebound height of the sealing ring is equal to the gap g_t of the sealing flange.

Assuming that the rebound rate V_h of the seal ring is greater than the increase rate V_g of the seal flange gap, the dynamic compression of the seal ring at this time is:

$$\Delta = h_t - g_t = \int_0^t v_h dt - \int_0^t v_g dt \tag{10}$$

At this time, the dynamic compression ratio of the sealing ring is:

$$\varepsilon(t) = \frac{\Delta}{h_t} = \frac{\int_0^t v_h dt - \int_0^t v_g dt}{h_0 + \int_0^t v_h dt} = \frac{\int_0^t v_h dt - \int_0^t v_g dt}{\left(1-\varepsilon_0\right) d + \int_0^t v_h dt} \tag{11}$$

If the seal ring rebound rate V_h and the seal flange gap increase rate V_g are constant, that is, the seal ring rebound and the seal flange gap increase at a uniform speed, the above formula can be simplified as:

$$\varepsilon(t) = \frac{\left(v_h - v_g\right)t}{\left(1-\varepsilon_0\right) d + v_h t} \tag{12}$$

The dynamic compression ratio of the sealing ring describes the change of the compression ratio of the sealing ring with time from the beginning of the pressure rise to the end of the rise in the process of ignition and pressure building. The above formula shows that when the pressure begins to rise, the flange suddenly relieves the pressure on the sealing ring due to the internal pressure, and the rebound rate of the sealing ring cannot be infinite, the sealing ring is not under pressure, and the compression rate is 0. After that, the compression rate is related to the rebound rate of the sealing ring and the opening rate of the flange. If the rebound rate is greater than the opening rate, the sealing ring is compressed, the compression rate is greater than 0, the indirect contact stress between the sealing ring and the flange is greater than 0, and the sealing is reliable;If the rebound rate is less than the opening rate, the sealing ring is not under pressure, the compression rate is equal to 0 (less than 0 is meaningless), and the contact stress between the sealing ring and the flange is 0, leakage may occur.Therefore, the failure criterion of O-ring sealing structure in the process of ignition and pressure building can be expressed as:

$$\varepsilon(t) \leq 0 \tag{13}$$

It can be seen that in the process of ignition and pressure building of the engine, when the pressure in the combustion chamber begins to rise and the rebound rate of the sealing ring is less than the opening rate of the flange gap, the contact stress between the sealing ring and the flange is 0, which may lead to leakage. But in fact, before the internal pressure of the engine begins to rise, the sealing ring is in a static compression state, and its compression rate is the initial compression rate ε_0. Although the internal pressure rises rapidly, it still rises continuously from the initial pressure, and the flange opening process also changes continuously from the initial gap. Therefore, there is no point of sudden opening of the flange, that is, the dynamic compression rate of the sealing ring is determined by the initial compression rate ε_0 decreases continuously, that is to say, the contact stress between the sealing ring and the flange also decreases continuously by the static contact stress. The time when the internal pressure begins to rise is not 0. Only when the rebound rate of the sealing ring is less than the opening rate of the flange, the compression rate is 0 and the contact stress is 0 after a period of time, which may lead to leakage.Therefore, formula (13) is essentially consistent with formula (8)

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4.2. Calculation of dynamic leakage rate of O-ring seal structure in the process of ignition and pressure building

From it can be seen from the previous discussion that when the solid rocket motor works in the static pressure state, the compression rate, contact stress and leakage rate of the O-ring sealing structure are calculated by equations (1), (2) and (5) respectively. When the solid rocket motor is stored for a long time, the compression rate of the rubber O-ring after natural aging is still calculated by formula (1), while the contact stress and leakage rate are calculated by formula (6) and formula (7) respectively.

In the process of ignition and pressure building, the pressure in the combustion chamber changes sharply. At this time, the compression rate, contact stress and leakage rate of the O-ring sealing structure change with the working time. The dynamic compression rate can be calculated by equation (13), Using the calculated dynamic compression ratio, the dynamic contact stress and dynamic leakage rate in the process of ignition and pressure building can be calculated from equations (2) and (5) or equations (6) and (7). Therefore, the performance of O-ring seal structure of solid rocket motor under ignition pressure building conditions and long-term storage conditions can be evaluated.

It should be noted that when calculating the dynamic contact stress and leakage rate, the pressure $p(t)$ in the engine combustion chamber is also a dynamic value, which changes with the working time.

When calculating the dynamic compression ratio, the second term $V_h t$ of the denominator in equation (13) is much smaller than the first term (1) of the denominator due to the very short ignition boost process of the engine $(1-\varepsilon_0)d$, which can be ignored in calculation for simplicity. In the formula, the pressure $p(t)$ in the engine combustion chamber, the rebound rate V_h of the sealing ring and the opening rate V_g of the flange gap are obtained from the test.

5. Numerical example

Below withTaking smotor1 of an engine as an example, the dynamic leakage rate of O-ring sealing structure during ignition pressure building is calculated. The calculation is simplified as follows:

1) There are many sealing parts of the engine. Select the part with the largest opening of the sealing gap in the process of ignition and pressure building for calculation. As long as its sealing is reliable, it can be considered that the overall sealing of the engine is reliable.In the whole process of ignition and pressure building, the sealing condition at the moment of maximum opening of flange gap is mainly investigated;

2) In the process of ignition pressure construction, the pressure change in the combustion chamber of the engine is not linear, but because the time of ignition pressure construction is short, the internal pressure $p(t)$ can be treated as linear change;

3) Rubber sealing rings have certain viscoelasticity, and their rebound rate is nonlinear. During the process of engine ignition and pressure construction, the flange opening rate is also nonlinear, but the ignition pressure setting time of engine is very short, so the rebound rate and flange opening rate can be treated as constant.

It can be seen from the test that in the process of ignition and pressure building, the opening gap of the sealing structure between the rear joint of the combustion chamber of the engine Smotor1 and the adiabatic rear cover is the largest. The O-ring of this sealing structure is G105-1100×5.5. Since the initial compression rate of the sealing ring is mostly in the range of 0.2~0.35, the initial compression rate ε_0=0.2 is taken. It is measured by the engine ignition test: the ignition pressure build-up time is about 0.11s, the maximum internal pressure of the combustion chamber is 6.4MPa, and the maximum flange gap opening rate is 8.92mm/s.

According to the accelerated aging test and rebound test, the rebound rate of the G105 sealing ring is 20.0mm/s when it is not aged, the rebound rate is 18.5mm/s after 3 years of aging, and the rebound rate is 15.2mm/s after 9 years of aging. The springback rate after 12 years of aging is 11.3mm/s.

After the engine Smotor1 is stored for 0 years, 3 years, 9 years, and 12 years, the leakage rate of the G105-1100×5.5 sealing ring is shown in Table 1.

Table 1: Opening rate and opening angle of primary engine seal structure

Test number	Company	01D09	14DP04
Flange opening angle of the first stage rear cover	°	1.65	201S
Maximum opening clearance of the end face of the first stage rear cover (1100×5.5 sealing ring)	mm	1.04	1.32°
Maximum opening rate of the first stage rear cover end seal (1100×5.5 sealing ring)	mm/s	4.55	0.83
Maximum opening gap of side seal of primary rear lid (1094×four×4 sealing ring)	mm	0.74	3.62
Maximum opening rate of side seal of primary rear lid (1094×four×4 sealing ring)	mm/s	2.99	0.55

It can be seen from the table that the dynamic compression rate and contact stress of the sealing ring during the ignition and pressure build-up of the engine decrease with the increase of storage aging time, while the dynamic leakage rate increases with the increase of storage aging time. However, even if stored for 12 years, the contact stress is still less than the maximum internal pressure of the combustion chamber (6.4MPa), and the leakage rate is still less than the minimum detectable leak rate of the soap bubble method (data show that the soap bubble method has the smallest leak rate. The detectable leak rate is generally greater than 10-5Pa•m3/s[16]), and the sealing is reliable.

6. Conclusion

The compression rate of O-ring seal structure directly affects the contact stress and leakage rate of the sealing structure, and then affects the sealing performance. The aging of rubber seal ring will lead to the decrease of elastic strain and increase of plastic strain, which will lead to the decline of sealing structure performance. The aging time factor is introduced into Roth leakage rate calculation model, which can evaluate the effect of aging of O-ring on the sealing performance of solid rocket engine under long-term storage.

In the dynamic process of engine ignition pressure construction, aging of rubber ring not only causes the contact stress to decrease, but also reduces the rebound rate of rubber ring, which further affects the sealing performance. The dynamic compression rate of the ignition pressure construction is calculated by using the test results of the rebound rate of the sealing ring and the flange gap opening rate. Then the dynamic contact stress and leakage rate of the O-ring seal structure during the ignition pressure construction are calculated, and the influence of aging of the sealing ring on the sealing performance of the engine during ignition pressure construction is evaluated.

The example shows that the maximum leakage rate of ignition pressure construction is still very small and the sealing is reliable after 12 years storage.

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