Analysis of Piston Seal Performance of Pure Water Cylinder of Hydraulic Support

Xinjian Zhou, Hongbin Shao *
School of Mechanical Engineering, Xi'an University of Science and Technology

*Corresponding author e-mail: 19205201089@stu.xust.edu.cn

Abstract. Taking the piston seal of pure water hydraulic cylinder of hydraulic support as the research object, the sealing performance and damage characteristics are compared and analyzed for mountain seal and drum seal structures under different compressions and working medium pressures by the ANSYS Workbench. The two-dimensional axisymmetric models for the two structures are established. The compression deformation and stress of mountain seal ring and drum seal ring are simulated by setting different amount of compression and medium pressure. Findings showed that the most vulnerable area of the mountain seal ring is in the middle of the contact surface with the cylinder, and that of the drum seal ring is in its outer edge. The maximum contact stress of both the structured sealing rings increased with the increase of the medium pressure, and is always greater than the medium pressure, indicating good sealing performance. With the increase of compression and working medium pressure, the sealing performance of both kinds of rings decreased. When applied to the same piston, the sealing performance of mountain seal is better than that of drum seal under the same compression amount and medium pressure.

1. Introduction

Recently, the coal mining has gradually developed to the trend of green mining, and the hydraulic support system with pure water as the working medium has entered people's attention. The application of pure water medium hydraulic technology can eliminate the pollution of leakage to the working environment and achieve the effect of clean, environmentally friendly and green mining [1].

The sealing performance of the hydraulic support column is not only the key to the normal work of the hydraulic support, but also an important guarantee for the safety of coal mining production, so the sealing performance of the hydraulic support column has always played a leading role in the hydraulic support [2]. With the research and development of hydraulic support in China for decades, and the digestion and absorption of imported sealing ring, the series of mountain-shape seal rings and drum-shape seal rings suitable for emulsion medium have been successfully developed [3]. Mountain-shaped sealing ring and drum-shaped sealing ring are also called piston sealing ring. They are double-acting piston seals. They are used with two guide rings and have two-way sealing effect [4-5]. In this paper, the mountain seal and drum seal of the piston of pure water hydraulic support are taken as the research objects. The working conditions of the mountain seal and drum seal are simulated by ANSYS Workbench finite element simulation software, so as to obtain the Von Mises stress and contact stress distribution curves of the mountain seal and drum seal under different sealing clearances and different
working medium pressures, and the maximum contact stress is extracted. Then, according to the Von Mises stress and contact stress, the damage characteristics and sealing performance of the mountain seal and drum seal are compared and analyzed, which provides reference for the design and optimization of the seal structure of pure water column.

2. Theoretical analysis

2.1. Contact stress analysis
The contact pressure reflects the sealing ability of the sealing ring, which is mainly related to the sealing pressure, fluid viscosity and relative motion velocity. Therefore, the Reynolds equation can be used for its analysis and calculation.

According to Reynolds lubrication theory equation [6], its expression is as follows.

\[
\frac{\partial}{\partial x} \left( h^3 \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left( h^3 \frac{\partial p}{\partial y} \right) = 6 \mu v \frac{\partial h}{\partial x} + 6 \mu v \frac{\partial h}{\partial y} + 12 \mu \frac{\partial h}{\partial t} \tag{1}
\]

In the formula, \( h \) is the sealing clearance, \( v \) is the fluid velocity, \( \mu \) is pure water viscosity, \( p \) is the pressure of fluid medium.

Since the sealing gap in the \( y \) direction is small, the flow in the sealing gap can be considered as laminar flow only along the \( x \) direction, and in the process of motion, the motion is considered to be equivalently constant, so the one-dimensional Reynolds equation is as follows.

\[
\frac{\partial}{\partial x} \left( h^3 \frac{\partial p}{\partial x} \right) = 6 \mu v \frac{\partial h}{\partial x} \tag{2}
\]

The sealing gap at the maximum pressure is set as \( h_m \), Owing to \( h = h_m \), then \( \frac{\partial p}{\partial x} = 0 \), thus.

\[
\frac{\partial p}{\partial x} = 6 \mu v \frac{h - h_m}{h^3} \tag{3}
\]

Suppose the flow rate of the fluid is \( Q \) and the length of the circumference direction is \( S \), then the flow rate is.

\[
Q = S \int_0^{h_m} v \hat{v} dy = S \left[ \frac{v}{2} h_m^2 - \frac{1}{12 \mu} \left( \frac{\partial p}{\partial x} \right)_{h_m} (h_m)^3 \right] \tag{4}
\]

Owing to \( h = h_m \), then \( \frac{\partial p}{\partial x} = 0 \), thus, \( h_m = \frac{2Q}{SV} \). Substituting it into Equation (3), the relationship among pressure gradient \( \frac{\partial p}{\partial x} \), flow rate \( Q \) and viscosity \( \mu \) can be obtained.

\[
\frac{\partial p}{\partial x} = 6 \mu v \frac{h - h_m}{h^3} = 6 \mu \left( \frac{vh - 2Q}{S} \right) \tag{5}
\]

For the sealing combination, when the contact stress is greater than the fluid medium pressure, it is almost impossible to pass, and the flow \( Q \) is close to 0. Therefore, the pressure gradient obtained by formula (5) is as follows.

\[
\frac{\partial p}{\partial x} = 6 \mu \frac{v}{h^2} \tag{6}
\]
Along the x direction, the pressure increases linearly. Assuming that the maximum contact pressure is \( P_m \), the contact stress formula for the sealing combination obtained by integrating formula (6) on the sealing interface length \( l \) is as follows.

\[
P_m - P = \frac{6\nu\mu l}{h^2}
\]

(7)

It can be seen from Formula (7) that the contact stress is related to the fluid medium pressure, fluid viscosity, sealing clearance and relative motion velocity. It is inversely proportional to the height of the sealing gap, and proportional to the fluid viscosity and velocity. The contact stress increases with the increase of the working medium pressure.

When the material and performance of the sealing structure cannot be changed and improved, because the viscosity of pure water and the viscosity of hydraulic oil and emulsion are very different, and the piston velocity of the same type of hydraulic support hydraulic cylinder is fixed, then we can adjust the sealing gap to improve the contact stress, so that it can be well sealed. Therefore, this paper analyzes the sealing performance under different working medium pressures through the finite element simulation of the sealing combination under different sealing gaps.

2.2. **Mechanical Properties of Materials**

Compared with hydraulic oil and emulsion, pure water medium has strong corrosion and poor lubrication. In order to prevent wire drawing and hydrolysis of sealing ring, polyurethane material is used in sealing ring [7-8].

In the finite element analysis, the 9-parameter Mooney-Rivlin model of polyurethane is selected [9]. Combined with the relevant literature, the material parameters are shown in table 1 and the fabric rubber material parameters in the drum seal ring are shown in table 2 [10]. In addition, the guide ring material is paraformaldehyde, density is 1420kg/m, elastic modulus is 2600Mpa, Poisson's ratio is 0.385. The piston and cylinder material are structural steel.

| Cij | Parameter/Mpa | Table 1. Polyurethane material parameters. |
|-----|---------------|------------------------------------------|
| C10 | 17.7          |                                          |
| C01 | 20.96         |                                          |
| C20 | 1.94          |                                          |
| C11 | 3.75          |                                          |
| C02 | 14.16         |                                          |
| C30 | 3.25E-09      |                                          |
| C21 | 5.6E-07       |                                          |
| C12 | 0.485         |                                          |
| C03 | 1.665         |                                          |
| D1  | 0             |                                          |

| Cij | Parameter/Mpa | Table 2. Fabric rubber material parameters. |
|-----|---------------|------------------------------------------|
| C10 | 1.88          |                                          |
| C01 | 2.17          |                                          |
| C20 | 0.37          |                                          |
| C11 | 0.19          |                                          |
| C02 | 0.91          |                                          |
| C30 | 5.2E-10       |                                          |
| C21 | 1E-10         |                                          |
| C12 | 0.09          |                                          |
| C03 | 0.09          |                                          |
| D1  | 0             |                                          |
2.3. Model scale

The modeling problem of sealing ring belongs to axisymmetric problem. Then, we convert the three-dimensional research on the seal ring, cylinder, piston and guide ring into the two-dimensional problem research. So take the upper half section of the sealing ring, the mechanical behavior and analysis results of this section reflect the mechanical behavior and analysis results of the sealing ring under ideal conditions. Figure 1 shows the structural dimensions of the mountain sealing rings and drum sealing rings and the corresponding sealing groove dimensions.

![Model size](image)

**Figure 1.** Model size.

3. Simulation analysis

3.1. Applied load

Taking the piston seal of ZY10000-20-40 DB shield hydraulic support column as an example. Through the actual investigation, it is found that the pressure of the high pressure cavity of ZY10000-20-40 DB shield hydraulic support column is 39.8Mpa, and the pressure of the low pressure cavity is 31.5Mpa, so the sealing ring must meet the sealing performance between the high pressure cavity and the low pressure cavity of the hydraulic support. In addition, the mountain seal and drum seal mainly rely on the compression of the cross section to ensure the sealing performance. In order to ensure that the seal has a certain amount of compression, it is required that the cross section has certain over the surplus. It can be seen from Fig. 1 that the over the surplus of mountain seal is 1.5 mm, and that of drum seal is 0.6 mm. Therefore, this paper adjusts the sealing clearance by compressing the sealing section, and simulates the sealing performance under different pressures.

3.2. Simulation result

When the compression is 0.6 mm, the mountain seal is in compression state. The results show that when the working medium pressure of high pressure chamber and low pressure chamber is 39.8Mpa/31.5Mpa, 29.8Mpa/21.5Mpa, 19.8Mpa/11.5Mpa and 9.8Mpa/1.5Mpa respectively, the maximum Von mises stress of piston inner stroke is 81.097Mpa, 67.965Mpa, 63.061Mpa, 59.341Mpa, and the maximum Von mises stress of piston outer stroke is 72.328Mpa, 63.555Mpa, 60.246Mpa, 53.81Mpa. The stress-strain nephogram is shown in Fig.2.

![Stress nephogram](image)

**Figure 2.** Von mises stress nephogram of mountain seal with 0.6 mm compression
When the compression is 0.5mm, the analysis results show that the maximum Von mises stress of the piston inner stroke are 78.768Mpa, 65.469Mpa, 59.316Mpa, 54.092Mpa, the maximum Von mises stress of the piston outer stroke are 69.879Mpa, 60.273Mpa, 55.479Mpa, 47.344Mpa. The stress-strain nephogram is shown in Fig.3.

Figure 3. Von mises stress nephogram of mountain seal with 0.5 mm compression

When the compression is 0.4mm, the analysis results show that the maximum Von mises stress of the piston inner stroke are 76.644Mpa, 63.581Mpa, 55.254Mpa, 48.328Mpa, the maximum Von mises stress of the piston outer stroke are 67.891Mpa, 56.551Mpa, 49.793Mpa, 39.765Mpa. The stress-strain nephogram is shown in Fig.4.

Figure 4. Von mises stress nephogram of mountain seal with 0.4 mm compression

When the compression is 0.6 mm, the drum seal is also in compression state. The results show that when the working medium pressure of high pressure chamber and low pressure chamber is 39.8Mpa/31.5Mpa, 29.8Mpa/21.5Mpa, 19.8Mpa/11.5Mpa and 9.8Mpa/1.5Mpa respectively, the maximum Von mises stress of piston inner stroke is 56.112Mpa, 47.082Mpa, 44.181Mpa, 38.564Mpa, and the maximum Von mises stress of piston outer stroke is 49.728Mpa, 42.354Mpa, 37.524Mpa, 34.943Mpa. The stress-strain nephogram is shown in Fig.5.
When the compression is 0.5mm, the analysis results show that the maximum Von mises stress of the piston inner stroke are 53.966Mpa, 43.1Mpa, 37.047Mpa, 26.496Mpa, the maximum Von mises stress of the piston outer stroke are 46.876Mpa, 38.412Mpa, 29.686Mpa, 20.104Mpa. The stress-strain nephogram is shown in Fig.6.

Figure 5. Von mises stress nephogram of drum seal with 0.6 mm compression

Figure 6. Von mises stress nephogram of drum seal with 0.5 mm compression

Figure 7. Von mises stress nephogram of drum seal with 0.4 mm compression
When the compression is 0.4mm, the analysis results show that the maximum Von mises stress of the piston inner stroke are 50.972Mpa, 41.7Mpa, 33.654Mpa, 26.152Mpa, the maximum Von mises stress of the piston outer stroke are 44.109Mpa, 32.607Mpa, 23.207Mpa, 14.324Mpa. The stress-strain nephogram is shown in Fig.7. According to Von-Mises stress, the contact stress distribution curves of mountain seal and drum seal under different working medium pressures in Figs. 2～7 are obtained, and the maximum contact stress is extracted, as shown in Table 3.

| Water pressure of high pressure chamber/Water pressure of low pressure chamber | Amount of compression |
|---|---|---|---|
| | 0.6mm | 0.5mm | 0.4mm |
| Mountain seal | Inside stroke of piston | 75.365 | 72.566 | 69.851 |
| | 67.351 | 65.225 | 62.005 |
| | External stroke of piston | 63.056 | 59.712 | 56.405 |
| | Inside stroke of piston | 56.392 | 55.225 | 52.005 |
| | External stroke of piston | 44.109 | 40.722 | 38.503 |
| Drum seal | Inside stroke of piston | 53.297 | 51.019 | 48.851 |
| | 46.883 | 44.452 | 42.313 |
| | External stroke of piston | 40.722 | 36.452 | 30.989 |
| | Inside stroke of piston | 35.916 | 31.652 | 24.589 |
| | External stroke of piston | 32.531 | 28.485 | 21.245 |

Making the trend diagram between the compression amount and the working medium pressure and the maximum contact stress can more intuitively analyze the change rule between the two and the contact stress, as shown in Figure.8.
3.3. Analysis of effect

When the cylinder is under pressure, the Von mises stress of the mountain seal ring and drum seal ring is shown in Figure 2~7. It can be seen from the figure that the Von Mises stress increases gradually with the increase of the working medium pressure when the cylinder body presses the seal ring, and the peak areas of their Von Mises stress are roughly the same. The Von mises stress in the middle of the contact surface between the mountain seal ring and the cylinder is the largest, and the Von mises stress in the outer edge of the drum seal ring is the largest. In general, the area with larger Von Mises stress is more prone to fatigue failure and crack, and the seal ring is more prone to damage, thus damage failure.

At the same temperature, the performance of pure water is greatly different from that of hydraulic oil or emulsion. The kinematic viscosity of pure water is much lower than that of hydraulic oil and emulsion, so it is more likely to leak at the same gap. However, it can be seen from Table 3 that under different working medium pressures, the maximum contact stress of mountain seal and drum seal is much higher than the applied working medium pressure, and increases with the increase of working medium pressure. For seals, the increase of contact stress is helpful to enhance the sealing effect, and the maximum value is always greater than the working medium pressure, which ensures the sealing performance of mountain seal and drum seal.

As shown in Figure 8, the contact stress increases with the increase of the compression amount, but with the increase of the working medium pressure, the growth trend of the contact stress between different compression amounts decreases gradually. Considering the compression amount and the working medium pressure, the sealing effect of the mountain seal ring and the drum seal ring decreases gradually with the increase of the compression amount and the working medium pressure.

It can be seen from Table 3 that under the same compression amount and working medium pressure, the contact stress of mountain seal is greater than that of drum seal, and from Fig. 8, the increase trend of contact stress of mountain seal is greater than that of drum seal. Therefore, when applied to the same piston, under the same compression amount and working medium pressure, the sealing effect of mountain seal is better than that of drum seal.

4. Conclusions

(1) The peak areas of Von mises stress of both mountain and drum sealing rings are approximately consistent with the increase of working medium pressure, indicating that the vulnerable areas of both rings are basically unchanged.

(2) Under different working medium pressures, the contact stress increases with the increase of working medium pressure, and the maximum value is always greater than the working medium pressure, ensuring the sealing performance of the seal ring.

(3) The sealing effects of mountain seal and drum seal gradually decrease with the increase of compression amount and working medium pressure.

(4) When applied to the same piston, the sealing effect of mountain seal is better than that of drum seal under the same compression amount and working medium pressure.

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