Research on Self-compensating Oil Sleeve for Hydraulic Chuck

Jiangbo Yang*, Song Wang, Pengbo Xu, Xiang Chen, Fenglei Chen
Xi’an Research Institute of China Cola Technology and Engineering Group Corp,
Xi’an, Shaanxi, 710077, China
Email: 364126797@qq.com

Abstract. Based on the oil supply principle of hydraulic chuck, analysis of the structural characteristics and failure reasons of the oil distribution sleeve showed that the main reason for the increase of the leakage of the oil sleeve is the increase of the value of the seal gap caused by the increase of the temperature and pressure of the hydraulic oil. The self-compensating oil sleeve for the rotary oil distribution of hydraulic chuck is designed by theoretical calculation, and the deformation of the self-compensating oil distribution sleeve and the common oil distribution sleeve are compared and analyzed by finite element software, and the sealing performance of the two kinds of oil sleeve is compared and analyzed by test. The results show that the sealing gap of the self-compensating oil sleeve has dynamic stability compared with that of the ordinary oil sleeve, and the leakage of the self-compensating oil sleeve is stable under the working condition, which can provide reference for the design innovation of the rotary oil distribution sleeve for the chuck of the full hydraulic drilling machine.

Keywords: Hydraulic Chuck, Oil Sleeve, Sealing Gap, Self-compensating, Leakage

1. Introduction

Oil sleeve is an important sealing element in the full hydraulic power head tunnel drilling machine. Its sealing performance directly determines the transmission efficiency of power head [1]. With the improvement of drilling rig’s working capacity, the leakage problem of oil sleeve gradually becomes prominent, and the leakage amount is proportional to the cubic square of seal clearance, so the size of seal clearance is the most important factor affecting the leakage amount of oil distribution sleeve [2, 3]. When drilling machine is working, the increase of working oil pressure and temperature will lead to the deformation and increase of inner diameter of oil distribution sleeve, which will lead to the increase of sealing clearance, the decrease of sealing performance of oil distribution sleeve and the decrease of hydraulic system efficiency.
Figure 1. The structure of self-compensating oil sleeve.

For improving the sealing performance of the oil sleeve, the self-compensating oil sleeve uses the pressure oil in the compensation gap between the inner sleeve and the outer sleeve to restrain the expansion and deformation of the inner sleeve.

The hydraulic oil in the compensation gap will sync with the increase of the pressure in the seal clearance increases, so that it can effectively inhibit oil distribution set of deformation of the expansion of the inner sleeve. This restraint method can effectively compensate for the increase of inner diameter of the outer sleeve after thermal expansion, and avoid the problem of reduced binding force caused by the expansion of outer sleeve. In addition, the compensation effect of high pressure oil can also greatly reduce the thickness of the outer sleeve, which will increase the buoyancy of oil sleeve. It is of great significance to realize the pressure maintaining of oil sleeve, increase the clamping force of chuck and improve the working performance of drilling rig. The structure of self-compensating oil sleeve is shown in figure 1.

2. Design and Calculation of Self-compensation Oil Sleeve

The design of self-compensation oil sleeve should be based on the good interchangeability with the existing oil sleeve. Therefore, the structural size of the power head and the external size of the existing oil sleeve should be fully considered in the design of self-compensation oil sleeve. In the design of self-compensation oil sleeve, the key parameters include the overall weight of the self-compensation oil distribution sleeve, the thickness of the inner sleeve of the sealing device and the location of the O-ring.

2.1. Calculation of Floating Power of Self-Compensation Oil Sleeve

The overall weight of the oil sleeve directly affects its buoyancy, and according to the leakage quantity formula in eccentric annular joint, the leakage quantity is 2.5 times as much when the oil sleeve is completely eccentric, so reducing the weight of the oil distribution sleeve is helpful to improve its buoyancy and reduce the leakage quantity [4].

The floating power calculation of self-compensation oil sleeve can refer to the floating principle of sliding bearing. The floating principle of the two is very similar, the difference lies in the oil sleeve and the spindle composed of "sliding bearing", floating is the oil sleeve, while sliding bearing floating is the shaft, bearing bush is fixed. The floating power of oil sleeve is calculated as follows [5]:

\[
W = 1.09 \mu ndL \left( \frac{L}{d} \right)^2 \left( \frac{d}{\delta} \right)^2 \frac{\varepsilon}{1-\varepsilon}
\]

Thereinto: \( W \) — floating power, \( N \);
\[\mu - \text{Hydrodynamic viscosity, } \mu = 0.01578 \text{ Pa s};\]
\[n - \text{Spindle speed, } n = 5 \text{ r/min};\]
\[d - \text{Sealing clearance diameter, } d = 0.12 \text{ m};\]
\[L - \text{Throttling length, } L = 0.072 \text{ m};\]
\[\delta - \text{Sealing clearance, } \delta = 2 \times 10^{-5} \text{ m};\]
\[e - \text{Eccentricity, } e = 1 \times 10^{-6} \text{ m};\]
\[\varepsilon - \text{Relatively eccentric, } \varepsilon = e / \delta = 0.05.\]

Put into Equation and calculate \(W = 144 \text{ N}\), then the maximum weight of the sealing device shall not exceed \(14.7 \text{ kg}\).

2.2. Calculation of Inner Sleeve Thickness of Self-Compensation Oil Sleeve

The inner sleeve thickness of self-compensation oil sleeve is determined by the pressure of compensating oil ring, the temperature of hydraulic oil and the pressure of hydraulic oil in the sealing gap. Let \(\alpha_1, E_1, \mu_1\) respectively be the linear expansion coefficient, elastic modulus and Poisson's ratio of the spindle material; Let \(\alpha_2, E_2, \mu_2\) respectively be the linear expansion coefficient, elastic modulus and Poisson's ratio of the inner sleeve material of oil sleeve; Let \(r_0, r_1, r_2\) respectively be inner radius of the spindle, the outer radius of the spindle (the inner radius of the inner sleeve), and the outer radius of the inner sleeve. Whereinto, \(r_0 = 37.5 \text{ mm}, r_1 = 60 \text{ mm}\).

When the working pressure of the sealing device is \(p = 25 \text{ MPa}\) and the temperature is increased by \(\Delta T = 40^\circ\text{C}\), the thermal expansion of the spindle caused by the temperature increase is:

\[
\delta_0 = r_1 \cdot \Delta T \cdot \alpha_1
\]

The thermal expansion of the inner sleeve of the sealing device caused by temperature increase is:

\[
\delta_1 = r_1 \cdot \Delta T \cdot \alpha_2
\]

The reduction of the hydraulic oil pressure in the sealing clearance to the outer diameter of the spindle is:

\[
\delta'_0 = \frac{2r_0r_1p}{E_2\left(r_1^2 - r_0^2\right)}
\]

The increase of hydraulic oil pressure in the sealing gap on the inner diameter of the inner sleeve of the oil sleeve is:

\[
\delta'_1 = \frac{r_1^2p}{E_2\left(r_2^2 - r_1^2\right)}\left[1 - \mu_2\right] + \left[1 + \mu_2\right]\frac{r_2^2}{r_1^2} - \left[1 - \mu_2\right]r_1 + \left[1 + \mu_2\right]\frac{r_2^2}{r_1}
\]

The internal diameter reduction caused by the hydraulic oil pressure in the compensation oil ring to the inner sleeve of the oil sleeve is:

\[
\delta''_1 = \frac{2r_1r_2p}{E_2\left(r_2^2 - r_1^2\right)}
\]

The sealing clearance reduction caused by the compensation effect of the compensation oil ring on the oil sleeve is:
\[ \delta = \delta_1^+ - (\delta_1^- + \delta_0^+) + (\delta_0^- - \delta_0^+) \]

Since the sealing gap of the oil sleeve is \( \delta = 0.02 \text{mm} \), the compression deformation of the inner sleeve of the oil sleeve shall not be too large in order to avoid the wear of the spindle and the inner sleeve of the oil sleeve caused by excessive compensation amount of the oil sleeve. The calculated minimum outer radius of the oil sleeve is \( r_2 = 67.8 \text{mm} \), and the minimum thickness of the oil sleeve shall not be less than \( 7.8 \text{mm} \).

### 2.3. Calculation of Self-compensation oil Sleeve O-ring Position

The O-ring position will directly affect the micro-shape of the sealing clearance of the oil sleeve under the working condition and the distribution of the compensation amount along the axial direction of the inner sleeve of the oil sleeve. Its position is determined by the maximum working pressure, the maximum working temperature rise, and the thickness of the inner sleeve. During calculation, the maximum working pressure was set as \( p = 25 \text{MPa} \), the maximum working temperature was set as \( \Delta T = 40^\circ \text{C} \), and the inner sleeve thickness of the oil distribution sleeve was set as \( h = 10 \text{mm} \). Let the O-ring position (the distance between the O-ring and both ends of the sealing device) be \( l \), the hydraulic oil pressure in the compensation oil ring be \( p_1 \), and the spindle's outer diameter compression deformation caused by pressure under this working condition is:

\[ \delta_0 = \frac{2r_0r_1^2p}{E_2 (r_1^2 - r_0^2)} \]

The outer diameter thermal expansion deformation of the spindle caused by temperature increase is:

\[ \delta_0 = r_1 \Delta T \cdot \alpha_t \]

Hydraulic oil pressure in compensation oil ring:

\[ p_1 = \begin{cases} p (l \geq l_0) \\ 0 (l < l_0) \end{cases} \]

Since the effect of the pressure compensating oil ring at different O-ring positions on the inner sleeve of the sealing device is different, the deformation curve of the inner diameter of the sealing device changes with the change of the O-ring position. The optimum O-ring position can be selected by comparing and analyzing the change of seal clearance under different O-ring positions. The specific structural parameters of the designed self-compensation ring seal are shown in the table 1.

#### Table 1. The structural parameters of self-compensating oil sleeve

| Structural parameters                              | Value/mm |
|---------------------------------------------------|----------|
| Inner diameter of oil distribution sleeve         | 120      |
| Outer diameter of inner sleeve (inner diameter of outer sleeve) | 150      |
| Outer diameter of oil sleeve                      | 176      |
| Inlet hole diameter                               | 18       |
| O-ring position                                   | 16       |

### 3. Comparative Analysis of Oil Sleeve Sealing Performance Test

Through the self-developed oil sleeve sealing performance testing device for hydraulic chuck, the sealing performance of the designed self-compensation oil sleeve and the common oil sleeve were
tested, and the sealing performance of the two different oil sleeves was compared and analyzed to verify the design results.

The test device is composed of three parts: rig simulation system, loading system and condition monitoring system. The rig simulation system is the basis for installing the oil sleeve under test. The installation plane of the platform can meet the installation requirements of oil sleeve of different structure sizes. The working environment of the oil sleeve can be simulated by simulating the power head structure of the drill. The working condition loading system mainly supplies hydraulic oil through the hydraulic pump station, and the speed regulating motor provides spindle rotation to realize the simulation of the working state of the oil sleeve. The state detection system includes hardware such as sensors and signal collectors and software of the detection system, which can receive, convert, display, record and backup data of oil sleeve parameters. The test device is shown in the figure 2.

![Figure 2. Oil sleeve sealing performance testing device for hydraulic chuck.](image)

The temperature rise of the hydraulic oil shall not exceed 2°C during the measurement of the common oil sleeve and the self-compensation oil sleeve measured in Figure 3. It can be seen from the figure that when the self-compensating oil sleeve operates under low pressure, its leakage amount is larger than that of the ordinary oil sleeve. This is because when the working pressure is low, the hydraulic oil in the pressure compensation clearance of the self-compensating oil sleeve has not generated enough compression force on its inner sleeve, resulting in its insignificant pressure compensation effect. In the outer area of the O-ring, the oil distribution sleeve can only rely on the inner sleeve itself to resist expansion and deformation. This part has a weak anti-expansion ability, leading to a large leakage amount. Due to the interference fit between the inner and outer sleeve, uniform extrusion force will be generated when the inner sleeve expands. Therefore, the expansion deformation and leakage amount of the common oil sleeve are small.

When the working pressure rises, the pressure compensation effect of self-compensation oil sleeve is gradually obvious, and its leakage quantity will be maintained in a stable range, while the leakage quantity of ordinary oil sleeve increases rapidly with the increase of pressure. It can be found from the Figure 3 that, when the working pressure reaches 21MPa, the leakage of self-compensating oil sleeve will be smaller than that of the ordinary oil sleeve.
4. Conclusions

1) The self-compensation oil sleeve design calculation formula can provide reference for the design of new oil sleeve.

2) The influence of the working pressure of the self-compensating oil sleeve on the leakage quantity is shown as follows: when the working pressure is low, the leakage quantity of the sealing device is large; with the increase of the working pressure, the pressure compensation function is enhanced, and the leakage quantity gradually decreases. It is suggested that the working pressure of the self-compensating oil sleeve is 21MPa.

References

[1] Yang J B 2016 Simulation study of the sealing performance of drilling rig oil sleeve Xi’an: Coal Geology & Exploration 44:132-136. (in Chinese)

[2] Arghir M, Nguyen M H, Tonon D, et al. 2012 Analytic modeling of floating ring annular seals Journal of Engineering for Gas Turbines & Power 134(5): 577-586.

[3] Ha T W, Lee Y B, Kim C H 2002 Leakage and rotor dynamic analysis of a high pressure floating ring seal in the turbo pump unit of a liquid rocket engine Tribology International 35(3): 153-161.

[4] Yang J B 2016 Research on Self-Compensating Sealing Ring for Full Hydraulic Drilling Rig Chuck. (in Chinese)

[5] Wang L L, Lu C H 2015 Numerical analysis of spiral oil wedge sleeve bearing including cavitation and wall slip effects Lubrication Science 27(3): 193-207.