Thermal analysis method of optical scanning system drive shaft system

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Abstract. In order to improve the heating problem of the rotating shaft components of the optical surveillance scanning system due to continuous operation, the feasibility of applying the oil-air lubrication technology to the drive shaft system of the optical surveillance scanning system was studied. Analyzed the contact load of the spindle bearing, obtained the calorific value of the heat source of the spindle component of the drive system, established the finite element analysis model of the temperature field of the spindle component, and calculated the thermal stability of the spindle component under the conditions of no lubrication and lubrication. Temperature rise. It is proposed to apply the oil-air lubrication method to the drive shaft system of the optical monitoring scanning system, and the corresponding lubrication parameters are calculated.

1. Introduction
In order to quickly scan the scene to form a panoramic monitoring, the optical scanning system needs to drive the spindle to rotate rapidly. As a result, the continuous high-speed rotation causes the inertial force of the motion mechanism to increase sharply, increasing the contact load and friction torque of the spindle bearing, and the temperature rise of the spindle component. Increased, worsened the dynamic characteristics of the spindle. Choosing a reasonable bearing lubrication method and reducing its friction torque is one of the measures to effectively improve the temperature rise of the spindle. Aiming at the lack of lubrication methods in a certain type of optical scanning imaging drive system, a new technology of oil-air lubrication is proposed. This technology uses compressed air to bring the gas-liquid two-phase mixed fluid to the lubrication area of the bearing evenly along the dedicated oil and gas pipeline wall in a fixed and quantitative manner to achieve the purpose of lubrication. This kind of lubrication method has been applied to the lubrication of spindles and rolling bearings in many occasions. Literature [1] conducted a systematic oil-air lubrication test study on high-speed electric spindle bearings, and analyzed parameters such as lubricating oil type, lubricating oil volume and oil-air pressure. Provide important parameters for the tribological design of the electric spindle. Literature [2] studied the optimal oil supply required for oil-air lubrication under different working conditions, and the study found that: compared with other lubrication methods, oil-air lubrication can maintain a lower temperature rise. Literature [3] pointed out that a large amount of frictional heat inside the high-speed electric spindle bearing will affect the rigidity performance and high-speed performance of the bearing, and the oil-air lubrication system is more suitable for the lubrication requirements of the high-speed spindle bearing. At present, most of the research on oil-air lubrication is limited to experimental verification [4]-[6], and the application of this technology in optical scanning drive systems has not been reported. This article...
takes a certain type of optical scanning imaging drive system spindle component as the research object, applies the oil-air lubrication method to the optical scanning imaging system, and analyzes it.

2. Spindle bearing heating analysis
The friction of the spindle bearing of the optical scanning imaging drive system is the main reason for the bearing heating. The increase of the frictional heat value in the raceway can easily cause the tempering and softening of the bearing contact surface material, leading to premature fatigue failure of the bearing [7]-[10].

2.1 Analysis of heating characteristics of non-lubricated bearings
When the bearing is running at high speed, the friction between the ball and the raceway in the load zone is the sum of rolling friction and sliding friction. Because rolling friction is much smaller than sliding friction, the calculation of bearing friction torque is calculated according to sliding friction. As shown in Fig. 1, two NSK6004 deep groove ball bearings are installed on the left side of the optical scanning drive assembly, and one bearing of the same type is installed on the right side. The inertial force generated by the optical scanning motion component acts on the bearing, which causes the bearing to bear the radial load \( F_r \) and deform.

According to the Hertz elastic contact theory and the force balance equation, the calculation expression of the friction torque of the bearing is:

\[
M_f = 0.5 \mu \left( Q_{max} + 2(Q_1 + Q_2) \right) d
\]

\[
Q_1 = Q \cos^t \varphi_{1_{max}}
\]

\[
Q_2 = Q \cos^t \varphi_{2_{max}}
\]

\[
Q_{max} = \frac{F_r}{1 + 2 \cos^t \varphi_1 + 2 \cos^t \varphi_2}
\]

\( \mu \) — The friction coefficient of rolling ball bearings without lubrication, \( \mu = 0.002 \)
\( d \) — Bearing inner diameter

![Figure 1. Schematic of principal axis](image1)

![Figure 2. Dry friction torque curve](image2)
When the working speed of the scanning component is 4500rpm, the periodic inertial force generated by the scanning component is applied to the radial load value generated by the front and rear bearings of the main shaft, and then the radial load value generated by the front and rear bearings of the driving component is obtained when there is no lubrication. The change curve of the friction torque of the ring is shown in Fig. 2.

It can be seen from Fig. 2 that the friction torque of the front end bearing is greater than that of the rear end. The calculated equivalent friction torques of the front and rear bearings are:

\[ M_{1e} = 2.1 \times 10^{-3} \text{Nm} \]
\[ M_{2e} = 3.2 \times 10^{-4} \text{Nm} \]  

When the bearing is running at high speed, the friction loss due to sliding friction of the bearing almost becomes heat inside the bearing, which causes the bearing temperature to rise. The power loss \( P_1 \) (W) of the bearing is the equivalent friction torque \( M_e (N\cdot m) \) of the rolling bearing and the angular velocity \( \omega \) of the bearing. The product, namely:

\[ P_1 = M_e \omega = M_e \frac{mn}{30} \]  

formula:

\( P_1 \)—Power loss due to bearing friction(W)
\( n \)—Bearing speed(rpm)

Bring the result of formula (2) into formula (3), \( n=60\)rpm, the heat generating power of the front and rear bearings of the optical scanning drive assembly are:

\[ P_{f1} = 2.1\times10^{-3} \times \frac{\pi \times 4500}{30} \]
\[ = 0.99(W) \]
\[ P_{f2} = 0.15(W) \]

2.2 Analysis of heating characteristics of lubricated bearings
Whenever lubricating oil is added to the bearing, a uniform lubricating oil film is formed between the ball and the raceway, thereby reducing the friction and heating between the components. Lubricating the bearing is an effective way to reduce the friction torque of the bearing. However, due to the presence of lubricating oil in the bearing, the viscosity of the lubricant will also produce a certain friction torque. Palmgren proposed that the total friction torque \( M_2 \) in the lubricated bearing is mainly composed of the friction torque \( M_u \) independent of the bearing load and the friction torque \( M_p \) related to the bearing load, that is, the total friction torque of the bearing during lubrication is:

\[ M_2 = M_u + M_p \]
\[ = 10^{-7} f_0 (vn)^{2/3} \times 0.031^3 \]
\[ + 0.0009\left(\frac{P}{C_0}\right)^{0.55} F_s \times 0.031 \]  

formula:

\( f_0 \)—coefficient related to bearing type and lubrication method, pressure lubrication is used in the drive assembly, \( f_0=1.5 \)
\( n \)—bearing spee(rpm)
\( v \)—Kinematic viscosity of lubricant at bearing working temperature(\( \text{mm}^2/\text{s} \)), \( v = 12 \text{mm}^2/\text{s} \)
$P_0$—Equivalent static(N), $P_0=Fr$

$C_0$—Basic static load rating(N), $C_0=5000N$

$Fr$—Bearing radial load(N)

When the working speed of the drive assembly is 4500 rpm, the value of the radial load of the front and rear bearings of the main shaft calculated above is brought into equation (4). When there is lubrication, the friction torque change curve of the front and rear bearings of the drive assembly for one revolution is shown in Fig. 3.

\[P_0 = Fr\]

\[C_0 = 5000N\]

When the working speed of the drive assembly is 4500 rpm, the value of the radial load of the front and rear bearings of the main shaft calculated above is brought into equation (4). When there is lubrication, the friction torque change curve of the front and rear bearings of the drive assembly for one revolution is shown in Fig. 3.

Figure 3. Friction torque curve with lubricating

When the driving bearing is lubricated, the equivalent moments of the front and rear bearings are as follows:

\[M_{1e} = 0.5 \times 10^{-3} N.m\]

\[M_{2e} = 1.1 \times 10^{-4} N.m\]  \hspace{1cm} (5)

Incorporating the calculation result of equation (5) into equation (3), the heat generation power of the front and rear bearings of the drive assembly during lubrication is calculated as:

\[P'_{f1} = 0.24(W)\]

\[P'_{f2} = 0.05(W)\]  \hspace{1cm} (6)

Based on the above analysis and calculation, it can be concluded that the friction torque of the bearing under dry friction and lubrication is very different. After the bearing is lubricated, the equivalent friction torque and heating power of the front end bearing are reduced by 76% compared with the dry friction, the equivalent friction torque and heating power of the rear bearing are reduced by 65% compared with dry friction.

3. Finite element analysis of heating characteristics of drive shaft system

The drive shaft is a key component of the optical scanning assembly. Its motion performance intensively reflects the dynamic characteristics of the optical device. The drive shaft will produce thermal expansion at high temperatures, resulting in shaft deformation, which will cause the optical device to vibrate and increase the motor load. Based on the heat balance equation based on the principle of conservation of energy, the ANSYS analysis software is used to calculate the temperature change and temperature field distribution of the spindle when the drive component is running.

The establishment of the finite element analysis model of the drive assembly shaft system is shown in Fig. 4. The heating power before and after the bearing lubrication calculated above is respectively brought into the spindle finite element analysis model for steady-state thermal analysis, and then solved.
to obtain the drive shaft system at the speed The steady-state temperature field distribution before and after lubrication at 4500 rpm is shown in Fig. 5 and Fig. 6.

![Figure 4. Finite element model of swing machine](image)

1—Spindle 2—Front end bearing (2 pcs) 3—Back end bearing 4—Chassis 5—Shaft sleeve

![Figure 5. Spindle temperature field of swing machine with dry friction](image)

![Figure 6. Spindle temperature field of swing machine with lubricating](image)

It can be seen from the results of Fig. 5 and Fig. 6 that when the rotation speed of the drive shaft is 4500rpm, the normal temperature is 20°, and the distribution of the steady-state temperature field before and after lubrication is analyzed, and the following conclusions are obtained:

1. When the main shaft bearing is not lubricated, the maximum temperature at the front end of the main shaft bearing installation is about 87°, and the temperature rise is 67; the maximum temperature of the front and rear bearings of the main shaft is 107° and 49°, and the temperature rise is 87° and 29° respectively;
2. When the main shaft bearing is lubricated, the maximum temperature at the front end of the main shaft bearing installation is 53°, and the temperature rise is 33°; the maximum temperature of the front and rear bearings of the main shaft is 62° and 34°, and the temperature rise is 42° and 14° respectively;
3. Comparing before and after lubrication, it can be seen that reducing the friction torque of the bearing after lubrication reduces the maximum temperature rise of the main shaft and the front and rear bearings by about 50%;
4. Based on the above analysis, choosing an effective lubrication method to lubricate the drive shaft bearing of the optical scanning assembly can effectively control the temperature rise of the main shaft and keep the machine in good running condition.
4. **Summarize**

This article analyzes the heating characteristics of the drive shaft system of the optical scanning assembly, and the results show that the inertial force of the drive assembly causes the radial load of the bearing, which causes the friction torque of the bearing to increase sharply, resulting in excessive temperature rise. Based on the research and analysis of the temperature rise of the finite element model of the spindle system with and without lubrication, it is proposed that the use of oil-air lubrication in the drive shaft of the optical scanning assembly instead of the original lubrication method can reduce the temperature rise of the spindle system, can effectively improve the thermal characteristics of the rotary shaft system, and enhance the reliability of the system's high-precision and stable operation.

5. **References**

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