Research on Fault Mechanism of Pendulum Shear Bearing Based on Stress and Thermal Analysis and Finite Element Simulation Technology

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Abstract. After using the bearings (NSK, FAG) of different manufacturers with the same external dimensions for a pendulum reducer bearing for thin steel slab continuous casting and rolling production line of a steelmaking plant, the bearing failure occurs in a short period of time, which seriously affects the safe operation and production efficiency of the equipment. According to the structure of the pendulum shear and its working characteristics, this paper analyzes its load characteristics and conducts on-site measurement of the force parameters of the pendulum shear. And using the classical bearing friction theory such as Hertz law, the contact pressure and the heat rate between the inner ring and the roller of different types of bearings are analytically calculated. Based on field measured force energy parameter data and analytical calculation results, the finite element technique is used to simulate the dynamics of the pendulum shear drive system and the temperature field, and the real reason for the bearing failure is obtained. According to the analysis of the research results, the replacement of the same size bearing (SKF) with better mechanical response performance is a reasonable measure to effectively solve the problem of short-term failure of the bearing.

Introduction

As one of the important parts in modern production equipment, pendulum shear bearing are widely used in ultra-high load and medium speed equipment such as metallurgical machinery. Once the bearing fails, it may cause serious economic losses and even cause life safety accidents. The key equipment for the thin slab continuous casting and rolling production line of a large steel company is the thin slab continuous casting machine. The bearings used in the pendulum shearing and transmission system of the equipment are SKF bearings, NSK bearings, NU2244 bearings, etc. In the production process, defects such as peeling of the inner ring of the bearing and cracking of the inner ring of the bearing often occur. Therefore, in the working process of the rotating machinery of metallurgical equipment, it is necessary to understand the working state of the bearing in a timely manner. The pendulum shear bearing is subjected to external load and thermal stress caused by frictional heat during the working process, the contact stress between the roller and the inner and outer rings of the bearing can be used as the technical index for judging the working state of the pendulum shear bearing\cite{1}. However, the pendulum shear bearing is mounted in the bearing housing, the structure is relatively compact, and the 1/3 to 1/2 space inside the bearing is occupied by lubricating oil or grease, it is difficult to place the sensor directly for temperature and stress testing\cite{2}. Therefore, the equipment is usually monitored on the outer surface of the bearing housing, the outer circumference of the shaft, and other parts suitable for mounting the sensor. The stress test curve of the key components indirectly reflects the change of the external load of the bearing.
thereby the dynamic parameters such as the contact stress between the roller and the inner jacket ring, the temperature distribution of the shaft system, the thermal stress are obtained, and the motion state of the bearing is evaluated. In this paper, the calculation method of contact stress between the bearing roller and the inner and outer rings is studied separately effected by external mechanical load and internal temperature field. And the research on fault mechanism of pendulum shear bearing based on force energy detection and finite element simulation technology are made, these provide relevant basis for relevant technical personnel to evaluate the working state of pendulum shear bearing. And a case study was introduced with a cylindrical roller bearing belonging to a pendulum shear reducer of a certain steel mills. The analysis results coincided highly with the testing data, showing the feasibility of the above analysis technologies. The analysis methods provided a technical route for the relevant technologists assessing the cylindrical roller bearing 's operating condition.

**Hertz Stress Calculation of Bearing under External Load**

Hertz[3] pointed out that the contact between the bearing rolling element and the inner and outer rings is a line contact, and the theoretical solution of bearing contact stress was given in 1982. According to Hertz theory, the contact field between the bearing roller and the inner and outer rings changes from a line to a rectangle under radial load, and the width $a$ of the rectangular area is satisfied by formula (1).

$$a = \frac{16RF}{\pi E'}$$  \hspace{1cm} (1)

In the formula, $R$ is equivalent radius, and $R = \frac{R_1R_2}{(R_1 + R_2)}$, $R_1, R_2$ is the radius of the roller and the ferrule respectively. $E'$ is equivalent elastic modulus, and $\frac{1}{E'} = \frac{(1-v_1^2)}{E_1} + \frac{(1-v_2^2)}{E_2}$, and $v_1, v_2, E_1$ and $E_2$ is the Poisson's ratio and elastic modulus of the roller and the ferrule respectively. $F$ is normal load between the roller and the inner and outer raceways.

![Figure 1. Force diagram of a single roller element.](image)

$$P = \sqrt{\frac{E'F}{\pi lR}}$$  \hspace{1cm} (2)

The maximum stress in the contact area is satisfied by the formula (2), so the force of a single cylindrical roller under radial load is shown in Figure 1, then the stress balance condition is founded by formula (3).

$$F_{oj} - F_{ij} - F_c = 0$$  \hspace{1cm} (3)

In the formula, $o$ is the outer ring of the bearing, $i$ is the inner ring of the bearing, $j$ indicates a rolling element at a certain position, $F_{oj}$: the force effected on the roller by the outer ring, $F_{ij}$: the force effected on the roller by the inner ring, $F_c$: the force effected on the outer ring produced by the roller revolution, and $F_c = 3.39 \times 10^{-11} D^3 l d_m n_m^2$, among them, $D$ is the roller diameter, $l$ is
effective contact length of the roller, \( d_m \) is pitch diameter of the bearing, and \( n_m \) is track speed of the roller.

For pendulum shear bearings with wire contact type, the rolling element load-displacement relationship at the position \( j \) is satisfied by equation (4).

\[
F = K \delta_j^{10^9}
\]  
(4)

In the formula, \( K \) is load displacement coefficient, \( K = 80500l_{10^9} \), \( \delta_j \) is radial displacement of the contact area. So the formula (3) is become to formula (5).

\[
K \delta_j^{10^9} - K \delta_j^{31^9} - F_\epsilon = 0
\]  
(5)

Each displacement component is satisfied: \( \delta_{o_j} = \delta_{ij} + \delta_{oj} \), \( r \) is expressed as radial, so formula (6) is gotten:

\[
(\delta_{ij} - \delta_{o_j})^{10^9} - \delta_{o_j}^{10^9} - F_{ij} / K = 0
\]  
(6)

For rigidly supported bearings under radial loads, the total radial displacement is expressed by formula (7).

\[
\delta_{ij} = \delta_i \cos \varphi_j - 0.5P_d
\]  
(7)

In the formula, \( \delta_i \) : radial displacement of the roller at the \( 0^\circ \) position, \( \varphi_j \) : an angle of the roller between the j-th roller and the \( 0^\circ \) position, \( P_d \) is radial clearance of the bearing. Substituting equation (7) into equation (6), then equation (8) is gotten.

\[
(\delta_i \cos \varphi_j - 0.5P_d - \delta_{o_j})^{10^9} - \delta_{o_j}^{10^9} - F_{ij} / K = 0
\]  
(8)

According to balance condition of force in which the direction of the radial load for the bearing:

\[
F_r - \sum_{j=1}^{z_1} F_j \cos \varphi_j = 0
\]  
(9)

Combined formula (4) and formula (9), then formula (10) is gotten.

\[
F_r / K - \sum_{j=1}^{z_1} \delta_{o_j}^{10^9} \cos \varphi_j = 0
\]  
(10)

Solving the nonlinear equations composed with equations (8) and (10), and the total radial displacement of the bearing \( \delta_i \) and the displacement of each roller \( \delta_{ij} \) are obtained, and the contact force of each roller between the inner and outer rings is gotten by bringing \( \delta_{oj} \) into the formula (4), then calculate the formula (2), the contact stress of the rolling bearing between the inner and outer rings of the pendulum shear bearing can be obtained.

**Temperature Field Calculation of Bearing under External Load**

The working temperature affecting the bearing mainly includes bearing load, bearing speed, bearing box structure, working environment and other factors. For pendulum shear bearings subjected to large loads and medium speeds, temperature levels (temperature is used as a monitoring target for bearing failures in many engineering applications) and thermal stresses under temperature should be considered. The contact friction between the various components of the bearing, especially the friction between the rolling elements and the inner and outer raceways, is the main cause of the temperature rise of the shafting.
In the early days, the heat equation of the whole system was established by using the flash temperature theory and the thermal resistance network method to calculate the temperature field of the bearing[5,6], then the steady state temperature value of the shafting is obtained.

However, used this method, a separate temperature node of each component is obtained by solving the nonlinear equations, but its accuracy is not high, and the temperature distribution and change history of each component cannot be obtained, therefore, the finite element is used in this study to calculate the thermal stress field of the shafting.

**Calculation of Friction Rate of Bearing UNDER External Load**

The power loss caused by bearing friction under external load is calculated as formula (11)[7].

\[ H = 1.047 \times 10^{-4} M \cdot n \]  

In the formula, \( H \): friction heat rate of bearing, \( M \): total friction torque, \( n \): shaft speed.

During the operation of the bearing, the friction load is generated by the applied load, palmgren uses the sum of the frictional moment caused by the external load \( M_f \), the viscous frictional moment \( M_v \), and the frictional moment between the end face of the roller and the rib \( M_f \)[8]. Relative to the frictional moment and viscous frictional moment, the viscous friction torque of the lubricant is small and can be ignored, so formula (12) is gotten.

\[ M = M_f + M_v + M_{f} \]  

(12)

According to the formula (12), the applied load moment \( M_f \) is calculated by equation (13).

\[ M_f = f_{t} F_{\beta} d_{m} \]  

(13)

Where, \( f_{t} \): coefficients related to bearing structure and the load, \( F_{\beta} = 0.8 \times F_{a} \cot \alpha \) or \( F_{\beta} = F_{r} \), which the maximum is gotten.

And the lubricating friction torque of lubricant \( M_v \) is calculated by formula (14) or (15).

\[ M_v = 10^{-7} f_{o} (v_{o} n)^{2} d_{m}^{3} \quad v_{o} n \geq 2000 \]  

(14)

\[ M_v = 160 \times 10^{-7} f_{o} d_{m}^{3} \quad v_{o} n < 2000 \]  

(15)

Where, \( f_{o} \) is coefficient related to bearing type and lubrication method, for heavy series pendulum shear bearings, \( f_{o} = 4 \cdot v_{o} \) is lubricant viscosity.

**The Boundary Condition of Thermal Analysis for the Bearing under External Load**

The temperature field finite element analysis process needs to convert the frictional heat rate into the heat flux density load \( q \) on the contact surface, where:

\[
\begin{aligned}
& t_i \leq t \leq t_i + d_i, q = k \times \frac{H}{A} \\
& t_i + d_i \leq t \leq t_i + t_{i+1}, q = 0
\end{aligned}
\]  

(16)

Where, \( k \) is partition coefficient of frictional heat generation on contact surface, \( 0 < k < 1 \). \( A \) is area of the contact surface, \( t_i \) is the starting moment of contact between the roller and the inner ring, \( d_i \): the time the roller passes the contact surface, \( t_{i+1} \): the starting moment of contact between the next roller and the inner ring.

The heat load generated inside the bearing is mainly radiated in the form of heat conduction and heat convection, and finally forms a stable working state. And the inner surface of the bearing cavity
is forced convection of lubricating oil, and the convective heat transfer coefficient is determined by formula (17).

\[ h = 0.332C_k \sqrt{Re} \sqrt{Pr} \times \frac{1}{d_w} \]  
\[ (17) \]

Where, \( h \) is convective heat transfer coefficient, \( C_k \) is thermal conductivity of lubricating oil, \( Re \) is Reynolds number of lubricating oil, \( Re = \frac{\omega D^2}{v_0} \), and \( \omega \) is axial angular velocity, \( P_r \) is Prandtl number of lubricating oil, and \( P_r = \frac{C_p v_0}{C_k} \), where, \( c \) : specific heat capacity of lubricating oil, \( g \) : gravity acceleration.

The convection coefficients of the other boundaries can be derived from references [9-11].

Case Study of the Bearing under External Load

Three-stage deceleration of helical gears between the high-speed shaft and the low-speed shaft of a shearing and rolling reducer in a continuous casting and rolling line of a steelmaking plant, which the rated speed of the motor is 1500 r/min and the transmission ratio is 35.16. The high-speed shaft adopts NU2244 pendulum shear bearing, the number of rolling elements is 15, the inner diameter of its inner ring is 220mm, the outer diameter of its inner ring is 259mm, the inner diameter of its outer ring is 367mm, the outer diameter of its outer ring is 400mm, the bearing width is 108mm, the rolling body diameter is 54mm, the diameter of its pitch circle is 313mm and the lubricating oil is EP460. The torque test result of the output shaft of the pendulum reducer is shown in Figure 3.

![Figure 2. Test signal for bearing torque during the first shear for pendulum.](image)

![Figure 3. Wireless test torque signal of the low speed shaft for pendulum reducer.](image)

The torque acting on the low speed shaft is 0 during the period of the shearing no shearing the strip steel. When the strip steel is sheared, the torque acting on the low speed shaft is a pulse signal, and the maximum torque value is \( 9.62 \times 10^8 N \cdot mm \). Then the equivalent load acting on the bearing is calculated based on the known maximum torque value, it is 204.226KN. Then the quasi-Newton method is used to iteratively solve the nonlinear equations composed of equations (8) and (10), and further the contact stress between the rolling elements and the inner and outer rings is obtained. At the same time, the stress distribution of the pendulum shear bearing under the radial load of
204.226KN is calculated by the finite element numerical method. The finite element calculation model has a total of 792,000 nodes and 3.439 million computational degrees of freedom.

The contact stress between the roller and the inner ring is similar by using the theoretical calculation and the finite element method, it is explained the correctness of the two methods. Because the stress state of the entire bearing can be obtained by using the finite element method, the finite element method can be used to evaluate and analyze the bearing state, and the theoretical calculation method is used to test whether the finite element model is suitable in scale and whether the boundary conditions are correct.

The radial load 204.226KN is brought into the equations (13) and (14), and the torque and viscous moment under the external load are 14829.16N·mm and 11842.42N·mm, respectively, so the total friction torque is 26671.58N·mm, and the friction heat rate of the bearing contact surface is obtained, it is 4188.77w.

Figure 4. Shafting structure and boundary conditions of thermal stress field.

Figure 4 shows the cross-section of the I-axis non-drive side bearing shafting of the pendulum shear reducer, the temperature field of cylindrical rolling bearing is calculated by moving heat source method. In order to reduce the amount of calculation and save CPU calculation time, thermal coupling plane strain unit is adopted. The heat flux between the roller and the inner and outer rings is given by equation (16), and the convective heat transfer coefficient is given by equation (17), and convective boundary conditions for the remaining open surfaces is: the outer surface of the cage with the inner and outer rings is \( h_4 \), and it is taken \( 200W/(m^2\cdot K) \), the outer surface of the shaft end ring and the side of the inner ring is \( h_5 \), and it is taken \( h_4/3 \), the outer surface of the outer ring bushing and the inner side of the bearing end cover is \( h_3 \), the heat conduction of the bearing and the air convection heat dissipation on the inner surface of the shaft are less than the convective heat dissipation with respect to the lubricating oil, and the air in the shaft is less exchanged with the outside, so \( h_3 \) is taken \( 5W/(m^2\cdot K) \). The outer surface of the bearing housing is the natural convection of air, and the convective heat transfer coefficient is \( h_6 \), and it is taken \( 15W/(m^2\cdot K) \), and the right end face of the shaft and the inner surface of the shaft are heat insulation surfaces. The heating time and heating interval of the heat source are simultaneously amplified by 1000 times, and the Hertz contact is established among the rolling element, the inner and outer rings, the finite element software is selected for calculation to obtain the temperature field distribution.

Figure 5. Finite element model for bearing temperature field analysis at 30000s.
Figure 5 shows the finite element model of the temperature field analysis of the bearing and its temperature distribution at 30000s. Figure 6 shows the temperature history curve of the center point A of the outer surface of the bearing end cap (point A in Figure 4), during the 0-5h period, the entire assembly of the bearing is in the temperature rise phase, and the temperature of the entire assembly of the bearing changes little during the relatively long time interval after 5h, this shows that the bearing is basically in thermal equilibrium from 5h. Throughout the time course, the temperature at point A of the outer surface of the bearing end cap is kept at about 58°C, which is the same as the on-site inspection record (as shown in Figure 7), it is indicated that the boundary conditions of the bearing temperature field are reasonable and the finite element calculation method is correct.

![Figure 6. Temperature change curve with time of bearing A point.](image)

Figure 7. The infrared heat maps from the field test.

Figure 8 shows the stress variation curve at the midpoint B of the inner surface of the inner ring of the bearing inner ring (Point B in Figure 4). Under the alternating action of heat source heating and lubricating oil cooling between the roller and the inner and outer rings of the bearing, the temperature of the contact surface between the roller and the inner ring constantly changes, and the contact stress changes accordingly. After the overall temperature of the bearing reaches equilibrium (after 5h), the contact stress at the midpoint of the inner surface of the bearing’s inner ring fluctuates between the minimum value of 200.7 MPa and the maximum value of 322.6 MPa.

![Figure 8. Thermal stress curve with time history of bearing B point.](image)

Considering the external load contact stress of the bearing when shearing the steel strip and the contact stress under the thermal load of the bearing, the maximum contact stress between the roller and the inner ring of the pendulum shear bearing reaches 1600 MPa, and the stress level has been large, long-term operation is easy to cause the inner ring to malfunction.

**Conclusions**

According to the pendulum structure and its working characteristics, the field force measurement, static load check and defect cause of the non-transmission side bearing force parameters are analyzed, and then the classical bearing friction theory such as Hertz law is used to calculate contact pressure and heat generation rate of the different types of bearing inner ring and roller. Finite
element technology for mechanical simulation and temperature field simulation is used based on field-measured force energy parameter data to analyze the real cause of bearing failure.

Considering the importance of mastering the working state of the pendulum shear bearing, based on the stress curve of the key components in the field, the technology combining of the theoretical calculation and finite element simulation technology is used, the contact stress between the roller and the ferrule is obtained acted on the pendulum shear bearing by the external mechanical load and internal thermal load respectively, and it is used as a key parameter for evaluating the working state of the bearing. The above analysis method was successfully applied to the bearing analysis of a shearing reducer in a steelmaking plant. The theoretical analysis results were verified by the finite element method, and the analysis results were consistent with the actual situation, that indicating the feasibility of the above analysis technique. The analysis method provides technical reference for field technicians to design and select the pendulum shear bearing.

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