Temperature Analysis Model of High-speed Railway Axlebox Bearing Based on Thermal Network Method

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Abstract: Axle box bearing, as the key component of the train running part, affects the running state and driving safety of the train. In the process of the rolling bearing operation, the temperature rise and the temperature distribution are the two key factors to decide the reliability of causative bearing. Considering the friction heat and flow resistance of heat source, this paper calculates the thermal impedance of axle box bearing, spindle system, bearing and lubrication, and joins the effect of air convection. Based on the thermal network method, a steady temperature analysis model of high speed rail axle box bearings is established. In this model, the axle box bearings of CRH3 high speed passenger train are solved and analyzed. The temperature calculation units and the temperature distribution of the outer ring surface are obtained. At the same time, the test on Netrol-AT.50/1 type railway bearing test machine is carried out. The temperature of the outer ring is coincided with the theoretical value. Thus the correctness of the model is verified and then the theoretical model can be provided for the thermal performance of the high-speed rail bearing.

Keywords: Axle box bearing; Thermal network; Temperature distribution

1 Introduction

With the rapid development of railway transportation industry, requirements for the bearing causative performance of high speed train is also increasing. Axle box bearing, as the key component of the train running part, affects the running state and driving safety of the train. The most common faults in high speed train running, such as hot axle, thermal deformation, hot box and burning spindle, are closely related to temperature distribution. The process of rolling bearing in operation, the temperature rises and the temperature distribution is one of the key factors to decide the reliability of causative bearing. The temperature distribution of the bearing is determined by the heat and heat transfer modes between the different parts and the different components of the bearing [1-2].If the temperature distribution of the bearing is not uniform or a part of the temperature rises sharply, will cause the uneven distribution of the thermal stress or thermal instability, thereby affecting the bearing performance and life.

Domestic and foreign scholars have carried out a great deal of research on the heat quantity and temperature distribution of rolling bearings. Harris etc. [3] given three heat

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transfer model calculation formula about the heat transfer, heat convection and heat radiation, and then established the bearing heat network model, and finally built and solved the heat balance equation. Chen [4] etc. established the temperature rise thermal deformation model of the spindle during the operation, and discussed the influence of the friction heat of the main shaft bearing on the spindle thermal expansion. Bercea etc. [5-6] considering the bearing assembly interference fit, load, lubrication parameters, overturning moment and other factors, established DRTRB model of tapered roller bearings, and then calculated the frictional heat of the whole bearing through the bearing power loss. Kang [7] considering the bearing preload and gyro moment, used Palmgren empirical formula to study the movement and stress state of the rolling body of the high speed motorized spindle bearing. The impedance of the bearing in the process of heat transfer was calculated, and the thermal temperature rise and the heat network model of the bearing were established.

Xing Lei etc. [8] studied the theory of thermal analysis of tapered roller bearings, and analyzed the steady-state temperature of tapered roller bearing field based on finite element simulation method and thermal network method. From the macro and micro two aspects they determined the distribution of the temperature in the working process of the bearing field. Qin Jianhua etc. [9] analyzed of the main forms of heat transfer and heat transfer mechanism of rolling bearing, and then given the calculation of heat generation of rolling bearing components in high speed environment, which provided reference for the study of temperature change and application of high speed rolling bearings. Zhu Pengfei etc. [10] used pseudo dynamic analysis method to analyze the interaction between the bearing elements and to analyze the heat generation of the bearings. A calculation model of the heat generation of the reverse bearing was established, and the main factors affecting the heat generation of the reverse bearing were studied. Wu Wei [11] analyzed tapered roller bearing friction heat source, established a box bearing thermal network model, and used the Newton iterative method for solving the steady state temperature value of each part, but they did not mention the thermal network model geometry and the contact characteristics of the tapered roller bearing. Based on the heat network method, Tang Wuchu [12] carried out the thermal calculation of the high speed axle box bearing, and carried out three-dimensional modeling and finite element temperature field analysis of the bearing. Finally, the accuracy of the theory was verified by the thermal test of the railway bearing.

It can be seen that the finite element method temperature field analysis can be applied to a variety of non-standard bearings, which have great advantages in bearing modeling and the intuition of solving the results. However, it is so difficult to accurately simulate for the lubrication conditions and the external load in the actual operation of the bearing. Some scholars have established a thermal network analysis model of tapered roller bearings, but did not take into account the friction heat source between the roller end and the inner ring flange, spindle-air environment convection heat and other factors on the temperature distribution; The current thermal network model boundary conditions are mostly the overall power consumption of the bearing, it is difficult to analyze the specific causes of heat, and the contact area of the heat source calculation is not accurate. Therefore, this paper comprehensively considers the heat source between the roller end face and the inner ring ribs, the air convection and the influence of the lubricating oil (grease), and establishes the steady-state thermal grid model of the high-speed rail axle box bearing, which is provided for the theoretical basis of the bearing thermal analysis.

2 Axle box bearing thermal network model

The domestic high-speed rail axle box bearing consists of cylindrical roller bearings, spherical roller bearings, needle roller bearings and tapered roller bearings. The tapered roller bearing has good bearing capacity of radial load, axle load and overturning moment and be widely used in the practical application, which mainly includes outer ring, inner ring, rolling body, cages and seals etc. Tapered roller bearings are installed in the axle box. The axle box is composed of spindle, box, bearing, seal plate, front cover and back cover, as shown in figure 1.

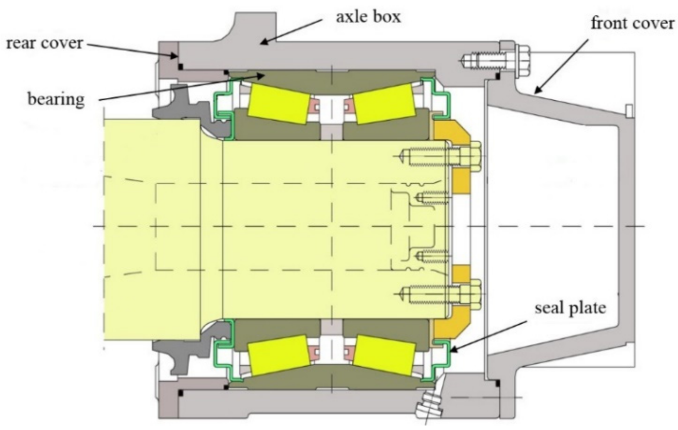

Fig. 1. Axle box and axle box bearing

2.1 Hypothesis

Before establishing the thermal network model diagram and the heat balance equations of the system, the following six assumptions and simplification should be made for the analysis system:

1）All the heat sources in the axle box bearing system are derived from frictional heat build-up in the bearings. In addition, there is no heat input outside the system;

2）The heat transfer impedance of each component of the axle box bearing system is independent of the heat flow direction, and the material of each part of the bearing is isotropic, and the heat transfer process is steady heat transfer;

3）The temperature of each component in the bearing system has little difference. In the steady state thermal analysis, the radiation heat transfer between the components can be neglected;

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4）The temperature of the oil and gas mixture in the bearing seat is the same and remains the same, and the air temperature outside the bearing seat is the same and remains the same;

5）Ignore the thermal resistance between the bearing outer ring and the bearing seat and ignore the thermal resistance between the bearing inner ring and the shaft;

6）Ignoring the convection heat transfer between the roller and the surrounding oil-gas mixture.

2.2 Node division

Based on the aforementioned model of high speed axle box bearings, according to the relationship between the bearing system heat transfer part, the bearing system is divided into 7 hot nodes, respectively, ambient temperature, outer surface temperature, the outer ring - roller contact temperature, roller temperature, roller end face - flange contact temperature, the inner ring – roller contact temperature and the inner surface temperature.

2.3 Thermal network model establishment

Based on the generalized Ohm's law, according to the node, starting from the external environment, connected with a bearing seat and a bearing outer ring, roller, bearing inner, spindle and external environment in turn, the thermal network model of axle box bearing system is established (Fig. 2).

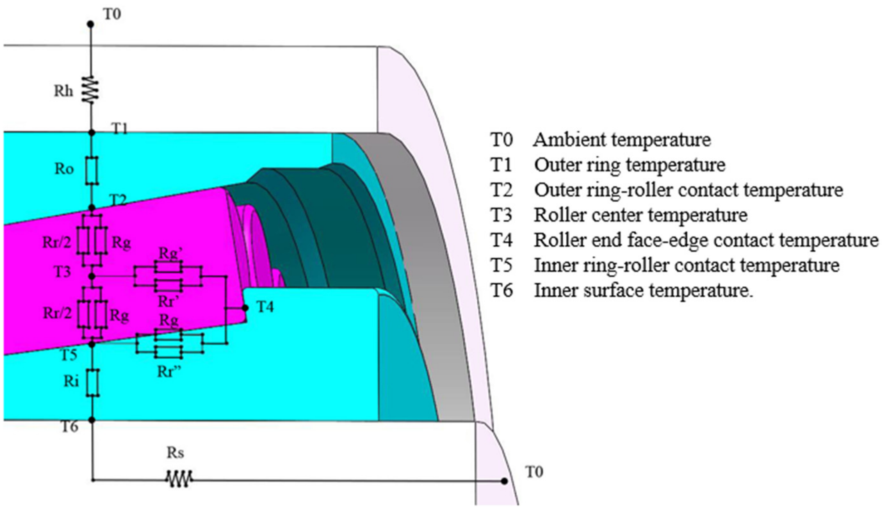

Fig. 2. Thermal network model of bearing system

According to the established thermal network model, the heat flow equations of the high speed axle box bearings under heat steady state can be listed:

$$\begin{cases} H_e = \dfrac{T_2 - T_0}{R_1} + \dfrac{T_2 - T_4}{R_2 + R_4} + \dfrac{T_2 - T_5}{R_2 + R_3} \\ H_f = \dfrac{T_4 - T_2}{R_2 + R_4} + \dfrac{T_4 - T_5}{R_5} \\ H_i = \dfrac{T_5 - T_0}{R_6} + \dfrac{T_5 - T_4}{R_5} + \dfrac{T_5 - T_2}{R_2 + R_3} \\ \dfrac{T_2 - T_3}{R_2} = \dfrac{T_3 - T_5}{R_3} + \dfrac{T_3 - T_4}{R_4} \\ \dfrac{T_3 - T_2}{R_2} = \dfrac{T_2 - T_1}{R_o} \\ \dfrac{T_2 - T_1}{R_o} = \dfrac{T_1 - T_0}{R_h} \\ \dfrac{T_5 - T_6}{R_i} = \dfrac{T_6 - T_0}{R_s} \end{cases} \tag{1}$$

$$\begin{cases} R_1 = R_h + R_o \\ R_2 = \dfrac{1}{2} R_r + R_g \\ R_3 = \dfrac{1}{2} R_r + R_g \\ R_4 = R_g' + R_r' \\ R_5 = R_g + R_r'' \\ R_6 = R_i + R_s \end{cases} \tag{2}$$

Where: Rh、Ro、Rr、Rg、Ri、Rs are the thermal impedance of bearing seat, bearing outer rings, rollers, lubricating oil film, bearing inner ring and spindle; The size of the *Rr'* and *Rr"* depends on the contact position of the roller-inner raceway, and $Rr' + Rr'' = Rr/2$.

2.4 Heat source calculation

There are three heat sources in the high speed axle box bearings, which are roller-outer raceway, roller-inner raceway and roller-flange. Each heat source is composed of friction heat source and flow resistance heat source and the heat source can be expressed as:

$$H_j = H_{fj} + H_{cj} \tag{3}$$

Where: $j = j, e, f$ are roller - inner raceway, roller - outer raceway and roller end - ribs respectively; H_{fj} is the friction heat source; H_{cj} is the flow resistance heat source.

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Friction heat

The heat generated by relative motion is a kind of frictional heat generation, and the friction heat flow can be expressed as:

$$H_{fj}=F_{fj}v_j \tag{4}$$

Where: F_j is friction, v is relative movement speed.

Flow resistance heat

The flow resistance loss is caused by the collision and agitation of the lubricant filled with the rolling body and the bearing chamber. Axle box bearing roller spoiler heat generation process can be equivalent to a tooth in the gearbox body agitation of the process of the lubricant, the heat calculation formula [13] can be expressed as:

$$H_{cj}=\frac{1}{2}\rho_{eff}w_c^2S_{mj}R_m^3C_m \tag{5}$$

Where: ρ_{eff} is the density of lubricant, w_c is the roller angular velocity, S_m is the area in which the roller enters the lubricant, R_m is the pitch radius of the bearing, C_m is the dimensionless torque associated with Re.

$$C_m=\begin{cases}\dfrac{20}{\mathrm{Re}} & (\mathrm{Re}<2000)\\ 8.6\times10^{-4}\,\mathrm{Re}^{1/3} & (2000<\mathrm{Re}<10000)\\ \dfrac{5\times10^{8}}{\mathrm{Re}^2} & (\mathrm{Re}>10000)\end{cases} \tag{6}$$

2.5 Thermal impedance calculation

Axial box bearing thermal resistance

The heat transfer impedance of the inner and outer bearing rings can be expressed as:

$$R_i=\frac{\ln(\mathrm{D}_i/d_i)}{2\pi\lambda_iB_i} \tag{7}$$

Where: $i=i,o$ can be respectively expressed as bearing inner and outer ring, D is the ring outer diameter, d is the ring diameter, λ is the thermal conductivity of ferrule, C is the width of the ring.

The radial heat transfer impedance of the roller can be expressed as:

$$R_r=\frac{d'}{\pi\lambda_rL} \tag{8}$$

Where: d' is the average diameter of tapered roller, L is the roller length, λ_r is the thermal conductivity of roller.

Spindle thermal impedance

In the high-speed railway bearing system, the main shaft is connected with the bearing inner ring of the heat transfer resistance is composed of three parts, respectively, radial and axial heat conduction impedance, and between the shaft and the air forced convection impedance. The composite thermal impedance can be expressed as [14]:

$$R_s = R_{s1} + R_{s2} + R_{s3} = \frac{d}{\pi\lambda_s B} + \frac{4B}{\pi\lambda_s d^2} + \frac{4}{\alpha_s \pi d^2} \tag{9}$$

where, R_{s1}, R_{s2} and R_{s3} are the radial and axial thermal conductivity impedance and the forced thermal convection impedance between the shaft end and the air, d is spindle diameter, B is spindle width, λ_s is thermal conductivity of spindle, α_s is convective heat transfer coefficient between shaft and air.

Thermal resistance of bearing seat

The heat transfer impedance of the seat is divided into the radial and axial heat conduction impedance, the heat convection resistance between the bearing seat end and the air, and the thermal convection resistance between the outer surface of the bearing seat and the air. The composite thermal impedance can be expressed as:

$$R_h = R_{h1} + R_{h2} + R_{h3} + R_{h4} = \frac{\ln(D_h / D)}{2\pi\lambda_h C} + \frac{4C}{\pi\lambda_h (D_h^2 - D^2)} + \frac{1}{\pi\alpha_h D_h C} + \frac{4}{\pi\alpha_h (D_h^2 - D^2)} \tag{10}$$

where, R_{h1}, R_{h2}, R_{h3} and R_{h4} are the radial and axial thermal conductivity of the bearing seat, the thermal convection resistance between the bearing seat and the air, and the thermal convection resistance between the outer surface of the bearing housing and the air, D_h is external diameter, D is internal diameter, C is width, λ_h is thermal conductivity, α_h is convection heat transfer coefficient between bearing seat and air.

Lubricant film thermal resistance

In the bearing system, the thermal resistance of the lubricant film belongs to the thermal convection resistance of the fluid, and the convective thermal impedance between the roller and raceway is:

$$R_g = \frac{1}{2\alpha_g bL} \tag{11}$$

where, α_g is lubricant convection heat transfer coefficient; b is roller - raceway contact half width; L is effective contact length.

The thermal convection resistance of the lubricating film between the roller end and the edge is:

$$R_g' = \frac{1}{\alpha_g \pi ab} \tag{12}$$

where, a and b are the semi-major axis and short half axis of the roller block raceway contact region

3 Analysis and solution

Taking the axle box bearing of CRH3 high-speed railway passenger train as an example, each roller-raceway contact can be a solution unit to solve the thermal impedance of each component, and based on the thermal network model the thermal node temperature values in each solution cell are obtained. Finally, the solution unit is connected to a bearing as a whole, that is, the temperature distribution of the whole axle box bearing in the case of thermal stability is obtained.

Tab. 1. Parameter table of axle box bearing

Parameter	Value	Parameter	Value
Internal diameter	130mm	Small end roller diameter	22.1mm
External diameter	230mm	Big end roller diameter	23.9mm
Roller half cone angle	1°	Outer ring contact angle	10°
Single row roller number	21	Inner ring contact angle	8°
Effective length of roller	45.8mm	Flange Contact angle	81°
Bearing width	173.2mm	Initial radial clearance	0.065mm

Define maximum loaded roller-raceway of CRH3 type high-speed railway axle box axle as 1# unit, each roller adjacent rolling analysis unit were composed of 2# unit, 3# unit, 4# unit, and so on. The schematic diagram of each analysis unit is shown in Figure 3. Based on the above thermal network calculation model, the 1#, 2#, 3# and 4# units are analyzed to obtain the temperature of each node of the 4 units, as shown in figure 4.

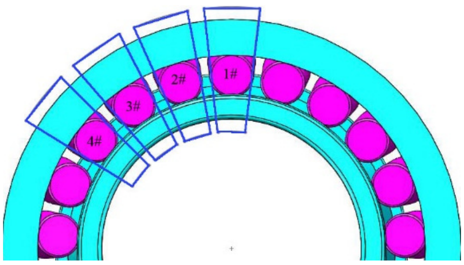

Fig. 3. Number of analysis cells

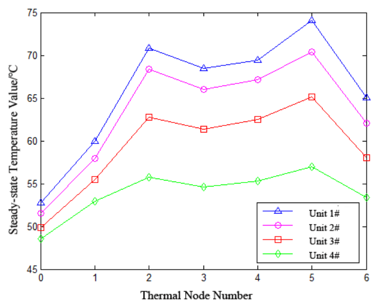

Fig. 4. Steady-state temperature value of each unit node

As can be seen from Figure 4, the temperature distribution law of the nodes in each analysis unit of the high speed axle box bearing is similar, and the highest temperature appears in the contact between the roller and the inner ring; The temperature value of each analysis unit is different, in which the maximum temperature of the steady state temperature is reached at 74.09 C, which is the maximum load in the load, namely the 1# analysis unit; The inner ring temperature of the high speed axle box bearing is obviously higher than that of the outer ring temperature, which accords with the common sense in engineering practice. The temperature difference between the outer ring and the inner ring of the 4 analysis units is 5.09 degrees C, 4.15 degrees C, 2.56 degrees C and 0.37 degrees C respectively, and the temperature difference between the inner and outer circles of the maximum roller is most obvious.

In engineering practice and bearing test, measurement for the crankcase bearing outer surface temperature is more intuitive and convenient, therefore, taking the steady temperature value of the outer surface of the outer ring as the object, the temperature distribution of the outer ring is analyzed in this example, as shown in figure 5

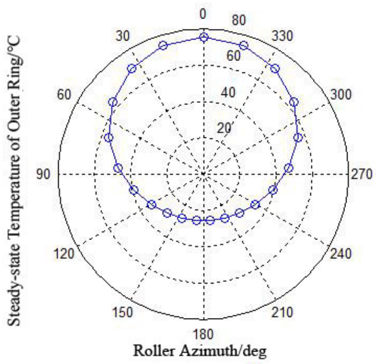

Fig. 5. Steady-state temperature of outer ring

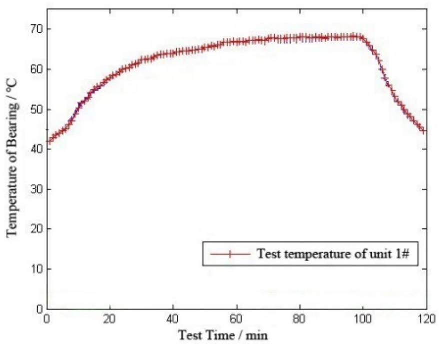

Fig. 6. Temperature of unit 1#

As shown in Figure 6, the temperature of the upper half ring is obviously higher than the temperature of the lower half, that is, the temperature of the bearing zone is obviously higher than that of the non-bearing zone; The maximum value of the steady-state temperature of the outer ring is 75.72 °C, which occurs at the top of the bearing and the maximum load corresponding to the roller; The minimum value of the steady-state temperature of the outer ring is 26.47 °C, which appears at the bottom of the non-loaded region; Taking the vertical plane of the slewing center of the bearing as the base plane, the bearing outer ring around both sides of the temperature distribution is symmetrical, and the bearing temperature distribution curve for the overall smooth round, no obvious temperature change.

The temperature distribution test of CRH3 type high-speed rail axle box bearing was carried out on Netrol-AT.50 / 1 type railway bearing testing machine. The outer surface temperature value of the outer ring of the axle box bearing was measured by the thermocouple mounted on the outer ring of bearing, as shown in Figure 6.

It can be seen from Figure 6, in the beginning of the bearing operation the outer ring temperature gradually increased and tends to be stable at 80 minutes. By comparing the experimental data with the theoretical values of the bearing temperature, it is known that the steady-state temperature of the 1# unit test point is about 65.7°C, and the difference is about 15.25% from the theoretical value of 75.72°C; The steady-state temperature of the 2# unit test point is about 67.4 °C, and the difference is about 12.34% from the theoretical value of 75.72 °C. The correctness of the model is verified in the range of error tolerance.

4 Conclusions

By analyzing the heat source and the heat transfer path of axle box bearings, the axle box bearings are divided into 7 heat nodes. Based on the basic calculation model of heat transfer, we get the thermal resistance value of the inner and outer ring, the roller, the spindle and the lubricating oil film. The thermal network model of axle box bearing system is established. Take CRH3 high rail speed axle box bearing as an example, on the high-speed railway bearing system is calculated and analyzed by the thermal network model, the temperature distribution of each unit and the outer surface temperature, found the similar distribution trend, and the maximum value appeared in the bearing area, in accordance with the actual situation; The temperature distribution test was carried out on the Netrol-AT.50/1 type railway bearing test machine, and the steady-state temperature of the outer ring was about 65.7°C. The difference between the theoretical and the theoretical values of 75.72°C was 15.25%. In the range of allowable error, the correctness of the temperature model is verified, and the theoretical model can be provided for the thermal analysis of the high speed railway bearing.

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