Thermal Characteristics Analysis of Feed Axis Ball Screw Pair Based on Thermal Network Method

Ning LIU*, Feng SUN 1*, Weiwei LIU*, Ran ZHOU*, Fangchao XU*, Koichi OKA**
*School of Mechanical Engineering, Shenyang University of Technology, Shenliao West Road, Shenyang 110870, China
**School of Systems Engineering, Kochi University of Technology, Kochi 780-8515, Japan

1. Introduction

The ball screw pair is a key transmission component in the feed system of modern CNC machine tools. Its performance directly affects the accuracy and stability of the system. Due to working conditions such as high load and high speed, the ball screw pair will generate a lot of heat during operation. This causes the temperature to rise, which in turn affects its lubrication state, wear and the dynamic performance of the entire system. Therefore, studying the thermal characteristics of the ball screw pair is of great significance to improving its working performance and extending its service life.

However, in the study of the thermodynamic and dynamic characteristics of the feed system, the analytical methods all take the support bearing as a point heat source. Although the finite element method improves the calculation accuracy, the front and rear bearings and the ball screw pair are still oversimplified. Some scholars have proposed a dynamic model of the feed shaft [1]. At present, only a few scholars have studied the influence of temperature on the feed shaft, bearings and nuts [2]. This study analyzes the thermal characteristics of the feed shaft ball screw pair based on the thermal network method. The thermal network model generates heat transfer through mutual contact between nodes. Zhan established a temperature prediction model based on the thermal network method and proposed a hybrid drive framework that combines data-driven and model-based methods. The model estimates uncertain thermal parameters and accurately predicts the thermal error of the spindle bearing [3].

According to the geometric structure and working conditions of the ball screw pair, the load power model of the ball screw pair is derived, and then the thermal network model of the temperature field distribution is established. Considering the influence of factors such as friction, load and speed, the temperature distribution of the system under different working conditions is calculated.

2. Analysis of frictional heat effect of ball screw pair

In a ball screw pair, part of the heat generated by ball friction is transferred to the screw Q_{ts}, and the other part is transferred to the nut Q_{tn}. The temperature of the nut will increase due to the heat Q_{tn}, and part of the heat of the nut will be transferred to the air in the form of convection and heat radiation. The heat transfer diagram is shown in Figure 1.

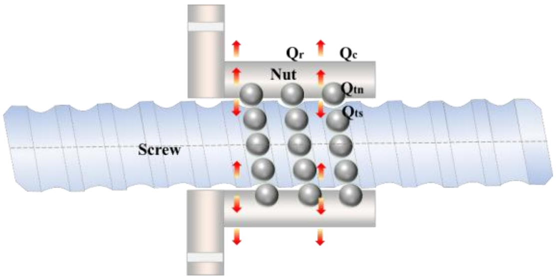

Fig. 1 Schematic diagram of heat transfer of ball screw pair

2.1 Ball screw pair related parameters

The friction heat of the ball screw pair is mainly generated by the friction between the ball and the nut raceway and the ball and the screw shaft raceway, as well as the viscous heating of the lubricating oil. The total heat H_{BS} generated by the friction of the screw pair can be expressed as Eq. (1).

$$H_{\mathrm{BS}} = \frac{2\pi}{60} n_{\mathrm{bs}} M_{\mathrm{BS}} \tag{1}$$

Where, M_{BS} is the friction torque between the nut and the screw shaft, which is obtained from Eq. (2).

$$M_{\mathrm{BS}} = M_e + M_g + 2 \cdot M_v \tag{2}$$

Me Friction torque due to external load, Mg Friction torque due to geometrical slip of the ball, Mv Friction torque due to viscous friction of the lubricant:

2.2 Numerical calculation method

The lumped parameter method in heat transfer can simplify the calculation target to the connection between nodes and thermal resistances, and establish the thermal balance equation . Figure 2 shows a thermal network with an unknown node O, four known nodes T_1–T_4, and four thermal resistances. When heat flows from O to T_1–T_4, the transient thermal balance equation can be written as Eq. (3).

$$\frac{T_0-T_1}{R_{0-1}}+\frac{T_0-T_2}{R_{0-2}}+\frac{T_0-T_3}{R_{0-3}}+\frac{T_0-T_4}{R_{0-4}}=Q_f-C_i\frac{dT_0}{dt} \qquad (3)$$

Among them, Q_f is the heat source, $R_{0\text{-}1}$-$R_{0\text{-}4}$ is the thermal resistance between nodes with corresponding subscripts, and the C_i heat capacity is related to the object properties. Then, the Euler method is used to calculate formula to obtain the transient temperature field.

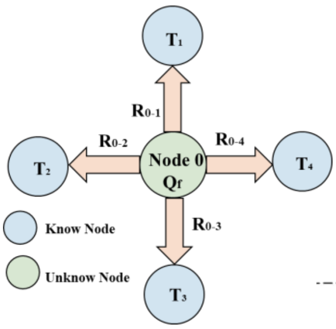

Fig.2 Thermal network with one node and four thermal resistances.

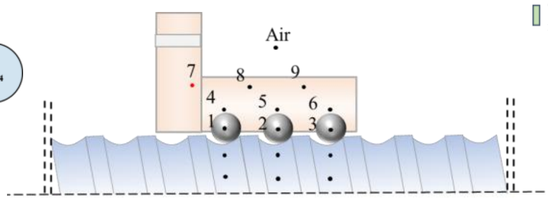

Fig. 3 Ball screw pair

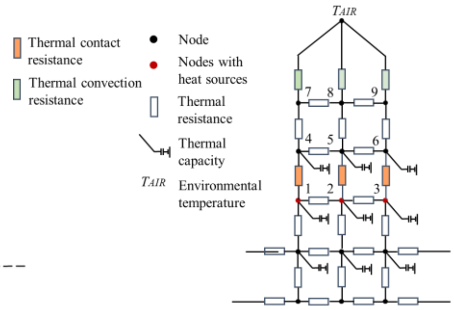

Fig. 4 Thermal Network Model

For the ball screw pair shown in Figure 3, the system is divided into 9 temperature nodes, 12 thermal conduction resistances, 3 thermal convection resistances, 3 thermal contact resistances and 3 heat sources. Figure 4 shows the divided thermal network model. A thermal balance equation is established for each node, and then combined into a thermal balance equation group. By solving the equation group, the transient temperature field of the ball screw pair can be obtained.

3. Simulation results analysis

The results of the feed speed and heat generation rate are shown in Figure 5. The heat generation rate increases linearly, with the frictional heat of the ball screw pair rising as the speed increases. This heat is then converted into measurable temperature values using the thermal network method, yielding the temperature data for each node. Experimental verification is carried out by comparing the experimentally measured temperatures with the predicted results from the thermal network method, allowing for an evaluation of the method's applicability and prediction accuracy.

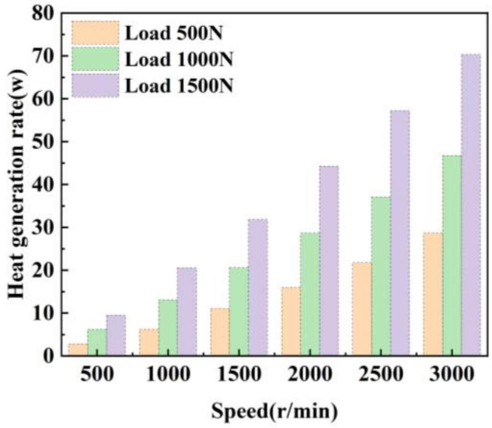

Fig. 5 Relationship between feed speed and fever rate

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