Performance Research on Bi-directional Tilting Pad Thrust Bearing Considering the Verticality Error of Thrust Plate

Runlin Chen1,*, Qin Han1, Xingzhao Wang1, Yahui Cui1, Kai Liu1
1School of Mechanical and Precision Instrument Engineering, Xi’an University of Technology, Xi’an 710048, China
*Correspondence: Runlin Chen; chenrunlin@xaut.edu.cn

Abstract. In order to improve the axial stiffness and its controllability of the CNC machine tool spindle system, a bi-directional tilting pad thrust bearing is used instead of the hydrostatic thrust bearing to bear the axial load. Due to the processing and installing, there must be a certain verticality error between the thrust plate and rotor axis. The lubrication model of the thrust bearing considering the verticality error is established in this paper. The Reynolds equation is solved by FDM (finite difference method), and the key performance data of the bi-directional tilting pad thrust bearing under rated conditions are obtained, including eccentricity, minimum film thickness, maximum temperature rise and axial stiffness, etc. The variation of performance parameters such as film thickness, temperature rise and stiffness of thrust bearing with different working conditions are mainly studied. The maximum allowable verticality errors in the whole working condition range of load and speed are given. According to the requirements of film thickness and temperature rise, the thrust bearing clearance is optimized based on the comprehensive consideration of lubrication performance and dynamic performance, and the allowable ranges of clearance under different verticality errors is analyzed. This research provides theoretical guidance for the design and manufacture of tilting pad thrust bearings used for the CNC machine tool spindle system.

1. Introduction
With the development of high-grade CNC machine tools, the spindle system is required to have high rigidity under high speed and light load. The axial stiffness of the traditional hydrostatic oil chamber thrust bearing is low, and the high pressure oil supply system will bring a large energy loss [1,2], small design clearance may cause friction, all of which bring difficulties to the improvement of axial stiffness. Therefore, this paper proposes to use bi-directional tilting pad thrust bearing instead of static pressure oil chamber thrust bearings, which can produce higher stiffness through dynamic pressure effect [3,4], and adjust the tilting pad fulcrum position can control the performance of the thrust bearing and reduce the vibration of the spindle system [5,7].

When the bi-directional tilting pad thrust bearing is applied to the spindle of CNC machine tools, due to machining and installation, there must be a certain verticality error between the thrust plate and the axis of the rotor [8], which will have a great impact on the running state of the bearing and the rotor [9,10]. Y S Wang et al. [11] analyzed the effects of deflection and elastic deformation on the lubrication performance of radial sliding bearings and thrust sliding bearing systems, and believed that deflection can improve the radial and axial load carrying capacity. Jiang Xiulong et al. [12] established an elastohydrodynamic lubrication model of single-sided tilting pad thrust bearing under the condition of axis deflection. The analysis showed that the small deflection angle causes the thrust bearing to...
produce uneven fluid dynamic pressure, which causes the minimum film thickness and maximum pressure to change significantly.

Based on the applied to high-speed machine tool spindle system of bi-directional tilting pad thrust bearing as the research object, analysis of the thrust plate and rotor axis perpendicularity error exists when the static and dynamic performance of thrust bearing, focuses on film thickness of bearing perpendicularity error size the influence law of temperature and axial stiffness, for machine tool spindle system of a double tilting tile thrust bearing design and manufacturing to provide theoretical basis and data support.

2. Basic structure and working principle of bi-directional tilting pad thrust bearing

When the bi-directional tilting pad thrust bearing capacity for greater axial stiffness and bi-directional bearing by reducing part of the bearing capacity. The structure diagram of the bi-directional tilting pad thrust bearing is shown in Figure 1, the same number of tilting pads are arranged symmetrically on both sides of the thrust plate, and the oil film pressure on the surface of each tilting pad acts on the thrust plate. The thrust disc is subjected to the same force in the opposite direction of the tilting pads on both sides, and the bearing capacity is 0 when it is in the middle.

![Diagram of verticality error of thrust plate](image)

In Figure 1, when the externa load $W$ force the thrust plate to move to the right, the fulcrum film thickness $h_z$ decreases which between the tilting pad on the right (main thrust tile) and the thrust plate, and the thrust force $F_1$ of the main tile increases; while the fulcrum film thickness increases which between the tilting pad on the left (secondary thrust tile) and the thrust plate, and the thrust force of the secondary tile $F_2$ decreases. The difference between the thrust of the main tile and the thrust of the secondary tile is equal to the external load, so that the thrust disc is balanced again. If the thrust of the $i$# thrust tile is $F_i$, and the number of thrust tiles on the left and right sides is $Z$, then there is:

$$W = F_1 - F_2 = \sum_{i=1}^{Z} F_{1i} - \sum_{i=1}^{Z} F_{2i}$$

3. Thrust bearing verticality error model and performance calculation method

During the processing or installation of the thrust plate, there is an inevitable verticality error between the thrust plate plane and the axis of the rotating shaft, as shown in Figure 1, which will make the fulcrum film thickness of each tile different, and during the rotation of the same tile, the force on the thrust plate will change periodically, which will affect the axial rigidity of the spindle.

If $Z$ tilting pads are evenly arranged on both sides of the thrust plate, assuming that the thrust plate is an absolute flat, and the tilt angle is $\alpha$ (angle) due to the verticality error due to installation. When the angle between the projection of the axis on the thrust plate and the fulcrum of the 1# tilting pad is $\beta$, if the inner diameter and outer diameter of the thrust pad are $D_1$ and $D_2$, the radial fulcrum coefficient is $\varepsilon$, and the unilateral clearance between the thrust plate and the thrust pad is $c$. Under the action of external load $W$, the eccentricity of the thrust plate movement is $e$, then the fulcrum film thickness of $i$# main thrust tile and secondary thrust tile are:
\[
\begin{align*}
 h_{11} &= (c-e) - \frac{D_1 + \varepsilon_r (D_2 - D_1)}{2} \cos \left( \frac{2\pi (i-1)}{Z} + \beta \right) \sin \alpha \\
 h_{21} &= (c+e) + \frac{D_1 + \varepsilon_r (D_2 - D_1)}{2} \cos \left( \frac{2\pi (i-1)}{Z} + \beta \right) \sin \alpha
\end{align*}
\]  

(2)

The thrust \( F_i \) of a single tilting tile in formula (1) is related to the fulcrum film thickness, by solving the following two-dimensional Reynolds equation:

\[
\begin{align*}
\frac{\partial}{\partial r} \left( r h^3 \frac{\partial p}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial \theta} \left( h^3 \frac{\partial p}{\partial \theta} \right) &= \frac{\omega r}{2} \frac{\partial h}{\partial \theta} \\
\text{Boundary conditions:} & \quad \frac{\partial p}{\partial \theta} \bigg|_{\Gamma_1} = 0, p \bigg|_{\Gamma_1} = 0
\end{align*}
\]  

(3)

In the formula: \( r \) is radial coordinate of the tilting pad; \( \theta \) is circumferential coordinates of the tilting tile; \( p \) is oil film pressure; \( h \) is oil film thickness; \( \eta \) is dynamic viscosity of lubricating oil; \( \omega \) is angular velocity of thrust disc; \( \Gamma_1 \) is rupture boundary of liquid film; \( \Gamma \) is peripheral boundary of liquid film.

The pressure distribution and film thickness distribution can be obtained by solving equation (3), and the thrust of a single thrust pad can be obtained by integrating the liquid film pressure:

\[
F_i = \int_0^1 \int_{h_1}^{h_2} \rho \, dr \, d\theta = F(h_i)
\]  

(4)

At this point, without considering the deflection moment, according to the force balance of the thrust plate, the external load \( W \) can be satisfied:

\[
W = \sum_{i=1}^{Z} F(h_{1i}) - \sum_{i=1}^{Z} F(h_{2i})
\]  

(5)

The simultaneous formulas (2) ~ (5) can be used to solve the bearing capacity of each tile of the thrust bearing pads. The axial stiffness of the thrust bearing is defined as:

\[
K = \frac{\partial W}{\partial e}
\]  

(6)

4. Rule of influence of verticality error on performance of thrust bearing

4.1. Basic parameters of case bearings

The thrust bearing structure of electric spindle of a precision grinding machine adopts bi-directional tilting pad, as shown in Figure 1. The tilting tile on both sides of the thrust plate is arranged symmetrically, and its structural parameters and operating parameters are shown in Table 1, Table 2.

| Table 1. Bi-directional tilting pad thrust bearing structural parameters |
| --- |
| Item | Symbol | Unit | Value |
| Inner radius | \( D_1 \) | mm | 100 |
| Outer radius | \( D_2 \) | mm | 150 |
| Thickness | \( H \) | mm | 20 |
| Radial fulcrum coefficient | \( \varepsilon_r \) | | 0.55 |
| Circumferential fulcrum coefficient | \( \varepsilon_\theta \) | | 0.55 |
| Warp angle | \( \theta \) | ° | 40 |
| Number of tilting pads on one side | \( Z \) | | 8 |
| Unilateral gap | \( c \) | µm | 50 |
| Verticality error of thrust plate | \( \alpha \) | ' | 0~2 |
| Angle between axis projection and tilting pad pivot | \( \beta \) | ° | 0 |

| Table 2. Bi-directional tilting pad thrust bearing operating parameters |
| --- |
| Item | Symbol | Unit | Value |
| Rated speed | \( n \) | r/min | 10000 |


4.2. Influence of operating parameters on the performance of thrust bearing when considering verticality error

4.2.1. Load

For the bi-directional thrust bearing in this case, the load range is 100-600N. Figure 2 shows the variation diagram of the minimum oil film thickness, the maximum temperature rise, the axial stiffness and the tilt angle of the thrust plate of the thrust bearing under loads of 100, 200, 300, 400, 500, 600N. The minimum film thickness decreases linearly with the increase of the tilt angle of the thrust plate, and little change under different load conditions. It is greater than 10μm in the range of load 100-600N and tilt angle 0-2’, which meets the requirement of lubrication film thickness of thrust bearing (≥10μm). The maximum temperature rise increases rapidly with the increase of the tilt angle of the thrust plate and little affected by the load. When the tilt angle is 1.8’, the maximum temperature rise is 20°C, which has reached the allowable value of the machine tool for the bearing temperature rise. The axial stiffness of the thrust bearings under different loads are almost the same, which increase with the increase of the tilt angle of the thrust plate. The stiffness does not increase significantly when the tilt angle is less than 1.5’, and the stiffness increases rapidly when the verticality error is greater than 1.5’.

4.2.2. Rotating speed

In the rotating speed range of thrust bearings from 2000-12000rpm, the key performance is affected by the tilt angle of the thrust plate as shown in Figure 3.

The minimum film thickness decreases with the increase of the tilt angle of the thrust plate, and the effect of the tilt angle on the minimum film thickness is almost the same at different speeds in the
range of high rotation speed; at low speeds, the minimum film thickness is smaller, the influence of tilt angle is slightly smaller but the speed effect is slightly larger. The change of the maximum temperature rise with the tilt angle is small and the difference is small at different speeds when the tilt angle is small (<1.5°), but when the tilt angle continues to increase, the maximum temperature rise rapidly increases, and the increase in temperature increases with increasing speed. The change trend of stiffness is similar to the temperature rise, which increase of the tilt angle can increase the stiffness, reduce the working speed and temperature rise, but the minimum film thickness needs to be considered comprehensively to ensure that the lubrication performance and dynamic performance of the thrust bearing can meet requirements.

4.3. Optimization of design clearance of thrust bearing

Due to the inevitable verticality error in the installation of thrust plate, the design value of the clearance is particularly important. Reasonable design of the clearance can make the bearing have good lubrication performance and dynamic performance in the whole working range.

By analyzing the key performance data of the thrust bearing with a unilateral clearance in the range of 30–70μm, comprehensively considering the index data of the lubricating performance (thickness and temperature rise) and dynamic performance (stiffness) of the thrust bearing. As the increase of the unilateral clearance and the decrease of the tilt angle of the thrust plate, the stiffness of the thrust bearing decreases, the film thickness increases, and the temperature rise decreases, and vice versa. For different tilt angles of thrust plates, the value range of the design clearance is different under the condition of satisfying the lubricating performance and dynamic performance indexes of the thrust bearing, as shown in Figure 4.

![Permissible range of unilateral gap under different bearing stiffness requirements](image)

Figure 4  Permissible range of unilateral gap under different bearing stiffness requirements

According to the influence law of the design clearance on the thrust bearing performance, the design point above the red line in Figure 4 indicate that the lubricating performance can meet the requirements of the minimum film thickness greater than 10μm and the maximum temperature rise less than 20℃, and the design point below the black line indicates that the dynamic performance can meet the corresponding stiffness index. Different black lines correspond to different stiffness data, and the figure shows the boundary line corresponding to the axial stiffness of 100–500N/μm. The range above the red line and below the black line is the design interval of the unilateral clearance, and with the increase of stiffness index and verticality error of the thrust plate, the design interval of the clearance gradually decreases. When the stiffness indexes are 300, 400, and 500 N/μm, the verticality errors are greater than 2.1°, 1.3°, and 0.9° respectively. The value of the design clearance cannot meet the lubricating and dynamic performance indexes at the same time.
5. Conclusion

1) The lubrication model of the thrust bearing when considering the verticality error between the thrust plate and the axis was established, and the key performance data of the bi-directional tilting pad thrust bearing under rated operating conditions were obtained, including eccentricity, minimum film thickness, maximum temperature rise and axial stiffness, etc.

2) As the verticality error of the thrust plate increases, although the rigidity of the bi-directional tilting pad thrust bearing can be increased to a certain extent, it will result in a decrease in the minimum oil film thickness and an increase in the bearing temperature rise, which is not conducive to the normal operation of the bearing; comprehensive consideration of the minimum film thickness and allowable temperature rise and other index requirements, the maximum allowable error of verticality corresponding to the full operating range of load and speed is given.

3) According to the requirements of performance indexes such as the film thickness and temperature rise of the thrust bearing, the design clearance was optimized, and the allowable range of the design clearance under different verticality errors was analyzed. This related research provides theoretical guidance and data support for the design and manufacture of bi-directional tilting pad thrust bearings.

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