Temperature rise characteristics of high-speed water-lubricated hydrostatic thrust bearing

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Abstract. Hydrostatic thrust bearings have been widely adopted in machine tools. However, high level of temperature rise due to film shearing and hydraulic power of water pump leads to decrease of machining accuracy while operating at high speeds. This paper aims to investigate the temperature rise characteristics of a high-speed water-lubricated hydrostatic thrust bearing. Based on Newtonian law of viscosity, hydrostatic theory and first law of thermodynamic, considering the influence of pressure flow, shearing effect and centrifugal effect, the temperature rise of lubricating water has been deduced. The influence of rotational speed and eccentricity has been studied. Result shows that high-speed water-lubricated thrust bearing has good thermal performance.

1. Introduction
Hydrostatic thrust bearings have been widely adopted in machine tools due to its high rotation accuracy, high stuffiness, low vibration, and long serving life[1]. As the core component of machine tools, thermal characteristics of hydrostatic bearings directly affects machining accuracy of machining tools. Thermal error will increase sharply with the rotation speed and has become the largest error source in high-precision machine tools, which accounts for about 70% of the total error[2]. Therefore, it is important to model the temperature rise of the hydrostatic thrust bearing.

Water is considered as an ideal lubricant for hydrostatic thrust bearing to address the thermal issues and has been successfully adopted in spindle products[3]. The viscosity of water is low, as a consequence, the heat generation due to water film shearing is relatively small; together with the large specific capacity, the temperature rise has been greatly reduced compared to oil-lubricated hydrostatic bearings. For hydrostatic thrust bearing, the centrifugal effect is often neglected[4,5] which plays a vital role in high-speed large-size thrust bearings.

In this paper, based on hydrostatic theory and first law of thermodynamic, temperature rise model of water-lubricated high-speed hydrostatic thrust bearing has been derived. In this model, the influences of pressure flow, shearing effect and centrifugal effect on flow rate have been considered. The effects of rotation speed and eccentricity on temperature rise have been studied.
2. Physical description

Figure 1 shows the schematic of the high-speed water-lubricated hydrostatic thrust bearing. After pumped out by a water pump, the lubricating water enters the water recess through the water restrictor and flows out through surrounding seal dam area.

![Fig.1 Schematic of water-lubricated hydrostatic thrust pad](image)

3. Temperature rise model of the hydrostatic bearing

The heat generation of water-lubricated hydrostatic thrust bearing results from two contributions: one part is the friction heat generation due to water film shearing; another is the consumption of hydraulic power delivered by water pump. Fig.2 shows a platform of the hydrostatic thrust bearing.

![Fig.2 One platform of hydrostatic thrust bearing](image)

3.1. Friction heat generation

To model the heat generation of the hydrostatic thrust bearing, the following assumptions have been introduced:

1. Friction heat is carried away by lubricating water totally;
2. Water is Newtonian fluid and follows Newton's internal friction law;
(3) Heat generation in water recess is small compared to heat generation in seal dam area, so it has been neglected;
(4) temperature is assumed to be isothermal in film thickness direction.
Friction force of the differential element \(d\theta - dr\) is
\[
F = \mu \frac{\rho r^2}{h} r dr d\theta
\]
Where \(\mu\) is dynamic viscosity of water, \(\omega\) is angular speed.
Friction heat power of the differential element \(d\theta - dr\) is
\[
N_f = \mu \frac{\omega \rho r^2}{h} r dr d\theta
\]
Then, friction heat powers in seal dam area 1, 2, 3, 4 can be obtained by
\[
N_f = \int \frac{\mu \omega \rho r^2}{h} dr d\theta
\]

3.2. Hydraulic power of water pump
In the following model of the flow rate, the influence of pressure flow, shearing effect and centrifugal effect have been considered. It should be mentioned that lubricating water is laminar flow for the Reynolds number is smaller than 2300 after calculation.
Considering pressure flow and shearing effect, flow rates of seal dam No.1 and seal dam No.2 are obtained by (Outward is the positive direction)
\[
Q_1 = \frac{bh^3 \Delta p}{12\mu L} - \frac{1}{2} bh\omega R_e
\]
\[
Q_2 = \frac{bh^3 \Delta p}{12\mu L} + \frac{1}{2} bh\omega R_e
\]
where \(\Delta p\) is pump feeding pressure, \(h\) is bearing clearance, \(R_e\), \(b\) and \(L\) is defined as
\[
R_e = \left( \frac{1}{2} \ln \left( \frac{R_s/R_e}{R_s/R_e} \right) + R_e \right) \left( \frac{1}{2} \ln \left( \frac{R_e/R_s}{R_s/R_e} \right) \right) / 2
\]
\[
b = \left( -R_e \frac{1}{2} \ln \left( \frac{R_s/R_e}{R_s/R_e} \right) + R_e \right) \left( \frac{1}{2} \ln \left( \frac{R_s/R_e}{R_s/R_e} \right) \right) / 2
\]
\[
L = R_e (\theta_1 - \theta_2) / 2
\]
Considering the centrifugal effect and pressure flow, flow rates of seal dam No.3 and the seal dam No.4 are derived
\[
Q_3 = \left( \theta_1 + \theta_2 \right) h^3 \left[ \Delta p + 0.15 \rho \omega^2 (R_s^2 - R_s^2) \right] / 24\mu \ln (R_s/R_e)
\]
\[
Q_4 = \left( \theta_1 + \theta_2 \right) h^3 \left[ \Delta p - 0.15 \rho \omega^2 (R_s^2 - R_s^2) \right] / 24\mu \ln (R_s/R_e)
\]
Then, hydraulic power delivered by water pump is
\[
N_p = \sum_{i=1}^{4} \Delta p Q_i, i = 1, 2, 3, 4.
\]
Temperature rise is then deduced
\[
\Delta T = \frac{\left( \sum_{i=1}^{4} N_{\beta} + \sum_{i=1}^{4} N_{\mu} \right)}{c \rho \sum_{i=4}^{4} Q_i}
\]  

where \( c \) and \( \rho \) are specific heat capacity and density of water, respectively.

4. Result and Discussion

The physical parameters of water-lubricated hydrostatic thrust bearing are listed in Table 1.

| Item | Value   |
|------|---------|
| \( R_1 \) | 11mm    |
| \( R_2 \) | 14mm    |
| \( R_3 \) | 32mm    |
| \( R_4 \) | 35mm    |
| \( h \)   | 20\( \mu \)m |
| \( \Delta \rho \) | 1.0MPa |

Rotation speed and eccentricity ratio are important factors affecting temperature rise of the hydrostatic thrust bearing and the influence of rotation speed and eccentricity ratio on temperature rise has been studied. Fig.3 shows the effect of rotation speed on temperature rise of hydrostatic thrust bearing. Fig.4 shows the effect of eccentricity ratio on temperature rise of hydrostatic thrust bearing. As can be seen, with the increase of rotation speed or eccentricity ratio, temperature rise of hydrostatic thrust bearing increases significantly.

![Fig.3 Effect of rotation speed on temperature rise of hydrostatic thrust bearing](image-url)
5. Conclusion

In this paper, the temperature rise of a high-speed water-lubricated hydrostatic thrust bearing has been studied. The temperature rise model has been established based on Newtonian law of viscosity, hydrostatic theory, and first law of thermodynamics considering the influence of pressure flow, shearing effect and centrifugal effect. The following conclusions have been drawn:

While operating at 16000rpm without eccentricity, the temperature rise is within 2°C. With the increase of rotation speed or eccentricity ratio, temperature rise of the water-lubricated hydrostatic thrust bearing increases significantly; however, the temperature rise is still relatively small. The high-speed water-lubricated hydrostatic thrust bearing has good thermal performance.

References

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