Thermal Properties Analysis of Compact Motorized Spindle Considering Fluid-Solid Thermal Coupling

Li Cui and Qingsheng Wang

College of Engineering, Shanghai Polytechnic University, Shanghai, China

cuili@sspu.edu.cn

Abstract. A new model for thermal properties analysis of compact motorized spindle bearing system is constructed. Heat generation model of ball bearing and compact spindle are given. Considering fluid-solid thermal coupling, a new model of temperature analysis of compact motorized spindle bearing is constructed by using moving heat sources method. Calculation model considering fluid-solid thermal coupling is given. Based on the model and finite element method, heat generation and temperature rise of a high-speed compact motorized spindle bearing system is studied. Temperature rising analysis have been done under different conditions, results show that temperature decreases when coolant flow becomes faster, preload of bearing decreases. It can be found that the maximum heat generation and temperature rise of the spindle system located on the rotor surface. When fluid-solid thermal coupling effect is considered, temperature rising becomes lower than without coupling, and the difference becomes more obvious with the increase of rotation speed of bearing. Experiment proves the accuracy of temperature calculation results considering fluid-solid thermal coupling effect. Fluid-solid thermal coupling should be considered in the calculation for predicting the thermal characteristics of high speed compact spindle bearing system. The study will provide evidence for analyzing thermal characteristics of high speed compact spindle bearing system.

1.Introduction

Compact motorized spindle is used widely in high speed machine center, which has a built-in motor rotor and it is directly involved in processing, therefore, temperature rise in the operation process will affect dynamic and thermal characteristics of spindle, which will directly affect the machining quality of products. Compare with traditional machine tool spindle, heat production and heat transfer of high speed compact motorized spindle system are more complex, therefore, thermal properties analysis of high speed electric spindle has attracted substantial attention because of heat stability effects.

Jeng[1] studied a infinite surface heat transfer method to analyze temperature field of bearing system. But the study only considered the gyro heat. Tu[2] investigatedoperating temperatures of a rolling bearing which combines dynamics calculation with finite element thermal analysis method, which can predict transient temperature responses of the bearing but the calculation cost too much time. Kim[3] reviseda friction heat equation of ball bearing through the temperature rising test of high speed ball bearings, results showed that temperature prediction by the transient model is much more accurate than the steady model. Bossmanns[4] constructed a thermal analysis model of the high speed motorized spindle, the heat transfer mechanism of the motorized spindle was studied. Creighton[5] proposed a method of thermal displacement compensation for spindle, in which was used to reduce the machining error caused by heat. Mizuta[6] studied heat transfer characteristics of the angular contact

ball bearing using finite element method. However, it cannot consider the local heat in the contact area of the bearing.In order to obtain more accurate temperature results, this paper will present a local friction model to construct the heat generation model of the roller bearing.

This paper present a new model of thermal analysisof high speed motorized spindle bearing system under fluid-solid thermal coupling.The influence of fluid-solid thermal coupling has been contrasted. The study will provide evidence for analyzing thermal characteristics of high speed compact spindle bearing system.

2. Heat generation model

A new heat generation of high-speed ball bearing is proposed by analyzing the local friction in the bearing. The friction power of high-speed ball bearings include: sliding friction power between balls and raceway, sliding friction power between cage and guide surface of rings, flow resistance power caused by balls move in the lubricant. Quasi-dynamic equations of bearing can be constructed based on Hertz contact theory. Displacements of bearing is obtained from the dynamic model of spindle bearing system, Newton-Raphson method and Runge-Kutta method are used to solve these equations, then, contact results and kinematic parameters of ball bearing can be obtained[7].

Contact force acting on dAcan be defined as

$$\sigma = \frac{3Q}{2\pi ab}\left[1-\left(\frac{x}{a}\right)^2-\left(\frac{y}{b}\right)^2\right]^{0.5} \tag{1}$$

Friction force and friction moment can be given as

$$dF = \frac{3Q\mu}{2\pi ab}\left[1-\left(\frac{x}{a}\right)^2-\left(\frac{y}{b}\right)^2\right]^{0.5}dA \tag{2}$$

$$M_s = \frac{3Q\mu}{2\pi ab}\iint\limits_{\Omega}(x^2+y^2)^{0.5}\left[1-\left(\frac{x}{a}\right)^2-\left(\frac{y}{b}\right)^2\right]^{0.5}\cos(\phi-\theta)dA \tag{3}$$

Power loss of the bearing can be calculated based on the friction force and friction moment, and the whole power consumption can be obtained by the sum of every local heat source[8].

The compact motorized spindle is different from the traditional machine spindle, the motor of the electric spindle is built in the inner of the spindle housing. There are three main losses in the loss of the motor, mechanical loss, electric loss andmagnetic loss.

The mechanical power loss are caused by the friction of stator, rotor of the motor and air. The power loss can be written as

$$P_n = \pi C\rho\omega^3 R_r{}^4 L_r \tag{4}$$

Where, P_n is mechanical power loss, C is friction coefficient, ρ is density of air, ω is rotating speed of rotor, R_r , L_r are radius and length of the rotor.

The electric power loss of the motor is caused by coil of the stator, which can be obtained from

$$P_e = I^2 R_c \tag{5}$$

Where, P_e is electric power loss, I is electric current, $R_c$is electric resistance.

Magnetic power loss is caused by the alternation of the magnetic field in the motor core. It includes eddy current power loss and hysteresis power loss.

Hysteresis power loss can be written as

$$P_t = C_t f_t B_{max}{}^2 \tag{6}$$

Where, $P_t$is hysteresis power, $C_t$is a constant value, $f_t$is magnetization frequency, B_{max} is maximum magnetic induction intensity.

Eddy current power loss can be calculated as

$$P_o = \frac{\pi^2 t_s{}^2 (f_t B_{max})^2}{6\rho_s r_c} \tag{7}$$

Where, $P_o$is eddy current power, $t_s$is thickness of silicon steel sheet, ρ_s is resistivity of iron core, $r_c$is density of iron core.

Heat generation rate of the motorized spindle is defined as power loss every unit volume, which can be obtained by

$$q_s = \frac{p_n + p_e + p_t + p_o}{\frac{\pi}{4}\left(D_o{}^2 - D_i{}^2\right)L_s} \tag{8}$$

Where, D_o, D_i, L_s are outside diameter, inner diameter, and length of the stator.

3. Modeling and Calculating method

Taking an compact spindle bearing system as an example, the rotating speed is 10000rpm, power of the spindle is 30kW, 7010contact angle ball bearing is used as front bearing, and 7008 is used as back bearing. The power of the motor is 30kW, the power loss of each part of the motorized spindle is calculated as Table 1.

**Table 1.** Power loss of the spindle bearing system

Location	Power loss (W)
Front bearings	903
Back bearings	293
Stator	1033
Rotor	1866

The results of the heat transfer coefficient of the main parts of the motorized spindle are shown in Table 2.

Table 2. Heat transfer coefficient of high speed motorized spindle

Location	Heat transfer coefficient w/(m^2 k)
Spindle and air	205
Housing and air	10
Rotor and air	228

3D model of compact spindle ball bearing system is established in Solidworks software, fluid and solid regions of bearing are defined and meshed in ICEM software. Convection heat transfer coefficient are calculated and set in FLUENT[9]. Figure 1 gives calculation flow chart considering fluid-solid thermal coupling.
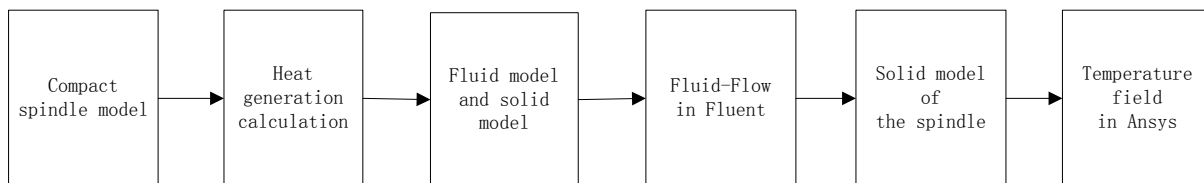
Figure 1. Calculation flow chart considering fluid-solid thermal coupling

Contacting surface between the internal fluid and solid parts is set as default coupling-surfacein order to consider fluid-solid thermal coupling effect, and the convection heat transfer is calculated automatically. Velocity boundary is set at the inlet and velocity is chosen as 50 m/s. Finite difference method is used to discrete continuous equation. The RNG two-equation model is used in the calculation[10]. SIMPLEC algorithm is used to simulate the coupling of pressure and velocity. Solid model of compact spindle bearing system is constructed in ANSYS software, heat transfer coefficient is applied to the model, which is shown in Table 3.

Table 3. Heat transfer coefficient of high speed motorized spindle

| Location	Heat transfer coefficient w/(m^2 k)
Stator and cooling sleeve	1353.1~1732.5
Front bearing and cooling	1685.8~1998
Rear bearing and cooling	761.6~808.8

4. Results and Discussions

According to the above modelling, thermal properties considering considering fluid-solid thermal coupling are analyzed based on FLUENT and ANSYS software. Fluid field and temperature field distribution of the spindle bearing system are obtained.

Assuming rotating speed is 10000r/min, fluid field of coolant and temperature filed results of the spindle are given in Figure 2. The temperature near the entrance of coolant is relatively low, while near the outlet temperature is higher. It is shown that when the coolant passes through the channel, the heat of the stator is absorbed by the coolant, and the coolant acts as a cooling agent.
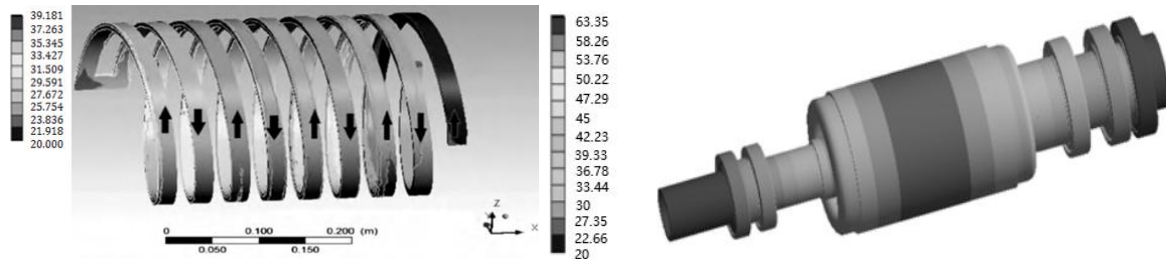
**Figure 2.** Temperature distribution of the compact spindle

Figure 3 shows the influence of rotating speed on temperature rising of spindle bearing system.

a) with coupling   b) without coupling
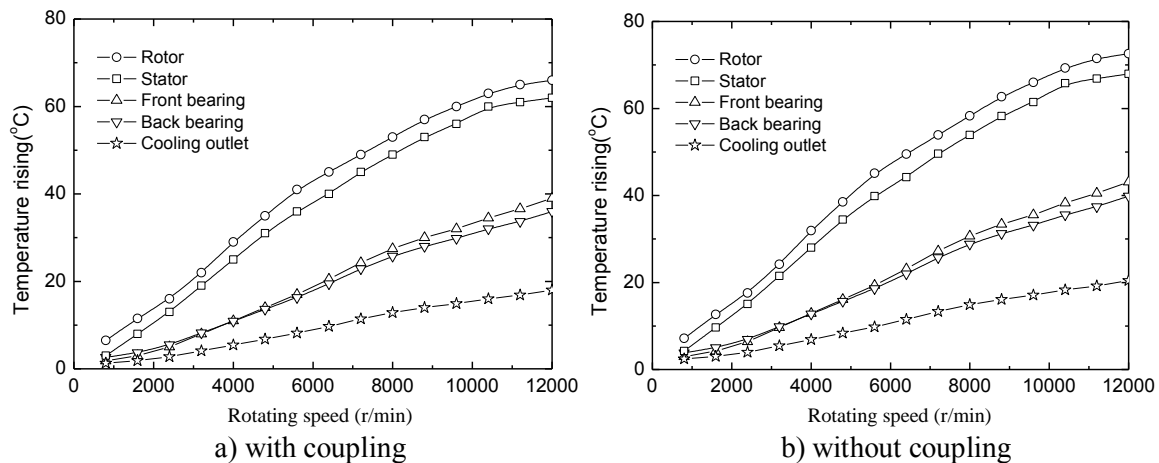
Figure 3. Effect of rotating speed on temperature rising of spindle bearing system

It can be seen that rotating speed has important influence on the temperature rising. When rotating speed changes from 1000rpm to 12000rpm, temperature rising of rotor, stator, front bearing, back bearing and cooling outlet increase to 65°C, 62°C, 39°C, 37°C, 19°C when considering coupling. While temperature rising of rotor, stator, front bearing, back bearing and cooling outlet increase to 72°C, 68°C, 43°C, 41°C, 21°C when coupling is not considered. It is found that the temperature rising is lower when considering the fluid-solid thermal coupling. The reason is that convective heat transfer is accelerated by the convection and conduction when fluid-solid thermal coupling effect is considered.

Figure 4 and Figure 5 give effect of coolant flowand bearing preload on temperature rising of rotor, front bearing and back bearing. It shows effect of coolant flow on temperature rising is obvious, and effect of preload is small.
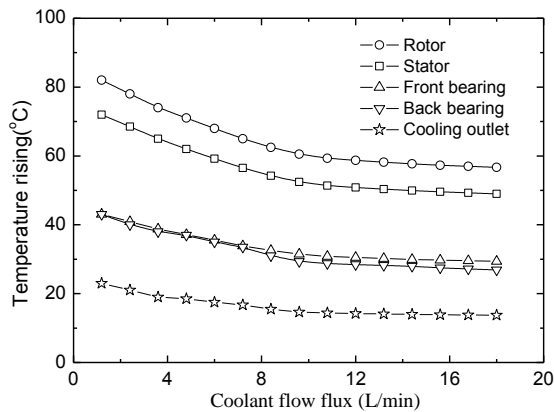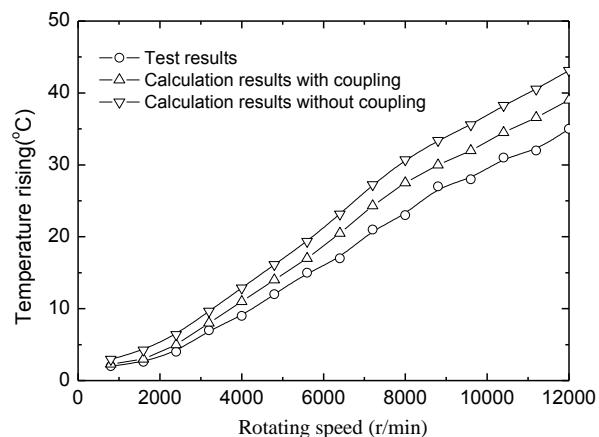
Figure 4. Effect of coolant flow
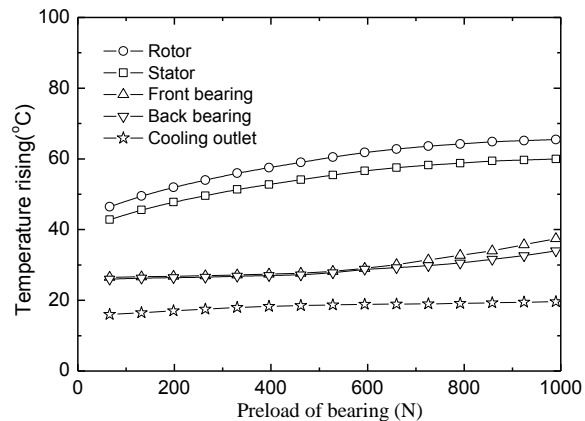
Figure 5. Effect of preload

Figure 6 is a high speed compact motorized spindle test rig under air/oil lubrication, which includes the electric spindle, frequency converter, water cooling device, oil/ air lubrication generator, air compressor, and temperature and vibration test system. The temperature rising of roller bearing can be measured by temperature sensors arranged on the outer sleeve of the electric spindle.

Temperature rising test of high speed compact spindle bearing system have done using this test bench. Figure 7 gives contrast between experimental results and calculation results of temperature rising on outer ring surface of bearing.
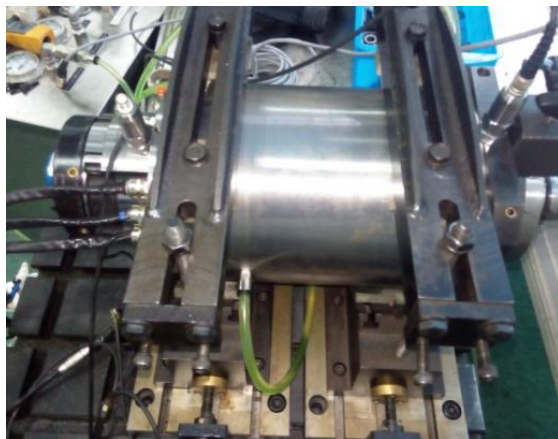
Figure 6. Compact motorized spindle test rig   **Figure 7.** Temperature rising contrast of bearing

It can be seen that bearing surface temperature rising increases gradually with the speed increase. When rotating speed changes from 1000rpm to 12000rpm, the difference between result with coupling and test result changes from 2.3% to 8.7%.While the difference between result without coupling and test result changes from 4.9% to 15.5%. The test results demonstrate that results with fluid-solid thermal coupling are more close to the experimental results, which verify the reliability of the method in this paper.

5. Conclusions

Thermal properties model of the high speed motorized spindle bearing system considering fluid-solid thermal coupling is constructed. Temperature rising analysis have been done under different conditions, results show that temperature decreases when coolant flow becomes faster, preload of bearing decreases. It can be found that the maximum heat generation and temperature rise of the spindle system located on the rotor surface.

When fluid-solid thermal coupling effect is considered, temperature value is lower than that without coupling, and the difference becomes more obvious with the increase of rotation speed of

bearing. Experiment proves the accuracy of temperature calculation considering fluid-solid thermal coupling effect. Fluid-solid thermal coupling should be considered in the calculation for predicting the thermal characteristics of high speed compact spindle bearing system.

Acknowledgment

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