Thermal deformation prediction of high-speed motorized spindle based on thermal behaviour simulation

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Abstract. This paper conduct research to the temperature field distribution and spindle's thermal deformation of motorized spindle by applying finite element thermal-structural coupled numerical simulation technology. And this paper also researched the radial displacement produced by the inner and outer ring’s axial displacement of the angular contact ball bearing. Thus the combination between the finite element thermal-structural coupled numerical simulation technology and thermal error analytic modelling is realized. The analysis results of motorized spindle error is made. The analysis results show that this method is effective in predicting the temperature and thermal error of motorized spindle.

1. Introduction
In the researches on motorized spindle’s thermal error modeling techniques, many scholars have developed many thermal error modeling methods for realizing the highest accuracy prediction of motorized spindle’s thermal error. Ashok et al. [1] built the temperature-radial thermal error model of motorized spindle’s testing table by using the method of curve fitting. Wu et al. [2] built the temperature rise-thermal error mathematical model by using the method of linear regression to realize the off-line test and compensation of motorized spindle thermal deformation. Li [3, 4] built the motorized spindle unit’s thermal error model by using the method of multiple linear regression (MLR) and back propagation network modeling technology. Kuo et al. [5] presented 10 spindle thermal deformation types and established the relationship between radial thermal drift error and key point temperature by means of physical modeling. Li et al. [6] designed a novel thermal error model for heavy machine tools, which is capable of better reflecting the tool’s physical characteristics. Wang et al. [7] came up with an autoregressive exogenous theory model for dynamic modeling, and they predicted the spindle’s thermal error online. Yang et al. [8] came up with a spindle thermal error model motorized according to a least square support vector machine. They made the prediction to be 90% accurate.

2. Finite element simulation of thermal performance of motorized spindle

2.1. Thermal performance simulation model
The construction of the three-dimensional geometry model is the basis for the finite element analysis. A geometric model in accordance with the actual size of motorized spindle is established. The thermophysical data for motorized spindle used in the simulation are listed in Table 1.
Table 1. Thermophysical data for numerical simulation

| Parameter                                      | Steel   |
|-----------------------------------------------|---------|
| Metal density (g/cm³)                        | 7.85    |
| Elastic modulus (MPa)                        | $21 \times 10^3$ |
| Poisson's ratio                              | 0.27    |
| linear expansion coefficient(°C)             | $1.2 \times 10^{-5}$ |
| Specific heat (J/(kg·°C))                   | 500     |
| Thermal conductivity (W/(m·°C))              | 44      |

2.2. Definition of the initial and boundary conditions
The motorized spindle is working in a certain environment, thus there will be convective heat transfer between main spindle box & each part surface and surrounding air. The specific thermal sources and boundary conditions of finite analysis model are shown as Figure.1.

![Figure 1. Heat sources and boundary setting.](image)

1 Heat generation in stator. 2 Heat generation in the rotor. 3 Forced convection in the cooling jacket. 4 Convection heat exchange between the rotor and air. 5 Convection heat exchange of air gap between stator and rotator. 6 Convection heat exchange of the rotating shaft. 7 Convection of ambient air. 8 Heat generation in bearing.

The initial conditions of motorized spindle finite analysis: the indoor constant temperature is 20°C; setting the water temperature of cooling system to 20°C; The cooling water flows of cooling system is 0.86L/min.

The motor lost power will be converted in heat energy and be emitted, so does the motorized spindle lost power. The approximate calculation formula is

$$Q = n_p \cdot (1 - \eta)$$

(1)

Where, $Q$ is the thermal generated by motorized spindle; $n_p$ is the rated power; $\eta$ is the efficiency; take $\eta = 0.8$. The motor rated power of the high-speed motorized spindle introduced in this article is 4.5kW, thus you can get the conclusion of $Q = 0.9kW$.

The heat generation rate $q$ means the generated heat by unit volume of the motorized spindle, it could be calculated by the following formula.

$$q = Q / v$$

(2)

Where, $q$ means the heat generation rate, $v$ means the volume of heat source.

According to relevant researches, the stator will produce 2/3 heats during the motor heating, the rotor will produce the last 1/3 heats [9]. Thus we can get the stator's heat generation rate by calculation, its $2q / 3 = 2Q / 3v = 1506071 W / m^3$; the rotor’s heat generation rate is $q / 3 = Q / 3v = 1987648 W / m^3$. 

According to relevant researches, when the rated rotary speed is 9000 r/min, we can get the convective heat-transfer coefficient [10]. The parameters of each boundary condition are shown as Table 2.

| Parameter                                                      | Value     |
|----------------------------------------------------------------|-----------|
| Heat generation rate of motor stator (W/m³)                     | 1506071   |
| Heat generation rate of motor rotor (W/m³)                      | 1987648   |
| Heat generation rate of bearing (W/m³)                          | 103130    |
| Convection heat transfer coefficient between jacket and water (W/(m²·°C)) | 4840      |
| Convection heat transfer coefficient between rotor and air (W/(m²·°C)) | 147       |
| Convection heat transfer coefficient between stator and rotor (W/(m²·°C)) | 136       |
| Convection heat transfer coefficient between surface and air (W/(m²·°C)) | 9.7       |

2.3. Simulation results of thermal performance

The temperature field obtained from the thermal analysis and simulation is shown in Figure 3. From the temperature field plot in Figure 2, it can be seen that when the motorized spindle system reached the thermal equilibrium temperature field, and the highest temperature appears at the rotor of the motor. The maximum temperature value of the motorized spindle system is 87.7°C, the maximum temperature value of the shaft is 87.1°C, which is almost the same as the temperature of the rotator.

![Figure 2. Temperature distribution of the motorized spindle](image)

Take the analysis result of the former temperature field as the load of thermal-structural analysis field, we get the result of spindle’s axial thermal displacement as shown in Figure 4. The maximum axial thermal displacement is 23μm, occurring at the front end of spindle. As the highest temperature on the spindle is at the middle, connecting to the stator, and the temperature will gradually decrease along both ends of the spindle. Thus the spindle will have more changes of thermal deformation on the middle, the both ends have small thermal deformation, as shown in Figure 3, and the axial thermal deformation at a point is close to the Max. Thermal deformation of front end.
The thermal deformation of the A point is same to the axial displacement of front end bearing, the deformation of the A point will affect the radial displacement of bearing. Thus we can get the corresponding temperature \( T_A \) and axial deformation \( \Delta_A \) of a point by the simulation of outer ring temperature of different bearings, the details are shown as Table 3.

Table 3. Simulation results of temperature and deformation

| Temperature of bearing outer ring (°C) | 20  | 21.5 | 23  | 24.5 | 26  | 27.5 | 29  | 30.5 |
|--------------------------------------|----|------|----|------|----|------|----|------|
| \( T_A (°C) \)                       | 20 | 22.7 | 25  | 27   | 28.8| 30.8 | 33.2| 34.5 |
| \( \Delta_A (\mu m) \)               | 0  | 6.7  | 9.6 | 12   | 13.8| 15.6 | 17.1| 18.4 |

3. Analysis of thermal deformation for bearing

3.1. Radial error caused by radial expansion

This motorized spindle has adopted the hybrid ceramic angular contact ball bearing. We assume that the bearing’s radial error is caused by the combined actions of the axial thermal displacement of the bearing’s inner and outer ring. Take the A and B point’s located section as the researching object of bearing’s inner ring, and take the C and D points’ located section as the researching object of bearing’s outer ring, as shown in Figure 4.

For the bearing’s inner ring, we can get the thermal deformation of B point.
For the bearing’s outer ring, we can get the thermal deformation of C point.

\[
\begin{align*}
\mathbf{u}_C &= \frac{\alpha}{r_C} \left[ (1 + \mu) \int_{r_C}^{r_D} T \, dr + \frac{(1 - \mu) r_C^2 + (1 + \mu) r_D^2}{r_D^2 - r_C^2} \int_{r_C}^{r_D} T \, dr \right]
\end{align*}
\] (4)

Where: \( \alpha \) represents linear expansion coefficient; \( \mu \) represents poisson's ratio.

Therefore, the bearing’s radial thermal error could be represented as

\[
\mathbf{u}_r = \mathbf{u}_C - \mathbf{u}_B
\] (5)

3.2. Radial error caused by axial thermal deformation

Due to the own characteristics of the angular contact ball bearing, when the bearing’s inner ring and outer ring occurring axial relative displacement, the radial error occurring as well. As shown in Figure 5, when the bearing’s inner ring occurring axial displacement \( \Delta \), as the existence of outer ring’s connecting angle, there will be radial clearance between the contacting point of rolling ball and outer ring \( u_2 \). Based on the above analysis, we can get the following formula.

\[
\mathbf{u}_2 = \Delta \cdot \sin \alpha / \cos \alpha
\] (6)

Where, \( \alpha \) is the contacting angle with the bearing.

![Figure 5. Bearing displacement diagram](image)

3.3. Analysis of total radial error

According to above analysis, we can find that the motorized spindle’s radial error is caused by the combined actions of the radial expansion displacement and axial thermal displacement of the bearing’s inner and outer ring. Therefore, the radial total error \( u_r \) could be represented as the following formula:

\[
\mathbf{u}_r = \mathbf{u}_1 + \mathbf{u}_2
\] (7)
4. Results and discussion

Based on the above section, we can get the total error $u_r$ as shown in Table 4.

| $T_c$ (°C) | $T_u$ (°C) | $u_1$ (μm) | $u_2$ (μm) | $u_r$ (μm) |
|-----------|-----------|------------|------------|------------|
| 20        | 20.0      | 0.00       | 0.00       | 0.00       |
| 21.5      | 23.1      | 0.15       | 1.81       | 1.96       |
| 23        | 26.3      | 0.30       | 2.57       | 2.87       |
| 24.5      | 29.4      | 0.45       | 3.22       | 3.67       |
| 26        | 32.6      | 0.60       | 3.70       | 4.30       |
| 27.5      | 35.8      | 0.76       | 4.18       | 4.94       |
| 29        | 38.9      | 0.91       | 4.58       | 5.49       |
| 30.5      | 42.1      | 1.06       | 4.93       | 5.99       |

Figure. 6. Comparison diagram of radial deformation
Figure. 7. Radial deformation ratio

According to above analysis, we can get the contrastive curve of radial deformation, as shown in Figure. 6. From this Figure, we can find that with the temperature rising $T_c$ of bearing’s outer temperature, the $u_r,u_1,u_2$ is quickly increasing. Figure 9 has analysed the proportion between partial error and total error. From this Figure, we can find that with the temperature rising $T_c$ of bearing’s outer temperature, the proportion of $u_2$ is decreasing, and the proportion of $u_1$ is increasing. When the temperature reaches 30°C, the proportion of $u_1$ is close to 20%. Therefore, the axial displacement between the bearing’s outer and inner ring contributes the most to the radial total error; as the bearing’s temperature rising, the contributions from the radial expansion of main bearing to radial total error have increased obviously.

5. Conclusion

The conclusions of this article could be summarized as following: 1. as the temperature of bearing’s outer ring increasing, the radial total error and partial error are increasing quickly. In addition, the axial displacement between the bearing’s outer and inner ring contributes the most to the radial total error; as the bearing’s temperature rising, the contributions from the radial expansion of main bearing to radial total error have increased obviously. When the temperature field is close to the stable state, the
The proportion of bearing radial expansion in total errors is close to 20%. This article applying the method combined finite thermal-structural coupled simulation technology and thermal error analytical modeling, provide a kind of theory & method applying to the error modeling of motorized spindle. This method has excellent accuracy in estimating characteristics such as motorized spindle temperature, thermal error, etc, it could provide theoretical support and guidance for designing and optimizing the thermal balance of motorized spindle unit.

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