Study on vibration characteristics of motorized spindle based on multi-physics fields

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Abstract. Ceramic motorized spindle plays an important role on CNC machine tool. Its dynamic characteristic determines the machining quality of spindle. This paper established a dynamic model of ceramic bearing, and explored the relationship of bearing stiffness and vibration response. The temperature field model of ceramic motorized spindle was established to analyze the temperature field. The motorized spindle air gap influence on unbalanced magnetic pull was studied. The dynamic model of ceramic motorized spindle was established through considering the multiple physical fields influence factors, the changing law of dynamic characteristics was studied. It has been verified by experiments. The average error of ceramic spindle decrease from 5.1% to 2.1%. The establishment of multi-fields dynamic model provided an important guidance for spindle design.

1. Introduction

The ceramic motorized spindle has a complex dynamic-thermal-magnetic coupling relationship. The thermal field and magnetic field are directly related to the vibration of the spindle. The stable dynamic output performance of ceramic motorized spindle is the important factor to ensure the machining quality. Ceramic motorized spindle has been widely used in aerospace, petrochemical and other fields due to its characteristics of small deformation, high rigidity and reverse magnetism. At present, scholars at home and abroad have done relevant research on temperature field [1], magnetic field [2], vibration [3, 4] and other aspects.

Aydin Gunduz [5] established a dynamic model through a five dimensional stiffness matrix to analyze the axial bearing preloads effect on the vibration response. Zhao Wanhua [6] proposed a new analytical modeling to calculate contact stiffness and clamping force, structure parameters based on the rotor system axial, and radial deformation. I.S. Barmanov [7] revealed radial and axial displacements of interference influence on ball bearing. Van-The Than [8] presented high-speed spindle related to preload which predict nonlinear thermal characteristics to find the thermal effects on bearing. Dexing Zheng [9] proposed angular contact ball bearings thermal performances model considering oil-air lubrication to analyze the bearing heat generation and transfer. Chen Xiaoan [10] established the electromagnetism and mechanical system to study the unbalanced force response on dynamic performance under different preload. Zhang Ke [11] established a magnetic model to calculate magnetic radial pull which have effect on spindle system dynamic characteristic.

However, the coupling of multiple physical fields on spindle system vibration has not been deeply studied. In the paper, the bearing dynamic characteristic, spindle magnetic and thermal distribution...
models are established. The relationship between the bearing stiffness, thermal displacement, unbalanced magnetic pull and vibration are analyzed. The ceramic spindle system dynamic mechanism is revealed through multiple physical fields models. The dynamic model provides technical support for motorized spindle design.

2. High speed ceramic spindle model

2.1. Ceramic bearing stiffness model

The bearing ball will appear centrifugal force when are in high speed rotating. There are obvious axial and radial thermal displacement in the some parts of bearing. Under the combined action of dynamic and thermal fields, the contact angle and load of the bearing ball was variational. The bearing stiffness model is a nonlinear equation composed of the deformation equation and centrifugal force equation through quasi-statics. The relationship of bearing center position is shown in figure 1. Before bearing loading, BD line is the curvature center of bearing, which is affected by ball load. The curvature center changes on different lines. The bearing line position is shown in equation (1).

![Figure 1. Center position relationship of bearing ball and channel curvature.](image)

\[ A_{1j} = BD \sin \alpha_v + \delta_r + \theta R \cos \varphi_j + u_a \]
\[ A_{2j} = BD \cos \alpha_v + \delta_r \cos \varphi_j + u_r \]
\[ BD = (f_o + f_i - 1)D_b \]

where: \( \delta_a \) and \( \delta_r \) are axial and radial displacement of bearing respectively, \( R \) is radius of curvature center, \( u_a \) and \( u_r \) are axial and radial thermal displacement of bearing.

The complex angle relationship between bearing ring raceway and ball is shown in equation (2).

\[ \cos a_{ij} = \frac{X_{2j}}{(f_o - 0.5)D_b + \delta_{oj}} \]
\[ \sin a_{ij} = \frac{X_{1j}}{(f_o - 0.5)D_b + \delta_{oj}} \]
\[ \cos a_j = \frac{A_{2j} - X_{2j}}{(f_i - 0.5)D_b + \delta_{ij}} \]
\[ \sin a_j = \frac{A_{1j} - X_{1j}}{(f_i - 0.5)D_b + \delta_{ij}} \]
2.2. Ceramic bearing magnetization and thermal model

There is a complex magnetic relationship inside the motorized spindle. According to the Maxwell principle, the spindle motor will generate the radial unbalanced magnetic pull. The motor magnetic pull have a direct correlation with magnetic field density, which is shown in equation (3) [11],

\[ F_r(\theta,t) = \frac{B^2(\theta,t)}{2\mu_0} \] (3)

where \( B(\theta,t) \) is air gap magnetic density.

The spindle owns cooling system, however, there are still complex heat phenomenon in the spindle. Based on the Comsol software and thermal model, the temperature field diagram of the spindle rotor system in figure 2.

![Figure 2. The temperature field of the motorized spindle rotor system.](image)

From figure 2, the relationship between the temperature rise of the rotor and the spindle speed is non-increasing based on Finite Element software. The temperature of rotor is the highest in the spindle due to the motor loss.

3. Analysis and verification of motorized spindle model

3.1. The analysis of multi-physical fields model

According to the multiple physical field coupling spindle model, through the calculation of bearing model, the distribution of bearing stiffness is analyzed in figure 3. The stiffness of metal bearing is smaller. The operation mechanism of the metal bearing stiffness appear to change at 18000rpm.

![Figure 3. Bearing stiffness.](image)
Through the ANSYS Maxwell software and the magnetic model, figure 4 presented the magnetic radial force distribution of the spindles. The maximum magnetic radial force of the metal spindle can exceed 150N is larger than that of ceramic spindle.

![Figure 4. The calculation of magnetic pull.](image)

### 3.2. Experimental verification

Spindle bearing lubrication adopted oil and gas lubrication under the experiment conditions. The spindle is cooled by cooling water system. The preload force supports 400 N. The spindle end vibration is measured through laser vibration instrument and data acquisition instrument. The measurement of the vibration response of the ceramic motorized spindle is shown in figure 5.

![Figure 5. The measurement of the spindle end vibration velocity.](image)

The relationship between spindle vibration velocity and speed is presented in figure 6. There is a direct correlation between vibration and rotational speed. The vibration speed is exceed 18mm/s under 18000rpm. Considering the multiple physical fields, the simulation results have a better accuracy comparison with the experiment.
Figure 6. The relationship between spindle vibration velocity and speed.

4. Conclusion
Considering the dynamic-thermal-magnetic multiply fields coupling, the temperature and vibration of spindle are studied and analyzed based on the spindle model. The conclusions are as follows:

- Due to the ceramic material, the stiffness of ceramic bearing is different with that of the metal through the bearing model; the temperature of rotor is the highest in the spindle due to the motor loss;
- The maximum magnetic radial force of the metal spindle is larger than ceramic spindle based on the electromagnetic model, the magnetic radial force, the stiffness and thermal field have a great influence on the motorized spindle vibration. The average error of ceramic spindle is 2.1%;
- The multi-physical fields dynamic model is helpful to the design and development of ceramic spindle.

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