Research on rotor performance of air-bearing based on fluid-solid coupling

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Abstract. To investigate whether the motorized spindle meets its technical specifications under working conditions, it is critical to analyze the performance of its rotor. Firstly, the three-dimensional model of the motorized spindle rotor is constructed. To study whether the rotor meets the load-bearing performance requirements, the static performance of the rotor is analyzed by ANSYS software to determine the maximum axial displacement of the front end of the motorized spindle rotor under working conditions. While working under the constraints of both axial and radial aerostatic bearings, the modal analysis of the spindle rotor is carried out and its natural frequencies and corresponding modes are obtained. Then, the harmonic response of the spindle rotor is analyzed to verify whether the axial runout requirement can be satisfied under the working conditions of the spindle. Finally, the stiffness test platform of the aerostatic thrust bearing and the modal test platform of the spindle rotor are designed.

1. Introduction
Generally, high-speed motorized spindle refers to spindle systems with a maximum speed of more than 100,000 r/min and axial runout of less than 5um, which are mainly used for PCB ultra-fine hole drilling and micro-milling. The high-speed motorized spindle has huge market space in the manufacturing industry, and the foreign high-speed motorized spindle technology tends to be mature. However, in some developing countries. The shortage of high-speed and high-precision motorized spindles restricts the further development of developing countries’ high-end manufacturing industry, so it is extremely important to study its performance. The high-speed motorized spindle technical indicators to be studied in this paper: the maximum speed of 250,000 rpm, the axial stiffness of 3N/um, the axial runout of fewer than 4 micrometres, and the axial load of 45N.

2. Theoretical calculation of related characteristics of air bearing
The gas film pressure of aerostatic thrust bearing which means the bearing capacity of the bearing W is defined as follows:

\[ W = \frac{8A}{15} \left( \frac{f_{12}^N}{f_{12}} + \frac{f_{12}^N}{f_{12}} + \frac{f_{12}^N}{f_{12}} \right) \]  

After solving the gas film stiffness of the aerostatic thrust bearing, the gas film of the aerostatic thrust bearing can be equivalent to the spring-damper system (Figure 1).
For the aerostatic thrust bearing with the designed structural parameters, where $M$ is the mass of the spindle rotor $M=0.080914\text{kg}$, the damping factor $B$ of the bearing is $B=974\text{Ns/m}$ obtained by the literature evaluation, and the bearing stiffness $K = 3.8243 \text{ N/um} = 3824300 \text{ N/m}$ is calculated by the MATLAB program.

Substitution of the value into Eq. (2) gives:

$$G(s) = \frac{z(s)}{F(s)} = \frac{1}{0.080914s^2 + 974s + 3824300}$$

$$= \frac{12.3588}{s^2 + 12037.5s + 94528758}$$

For the dynamic response of the aerostatic thrust bearing film, the input is a step signal of 25N, and the transfer function is $G(s)$. The system is built in MATLAB SIMULINK as shown in Figure 2.

In order to define the dynamic performance parameters of the designed aerostatic thrust bearing, the MATLAB solver is programmed to solve the rotor axial displacement response when the step signal is applied at $F=25\text{N}$ as shown in Figure 3.

The dynamic performance parameters of the bearing film can be obtained from the programmed MATLAB program: rise time $t_r$: 0.19ms, peak time $t_p$: 0.41ms, maximum overshoot $\sigma_p$: 8.4043\%, transition time $t_s$: 0.61ms. The rise time is only 0.19ms, and the maximum overshoot is only 8.4\%. It can be seen that the designed aerostatic thrust bearing has good dynamic performance.

3. Finite element analysis of static characteristics of motorized spindle rotor

The static characteristics of the rotor of the motorized spindle refer to the ability of the rotor to resist deformation when subjected to static external loads, that is, the deformation of the rotor of the electric spindle under a certain static load. For the axial stiffness $K$ of the high-speed and high-precision motorized spindle rotor, that is, when the unit shaft axial displacement $\delta$ is generated at the front end of the electric spindle, the force $F$ applied to the rotor of the motorized spindle is the axial stiffness of the electric spindle: $K=F/\delta$. 
3.1. Model establishment of motorized spindle rotor
The total length of the rotor of the motorized spindle is 129mm, the outer diameter of the rotor is 11.75mm, the thickness of the thrust plate is 3mm and the outer diameter is 28mm. The rotor material of the motorized spindle is 2Cr13 stainless steel. The main performance parameters are: Young's modulus is 193Gpa, Poisson's ratio is 0.31. The density is 7750Kg/m³. After quenching and high-temperature tempering treatment, the microstructure is obtained as tempered sorbite, the plastic toughness is good, and the strength and hardness are low. The rotor structure of high-speed and high-precision motorized spindle is established by using UG7.0 software as shown in Figure 4.

![Figure 4. The schematic diagram of the spindle rotor](image)

The UG model of the established motorized spindle rotor, static analysis on the rotor of the motorized spindle was performed by introducing the model into WORKBENCH through the interface of the CAD software provided by ANSYS. In WORKBENCH, the material property is 2Cr13, the Young's modulus is 193Gpa, the Poisson's ratio is 0.31, the density is 7750Kg/m³, and the rotor mesh model is shown in Figure 5.

![Figure 5. The mesh of spindle rotor](image)

3.2. One-way fluid-solid coupling setup
Fluid-solid interaction (FSI) calculation is usually used to analyze the system performance, considering the interaction between the fluid and the solid at the interface while the interaction exists. The one-way coupling, i.e., the pressure obtained by the fluid simulation calculation, The one-way fluid-solid coupling flow chart for the fluid calculation to solids calculation is shown in Figure 6.

![Figure 6. The flow chart of one-way fluid-solid coupling](image)

The thrust plate of the rotor of the motorized spindle is the surface in contact with the gas film. The calculation of the performance of the rotor requires the calculation of the pressure of the film to the rotor, which indicates the requirement of the one-way fluid-solid coupling from the fluid to the solid.
Figure 7. The distribution of gas film pressure

The structure of the one-way fluid-solid coupling analysis project established in WORKBENCH is shown in Figure 8.

Figure 8. One-way fluid-solid coupling analysis in WORKBENCH

The thrust plate of the rotor of the electric spindle is a contact surface with the bearing film, which is set as a fluid-solid interface, and the pressure calculated by the fluid CFD is introduced at the thrust plate. Its setting in ANSYS is shown in Figure 9.

3.3. Static characteristics of motorized spindle rotor

The stiffness of the thrust bearing is calculated by MATLAB $K=3.8243\text{N/um}$. In WORKBENCH, an elastic constraint is applied to both sides of the thrust plate of the thrust bearing, and the value of the constraint is 16.561 N/mm$^3$, and the elastic constraint is applied to the corresponding position in the WORKBENCH.
The static analysis of the rotor of the motorized spindle is carried out by WORKBENCH through fluid-solid coupling, and the total strain of the rotor is shown in Figure 10.

Figure 10. Total strain of the motorized spindle rotor

It can be seen from the total strain diagram that when the axial force of 45N is applied, the maximum strain is the top end of the rotor front end of the electric spindle. The maximum static strain value is 3.1483um, that is, the strain is small, and the axial runout is 4um. Performance requirements.

4. Finite element analysis of static characteristics of motorized spindle rotor

The dynamic analysis is mainly composed of two parts: modal analysis (solving natural frequency and mode shape) and harmonic response analysis. In order to study the dynamic performance of high-speed motorized spindles, this section analyzes the dynamic characteristics of the rotor of the motorized spindle and mainly performs modal analysis and harmonic response analysis.

4.1. Modal Analysis of Electric Motorized Rotor

While analyzing modal properties, the material properties were set to: Young's modulus of 193 Gpa, Poisson's ratio of 0.31, and density of 7750 Kg/m³. Through the structural analysis of the motorized spindle, considering the nonlinear elastic deformation characteristics of the aerostatic thrust bearing, the constraint of the air bearing on the high-speed electric spindle is simplified, and the air bearing is replaced by the elastic bearing. In the dynamic performance analysis of the electric spindle using ANSYS WORKBENCH, the elastic bearing is used to simulate the bearing of the air bearing.

the thrust bearing film stiffness $K = 3.8243 \text{ N/um}$ calculated with MATLAB, the elastic constraint is applied to both sides of the thrust plate in WORKBENCH, the constraint value is $16.561 \text{ N/mm}^3$. From the design task book, the radial bearing film stiffness $K=5.1325 \text{ N/μm}$, an elastic constraint of $1.0805 \text{ N/mm}^3$ is applied to the rotor.

After the above settings, the first 9th mode of the rotor of the electric spindle is analyzed in ANSYS WORKBENCH, and the first 9th mode is obtained as shown in Figure 11.

Figure 11. Mode corresponding to the first 9th natural frequency of the rotor of the motorized spindle
The relationship between the speed and frequency of the rotor is: \( n = 60 \times f \). In ANSYS WORKBENCH, the sub-space mode extraction method is used to calculate the first 9-order natural frequency of the rotor, the critical speed of the corresponding rotor of the motorized spindle and the natural frequency and the corresponding mode shapes (Table 1).

| Order | Natural frequency (Hz) | Rotor speed (RPM) | Modal mode                        |
|-------|------------------------|-------------------|-----------------------------------|
| 1     | 2.2615                 | 135.7             | Rotating around the rotor axis    |
| 2     | 549.19                 | 32951             | Vibrate along the X axis.         |
| 3     | 549.23                 | 32954             | Vibrate along the Y-axis          |
| 4     | 863.08                 | 51785             | Both ends of the rotor vibrate in opposite directions along the axis |
| 5     | 863.12                 | 51787             | Both ends of the rotor vibrate in opposite directions along the axis |
| 6     | 2141.6                 | 128496            | Translated along the axis         |
| 7     | 3439.2                 | 206352            | First-order bending vibration of the rotor along the X axis |
| 8     | 3439.7                 | 206382            | First-order bending vibration of the rotor along the Y-axis |
| 9     | 7936.4                 | 476184            | The rear end of the shaft expands in the radial direction |

4.2. Harmonic Response Analysis of Motorized Spindle Rotor

The harmonic response analysis is used to analyze the steady-state response of the structure under load subjected to harmonic changes. The harmonic response analysis module of ANSYS WORKBENCH is used to take the excitation frequency from 0 to 8000 Hz and the load substep to 200. In the solution method, the Full method is used to analyze the amplitude-frequency curve of the radial response of the front end of the rotor of the electric spindle as shown in Figure 12.

Figure 12. Displacement-frequency response of the front end of the spindle rotor

Through the static and dynamic analysis of the high-speed motorized spindle bearing-spindle rotor system, the static stiffness and the main mode of the natural frequency of each order are obtained. On this basis, the dynamic response of the spindle under different excitations is obtained by harmonic response analysis. The results show that the motorized spindle can achieve the performance required by the design.

Modal Test for Motorized Spindle Rotor

For the modal analysis of the rotor of the electric spindle, the equipment is a hammer, an accelerometer sensor, a pressure sensor, an acquisition card and a 2K-KZ2 type vibrometer. The modal test platform for designing the rotor is shown in Figure 13.
The force hammer is used to strike the middle part of the tool holder, and the dynamic response analyzer the response of each point can be obtained using dynamic response analyzer, The test bench is shown in the Figure 14.

The frequency response function of each point as shown in Figure 15. The frequency of system is 1835 Hz. During the experiment, which made the measured data slightly less than 2000 Hz, thus meeting the design requirements.

5. Conclusion
In this paper, the three-dimensional modeling of the spindle rotor was firstly carried out, and then the static characteristics of the rotor are analyzed by one-way fluid-solid coupling. The results show that the static characteristics of the motorized spindle rotor meet the requirements. The rotor is restrained by the stiffness of the gas bearing, and the modal analysis of the rotor is carried out. The main research is to study the first-order bending of the mode in the X and Y directions. The harmonic response analysis of the spindle rotor shows that the rotor dynamic characteristics meet the requirements. Finally, a modal test platform for bearing film stiffness test platform and spindle rotor is designed.

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