Simulation and Analysis on Temperature Field of Bearingless High Speed Motorized Spindle

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***Abstract*—The bearingless high speed motorized spindle (BHSMS) is a new type of spindle structure, which is driven by the torque winding of a modified motorized spindle and supported by a radial magnetic bearings, an axial magnetic bearings and the magnetic suspension winding of the modified motorized spindle. Without any contacting, BHSMS can reach extremely high speed when it rotates. Meantime, the temperature rise of BHSMS is also serious, because the electromagnetic loss of the motorized spindle and magnetic bearings produces a lot of heat during the process of rotation, which will affect machining stability. Therefore, in this paper, the heat sources and boundary conditions of BHSMS are analyzed and calculated. Then, a finite element model of BHSMS is established and its temperature field is simulated. The temperature distribution of BHSMS in the steady state is obtained. The interaction relationship among the internal heat sources is analyzed. It provides a theoretical basis for further study on the thermal performance of high speed motorized spindle.**

***Index Terms*—bearingless high speed motorized spindle, magnetic bearings, heat generation, heat transfer, temperature field**

I. Introduction

High speed motorized spindle is the critical part of high speed machining systems and has been widely used in numerical control machine tools. It affects the precision, stability and application range of the whole machining system, and has become one of the hotspots in the research of advanced manufacturing technology [1-3]. The length of the main drive chain of the machine tools is shortened to zero because the transmission system between the motor and the shaft is omitted by using high speed motorized spindle which integrates the motor and the rotated shaft into one [4]. High speed motorized spindle realizes the "zero transmission", solves the driving problem of the power source and makes the shaft of the machine tools reach higher speed. Therefore, bearings becomes the main factor that limits the speed and life of high speed motorized spindle [5, 6]. The magnetic bearings is different from the traditional mechanical bearings. It has the advantages of no mechanical contact, no friction, no lubrication, high speed, high precision and long life. It has been effectively used in the motorized spindle [7-9]. But because of its complex structure, high cost and large volume which occupies a certain axial space, the critical speed and output power of magnetic bearings are restricted, and the miniaturization of high speed motorized spindle is also affected.

The bearingless motor doesn't mean that it needn't bearings to support the motor rotor, but it does not need to design special bearings. It uses the similarity between the structure of magnetic bearings and motor to superimpose the suspension winding of the magnetic bearings with the torque winding of the traditional motor in the stator slot of the motor. In this way the motor can generate electromagnetic torque and levitation force at the same time. The bearingless motor combines the rotating function and suspension supporting function into one. It not only has the advantages of the magnetic bearings, but also has short axial length and low loss [10, 11]. It can realize higher power and rotational speed, and has important industrial application value. Now, the bearingless motor is widely applied in semiconductor production, human heart pump, mechanical engineering, flywheel energy storage and other fields [12, 13].

According to the characteristics of high speed motorized spindle and bearingless motor, in this paper, they are integrated to form a new type of spindle structure—bearingless high speed motorized spindle (BHSMS) which not only provides speed and torque for cutting but also directly affects the quality of machining. Since the heat sources such as motorized spindle and magnetic bearings are inside the BHSMS, a lot of heat loss is produced during high speed rotation, which will make the temperature rise and affect the dynamic behavior of the machine tools. Thus, it is necessary to analyze the temperature field of BHSMS. In this paper, the heat sources and boundary conditions of BHSMS are calculated. The three-dimensional model of BHSMS is set up and the temperature field is simulated by the finite element software. Based on the simulation results, the relationship among the heat sources of the BHSMS is analyzed so as to provide some references for the performance research on the BHSMS.

II. Structure of BHSMS

The structure of BHSMS is shown in Fig.1. It is composed of a radial magnetic bearings, an axial magnetic bearings and a modified motorized spindle. The modified motorized spindle combines the motorized

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spindle and bearingless motor into one, that is, a set of suspended winding is added to the motorized spindle to support the shaft when it rotates. So the modified motorized spindle together with the radial magnetic bearings realizes the radial supporting of BHSMS. The axial movement of the BHSMS is limited by the axial magnetic bearings. In this way BHSMS can frictionless, contactless, stable rotate and achieve higher speed. Moreover, its structure is more compact than magnetic suspension motorized spindle.

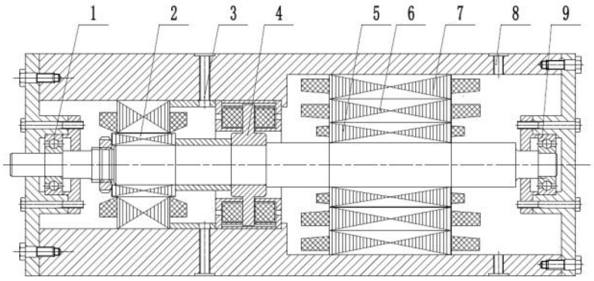

Figure 1. Bearingless high speed motorized spindle structure.
1,9-auxiliary bearings 2-radial magnetic bearings 3,8-radial sensor reserved hole 4-axial magnetic bearings 5-modified motorized spindle 6-suspended winding of motorized spindle 7-torque winding of motorized spindle

In order to improve the kinematic accuracy of BHSMS, it is need to detect the radial displacement of the rotating shaft during high speed rotation. There are reserved four mutually perpendicular holes for installing sensors at the cross section of magnetic bearings and modified motorized spindle, respectively. Common mechanical bearings is selected as the auxiliary bearings. It only plays a supporting role when the shaft does not work, or a protecting role when the shaft is accidental falling in the process of suspension.

III. Analysis on Heat Sources of BHSMS

The modified motorized spindle, radial magnetic bearings and axial magnetic bearings are three internal heat sources of BHSMS. A large amount of heat will be produced during the rotation, which influences the performance of the BHSMS.

A. The Heat Generated by Loss

The heating of modified motorized spindle and magnetic bearings mainly comes from the magnetic loss, electrical loss, mechanical loss and additional loss, among which the additional loss is in a very small proportion. Therefore, the first three losses are analyzed and calculated.

Magnetic Loss: Magnetic loss includes eddy current loss and hysteresis loss. The eddy current loss is caused by the change of magnetic flux density in the iron core. The high speed rotation of the rotor and the constant change of the current in the control coil also produce the eddy current loss. When the magnetic field in the iron core changes, the eddy current loss caused by the induced current is:

$$P_e = \frac{\pi^2 h^2 \left(f B_{\max}\right)^2}{6 \rho_{Fe} r_{Fe}} \tag{1}$$

where, h-the thickness of the silicon steel sheet, mm; ρ_{Fe}-the density of the iron core, kg/m^3; r_{Fe} -the resistivity of the iron core, $\Omega\cdot$m.

The hysteresis loss is caused by the magnetic material repeated alternating magnetization, which is expressed as:

$$P_h = C f B_{\max}^{\alpha} \tag{2}$$

where, C-material constant; f-magnetization frequency, s^{-1}; $B_{\max}$-maximum magnetic flux density, T; α-1.6~2.2.

Electrical loss: Electrical loss is caused by controlling current flowing through winding resistance. So,

$$P_{Cu} = I^2 R \tag{3}$$

where, I-the current in a winding, A; R-the total resistance of the winding, Ω.

Mechanical loss: Mechanical loss is mainly composed by the friction loss between BHSMS and air when rotating at high speed.

$$P_M = \pi C_f \rho \omega^2 r^4 L \tag{4}$$

where, C_f-the friction coefficient; ρ-air density, kg/m^3; ω-angular velocity, rad/s; r-outer radius of the rotor, m; L-the length of the rotor, m.

B. Calculation of the Heat Generation Rate

The heat generation rate q of motorized spindle and magnetic bearings refers to the heat generation per unit volume of heat source.

$$q = Q/V \tag{5}$$

where, Q-heat generation of the heat source, W; V-the volume of the heat source, m^3.

In this paper, the rated power and its efficiency of BHSMS is 2.2kW and 85%, respectively. Assuming the power loss is almost entirely converted to heat, the heat generation rate of each main component of BHSMS is calculated using (1)-(5). The results are shown in Table I.

IV. Heat Transfer Calculation of BHSMS

Due to the thermal conductivity of the material, the convection and radiation of the surrounding medium, the heat generated in the BHSMS will be transferred. Finally, the spindle system reaches a certain stable temperature and is in a state of heat balance.

Heat transfer at the end of the rotor: Except the heat transmitted to the stator and the shaft, a part of heat generated by the rotor is dissipated through convective and radiative heat transfer from the rotor end to the surrounding air. The heat transfer coefficient of the heat exchange is shown as below.

$$\alpha = 28\left(1 + \frac{\sqrt{3 n \pi d_l}}{20}\right) \tag{6}$$

where, n-the speed of the spindle, r/min; d_l-the diameter of the end of the rotor, m.

Convective heat transfer between BHSMS and surrounding air: The natural convective and radiative heat transfer are caused by the temperature difference between the stationary surface of BHSMS and the surrounding air. The heat transfer coefficient α of the compound heat transfer is:

$$\alpha = \alpha_c + \alpha_r \tag{7}$$

where, α_c-convective heat transfer coefficient, W/(m^2 ·℃); α_r-radiant heat transfer coefficient, W/(m^2 ·℃).

According to (6)-(7), the heat transfer coefficient of each part of the BHSMS is calculated, as shown in Table II.

V. Temperature Field Simulation and Analysis on BHSMS

A. Steady State Temperature Field Simulation

The materials and their physical performance parameters of BHSMS are shown in Table III. A three-dimensional model is set up by the finite element analysis software. In order to establish an effective finite element model for the temperature field analysis on BHSMS, according to its structure and characteristics, the shell and shaft are regarded as rotation shaft for analysis, but actually the shell does not turn. The rotor disc of axial magnetic bearings, the rotor of radial magnetic bearings and BHSMS are interference fit on the shaft. The bearing housing, stator of magnetic bearings and BHSMS are considered as additional mass units on the shaft. The auxiliary bearings, which neither supports the shaft nor produces heat in the working process, is clearance fit with the shaft. So, it is ignored during the temperature field simulation and analysis process. Meshing is the most important step in the finite element modeling process, which directly affects the accuracy and speed of the calculation. Therefore, the size and the density distribution of the mesh should be paid attention to. Then, the values listed in Table I and Table II are used as thermal load and boundary conditions set on the meshed finite element model. The simulation of the steady temperature field is carried out at the speed of 12000r/min and the ambient temperature of 20℃. The simulation results are shown in Fig.2-4.

TABLE I. Heat Generation Rate of BHSMS.

Heat generation rate (kW m^{-3})	Value
modified motorized spindle stator	243851
modified motorized spindle rotor	226159
radial magnetic bearings copper loss	10008
radial magnetic bearings iron loss	162516
axial magnetic bearings copper loss	52135
axial magnetic bearings iron loss	137788

TABLE II. Heat Transfer Coefficient of BHSMS.

Convective heat transfer coefficient (W m^{-3} ·℃)	Value
modified motorized spindle rotor and air	231.17
radial magnetic bearings' rotor and air	137.81
axial magnetic bearings' rotor and air	179.84
BHSMS surface and ambient air	9.7

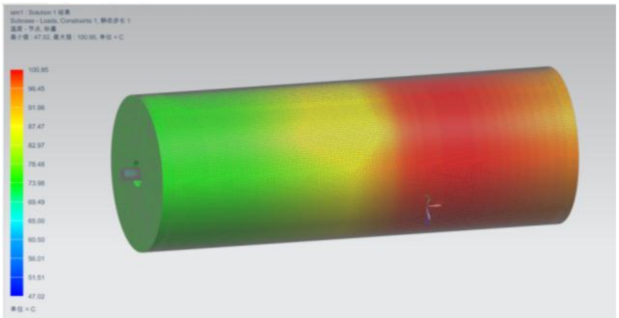

Figure 2. Simulation results of BHSMS with shell.

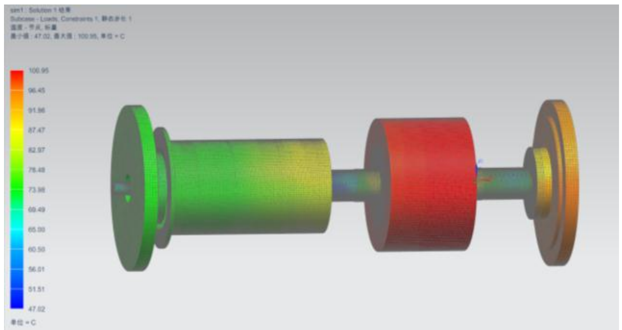

Figure 3. Simulation results of BHSMS without shell.

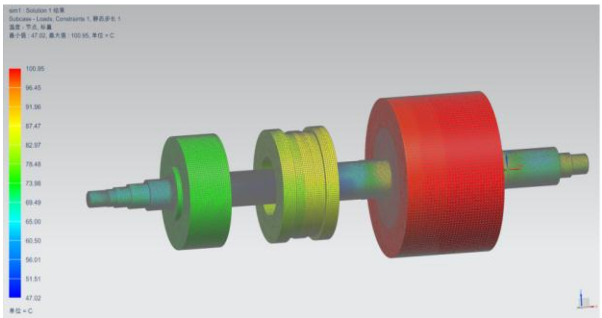

Figure 4. Simulation results of rotor system of BHSMS.

TABLE III. Physical Performance Parameters of BHSMS [14, 15].

Materials	Density (kg m^{-3})	Modulus of elasticity (GPa)	Poisson ratio	Thermal conductivity (W m^{-1} ·℃$^{-1}$)	Specific heat (J kg^{-1} ·℃$^{-1}$)
40Cr	7870	211	0.277	44.0	460
Silicon steel sheets	7833	197	0.26	51.9	465
Copper	8954	108	0.32	379	380
DT4c	7800	206	0.30	67.5	452
45 carbon steel	7753	207	0.25	36.3	486

B. Simulation Analysis

Fig.2 is the temperature distribution of the BHSMS with the shell. From the steady state temperature field cloud chart of the BHSMS, it is can be seen that the temperature rise of the front end is lower than the rear end, the highest temperature close to 101℃ and the lowest temperature appears at the front of the rotor. The reason is that the driving motor of the motorized spindle which need to provide both torque and support located in the rear part generate more heat than magnetic bearings. Meanwhile, the convective heat transfer between the front end of the shaft and the surrounding air is better than the rear end, which accelerates the heat conduction of the front end.

For further analysis on the temperature distribution, the shell of the BHSMS is removed, as shown in Fig.3. And then the rotor system is separated individually, as shown in Fig.4. It is clearly that the internal temperature of BHSMS is uneven distribution. Its temperature difference is larger. This is because the magnetic bearings and the modified motorized spindle are the main heat source which heating seriously. The highest temperature appears at the motorized spindle and the second highest temperature is presented around the axial magnetic bearings in the middle of the shaft. The second highest temperature here is result from not only its own heating more, but also the radial magnetic bearings and motorized spindle both have heat effect on it. The third highest temperature arises in the radial magnetic bearings, whose heat generation rate is the lowest one among the three main heat sources. In addition, the radial magnetic bearings is far away from the motorized spindle and close to the outstretched end of the shaft which make the heat can be sent out by the air convection. Hence, its temperature is lower than the other two heat sources.

VI. Conclusion

1) BHSMS is a new type of spindle structure, which combine the motorized spindle and bearingless motor together. It has two winding sets: torque winding and suspended winding, which can produce torque and levitation force simultaneously during machining process. It has the characteristics of high speed, long life, small volume and so on.
2) There are three main heat sources in BHSMS: the modified motorized spindle, axial magnetic bearings and radial magnetic bearings. In the working process, they produce a lot of heat, which are transmitted through heat conduction, heat convection and heat radiation to make the BHSMS reach the state of heat balance. In this paper, the heat generation rate and heat transfer coefficient of each heat source are calculated. Then, a three-dimensional model is established to simulate the steady temperature field of the BHSMS.
3) According to the results of calculation and simulation, it is clearly that the highest temperature rise of the BHSMS appears in the position of modified motorized spindle. The axial magnetic bearings is the second highest temperature rise region. The temperature rise of radial magnetic bearings is lowest in three heat sources. Strengthening the air flow is one of the way to reduced the temperature rise. In order to achieve better cooling effect, the cooling groove can be set up on the shell. Thus, the stators of the modified motorized spindle and magnetic bearings are forced to cool down and the heat dissipation of the rotors are also enhanced indirectly.
4) BHSMS which appeared in recent years is a multi-input, multi-output, non-linear, tight coupling and uncertain system. Classical linear control theory can't satisfy the control requirement of it. In the further, the control method suitable for BHSMS will be studied.

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