Investigation of camshaft grinder’s electric spindle mounted with electromagnetic bearings

Jianjun Feng*, Zhi Wu, Zhiqiang Xu
School of Mechanical Engineering, Xiangtan University, Xiangtan, China

*Corresponding author e-mail:suiriyu@qq.com

Abstract. In the process of high-speed grinding, the deflection of the spindle axis of the grinder has a severe impact on the surface quality of the workpiece. To solve the problem of bending deformation of the motorized spindle, aiming at the traditional cam grinder, the structure of grinding spindle is designed with active control of electromagnetic bearing. Due to the influence of centrifugal inertia force on deformation, the equation of deformation of the rod is deduced, and the relationship between minimum distortion of the motorized spindle and the displacement of grinding wheel end and the electromagnetic loading force is obtained. The finite element method is used to analyze the relationship between the minimum bending deformation of motor The most suitable electromagnetic force to restrain the spindle is received at different rotational speeds due to the deflection of the motorized axis. The results show that the deviation of grinder spindle is effectively suppressed by applying appropriate electromagnetic force. Reduce the vertical displacement of the spindle grinding wheel end. The results obtained have specific guiding significance for the design of electromagnetic bearing motorized spindle and the improvement of grinding accuracy.

1. Introduction
"Made in China 2025" clearly mentions "to vigorously develop remanufacturing, implement high-end remanufacturing, intelligent remanufacturing, in-service remanufacturing, promote product certification, and promote sustainable and healthy development of the remanufacturing industry." In-service remanufacturing is the active implementation of remanufacturing for active mechanical equipment, restoring and improving its functions and performance. China’s manufacturing industry has experienced many years of rapid development. In-service machine tool equipment has long been responsible for heavy processing tasks. In-service machine tool equipment accuracy and performance degradation are serious, it is difficult to guarantee the processing accuracy of parts, affecting product quality and consistency [1].

In recent years, many researchers at home and abroad have studied the problem of spindle deformation. Based on Timoshenko beam theory, Jorgensen [2] considers the effects of high-speed centrifugal force and cutting force on the deformation of the spindle system. The application of electromagnetic bearings can realize automatic compensation of spindle deformation through precise computer control, achieving high precision and high-efficiency machining [3]. Matsubara [4-5] and so on exerted the electromagnetic force on the main shaft by the self-made electromagnetic force device, and obtained the relationship between the force and the deformation of the main shaft, thereby measuring
the rigidity of the main shaft bearing. Hans-Joachim [6] improved the machining quality of the workpiece by designing atypical adaptive electric spindle and introducing radial electromagnetic bearings to suppress the vibration of the end of the cutting tool. Matthias [7] designed a timing control method for the active electromagnetic bearing system, studied the damping of the spindle motor, and confirmed the effectiveness of adaptive closed-loop control for tool offset and vibration compensation. Many scholars have shown that it is feasible to apply electromagnetic bearing technology to machine tools, and at the same time, the machine tool has better handling [8]. In summary, the research on the dynamic performance of the machine tool spindle with electromagnetic bearing has important application significance.

This paper will carry out research on the dynamic deformation of the machine tool spindle with electromagnetic bearings. The contents of the research are as follows: Firstly, the structural design of the camshaft grinding machine electric spindle with electromagnetic bearing is carried out, and the mechanical model considering the distribution of the rotor mass of the motor and the centrifugal inertial force caused by the high-speed rotation is established; the electromagnetic force is derived. The deformation equation of the main shaft under the compensation mechanism; according to the structural design, the three-dimensional model of the electric main shaft is created, and the deformation analysis is carried out by the finite element method (FEM); the results of theoretical calculation and simulation analysis are compared and analyzed. Finally, the conclusions obtained in this paper are summarized in the conclusion.

2. Electromagnetic main shaft deflection curve equation under the combined action of electromagnetic bearing and mechanical bearing

As the core index of machine tool performance, the deflection and rotation accuracy of the spindle system directly affects the machining performance of the machine tool and the machining quality of the workpiece, including the coordination between the spindle and the bearing, resulting in uneven bearing wear, noise generation, and machine tool reduction. Life and machining accuracy. In order to improve the performance of the electric spindle, the following describes the structure of the electric spindle of the cam grinder with the electromagnetic bearing and the calculation method of its deformation.

2.1. Camshaft grinding machine electric spindle structure with electromagnetic bearing

After the electromagnetic bearing is installed on the camshaft grinding machine spindle, the electromagnetic bearing generates a radial electromagnetic force. The direction of the electromagnetic force is opposite to the direction of the spindle deformation, which can suppress the bending deformation of the main shaft, effectively improve the rigidity of the main shaft and reduce the spindle grinding wheel end. The bending deformation of the grinding head is caused by the grinding force. A pair of electromagnetic bearings are added to the main shaft of the conventional camshaft grinding machine to form an electric spindle structure in which the electromagnetic bearing and the mechanical bearing cooperate. In order to facilitate the expression, the electromagnetic bearing near the end of the grinding wheel is called the front electromagnetic bearing, and the electromagnetic bearing near the end of the electric spindle is called the rear electromagnetic bearing, as shown in Fig. 1. The spindle structure in the figure is mainly composed of an electric spindle rotor, a mechanical bearing, an electromagnetic bearing, a sensor, a grinding wheel and the like.
2.1.1. Structure of electromagnetic bearing. The electromagnetic bearing is used to apply a contactless load to the main shaft to reduce the deformation of the main beam. The electromagnetic bearing is composed of a coil, an iron yoke, an iron core and the like. The electromagnetic bearing control part is formed of a rotor, an electromagnet, a displacement sensor, a converter, a power amplifier, a controller, etc.

2.1.2. The working principle of electromagnetic bearings. When the electromagnetic bearing is working, the electromagnetic coil current controls by the computer. The displacement sensor detects the displacement, the signal is transmitted to the controller, and the controller outputs the current. After being amplified by the power amplifier, it is input to the electromagnetic coil to generate radial electromagnetic force; radial electromagnetic The bearing applies a radial load at a specific position on both ends of the rotor to compensate for the deformation of the main shaft caused by forces such as grinding force, gravity, and centrifugal inertial force during machining. Besides, the electromagnetic bearing can provide four degrees of freedom constraints, limiting the displacement and rotation of the radial X, Y.

2.1.3. Equivalent radial electromagnetic force. The electromagnetic force generated by the electromagnetic bearing corresponds to the radial X and Y deformation caused by the shaft, and the magnitude of the electromagnetic energy controls according to the amount of distortion. To analyze the convenience of the deformation of the main shaft, the electromagnetic energy shown in Fig. 2 is decomposed in the X and Y directions, and the equivalent authority in the X and Y directions can be obtained as follows:

\[ F_x = \sum F \sin \theta \]  
\[ F_y = \sum F \cos \theta \]

Where: F is a pair of electromagnetic forces, and indicates \( \theta \) that the clamps Fx and Fy between the magnetic force and the X-axis respectively indicate the resultant force of the electromagnetic force in the X and Y-axis directions.
2.2. Mechanical model of the grinding machine spindle

The grinding machine spindle is simplified to the mechanical model of the overhanging beam, as shown in Figure 3. The front and rear mechanical bearings of the grinding machine spindle act as the hinge support of the main shaft, and the right end of the main shaft is subjected to the grinding force during machining; the gravity of the main shaft is evenly distributed along the axial direction, and the distance between the gravity center of gravity and the left end bearing is b. The magnetic bearing provides an applied radial load, the position of which is a from the left end bearing, the distance between the left end bearing and the right end electromagnetic bearing is c, the span of the two mechanical bearings is d, and the cantilever length of the right end of the grinding wheel spindle is e.

2.3. Curvature curve equation of grinding machine spindle

In the actual machining process, the force directly affecting the surface quality of the machine is the direction of the vertical direction (Y direction) in the figure. The following mainly studies the problem of deformation in the Y direction. In Fig. 5, the Y-direction reaction forces of the left and right bearings are respectively $F_{Ay}$, $F_{By}$, and the electromagnetic forces of the front and rear electromagnetic bearings are respectively $F_{FY}$, $F_{RY}$, gravity $W=mg$, according to the uniform cross-section load, and the length is $x$, the central axis gravity is $Q=Wx/(d+a)$, the grinding force $P_y$, The centrifugal inertial force $F_I$ caused by the rotation of the shaft can be expressed as $F_I = \int_0^x Ar\omega^2 dx$ the force arm is $l=x-x_i^c$. According to the equilibrium condition, its equilibrium equation can be expressed as:

$$
\begin{align*}
F_{Ay} + F_{Ry} - W + F_{FY} - F_{BY} + P_y + F_I &= 0 \\
F_{Ay} \cdot d + F_{Ry} \cdot (d-a) - W \cdot (d-b) + F_{FY} \cdot (d-c) + P_y \cdot e + F_I \cdot l &= 0
\end{align*}
$$

(3)

Take a micro-segment length $dx$ in the main axis, and its centrifugal inertial force is expressed as:
\[
dF_i = \rho \left( \frac{D}{2} \right)^2 \pi d x \cdot y(x) \cdot \omega^2
\]  

Where: \(y(x), \rho, D, \omega\), represents the deflection at \(x\), the material density of the main shaft, the diameter of the cross section, and the rotational speed.

The gravity and centrifugal inertial forces of the shaft distribute loads. According to the mechanical bearing, electromagnetic bearing, and the power receiving the position of the concentrated load of the grinding force, the main shaft is divided into four sections of 1, 2, 3, and 4, and the deflection deformation is solved in stages. The bending moment at the \(x\)-section on the main shaft can express as:

\[
[M] = [M_1(x) \quad M_2(x) \quad M_3(x) \quad M_4(x)]^T = [F] \times [X]
\]

Where: \([M]\) represents a bending matrix, representing a segmented bending matrix, called a force arm matrix, called a force matrix, whose expression is:

\[
[X] = \begin{bmatrix}
x & 0 & 0 & 0 & x-x_i^e & \frac{1}{3} x \\
x & x-\alpha & 0 & 0 & x-x_i^e & \frac{1}{3} x \\
x & x-\alpha & x-\epsilon & 0 & x-x_i^e & \frac{1}{3} x \\
x & x-\alpha & x-\epsilon & x-d & x-x_i^e & \frac{1}{3} x
\end{bmatrix}^T
\]

\[
[F] = [F_{x_1} \quad F_{x_2} \quad F_{x_3} \quad F_{x_4} \quad F_i \quad Q]
\]

Where: \(x_i^e\) of \([X]\) Coordinate value indicating the point of action of the centrifugal inertial force. Its expression is:

\[
X_i^e = \int_0^{x_i^e} x ' \cdot \rho \left( \frac{D}{2} \right)^2 \cdot \pi \cdot y_i'(x) \, dx' + \int_0^{x_i^e} \rho \left( \frac{D}{2} \right)^2 \cdot \omega^2 \cdot \pi \cdot y_i'(x) \, dx'
\]

The value of \(i\) is 1, 2, 3, 4, corresponding to the four positions on the spindle.

Under the condition of the centrifugal inertia caused by the rotation, the differential equation of the deformation at the \(x\)-section can express as: under the grinding force of the spindle grinding wheel, the electromagnetic energy and the gravity of the shaft:

\[
E I y'' = M(x) \times \delta
\]

Where: \(E, I\) represent the elastic modulus and the moment of inertia, respectively, \(\delta\) can be expressed as:

\[
\delta = [1 \quad 1 \quad 1 \quad 1 \quad 0 \quad 1]^T
\]

The centrifugal inertia caused by the rotating spindle is \(y'\):
\[ F_i = \int \left( \rho r \left( \frac{D_i}{2} \right)^2 \right) \frac{w_i}{\rho} \frac{1}{EI} \int \left[ M(x) \times d \right] dx \text{dx} \]  

(11)

As the structure size is known, \( c > b > a \), because all the structural dimensions in the above formula are constant, the variable is \( P_y, F_{1y}, F_{2y}, \) and this paper makes a reasonable assumption through the structural relationship. As shown in the figure, the distance distribution of the force segment shows in this paper. The relationship makes a reasonable assumption, let \( e = a, b = 2a, c = 3a, d = 4a, \) with \( a > 0. \)

The electromagnetic force \( F \) applied to the left and right two electromagnetic bearings, during the actual grinding process, the grinding force at the grinding wheel head is:

\[ P_y = \frac{60P_E \eta_E}{\pi n_s D_s} \times 10^6 \]  

(12)

Where: \( P_E, \eta_E, n_s, D_s \) represents motor input power, transmission efficiency, grinding wheel speed, grinding wheel diameter.

As described above, according to the position of the main axis of the force, the spindle is divided into four sections, and the spindle mass is uniformly distributed. The deflection generated by any section of each section is calculated according to the superposition method as follows:

1: \( y_1 = \frac{mg}{120EIa} (x^3 + 64a^3x - 8a^5x) - \frac{F}{24EI} (4x^3 - 36a^2x) + \frac{P_y}{24EI} (x^3 - 16a^2x) \)  

(13)

2: \( y_2 = \frac{mg}{120aEI} (x^3 + 64a^3x - 8a^5x) - \frac{F}{24EI} (12ax^2 - 48a^2x + 4a^3)x + \frac{P_y}{24EI} (x^3 - 16a^2x) \)  

(14)

3: \( y_3 = \frac{mg}{120aEI} (x^3 + 64a^3x - 8a^5x) + \frac{F}{24EI} (4x^3 - 48ax^2 + 155a^2x - 112a^3) - \frac{P_y}{24EI} (16a^2x - x^3) \)  

(15)

4: \( y_4 = \frac{mg}{5aEI} \left( \frac{1}{24} x^3 - \frac{1}{24} x^3 + \frac{a^2}{4} y^2 - \frac{8a^3}{3} x \right) - \frac{F}{8EI} (5a^3 - 7a^3)x - \frac{P_y}{6EI} (x^3 - 3ax^2 - 8a^3x) \)  

(16)

The deflection \( y \) of any section of the electric spindle can be expressed as a second order differential equation:

\[ EI \ddot{y} = M(x) \]  

(17)

The second integral can be used to obtain the main shaft deformation displacement under the new structure:

\[ y_{new} = \int \left[ \int \frac{M(x) dx}{EI} \right] dx = \left[ y_1^{new}, y_2^{new}, y_3^{new}, y_4^{new} \right] \]  

(18)

2.4. Analysis of the results of the grinding curve equation

Through the analysis of the four-part deflection curve equation of \( y_1^{new}, y_1^{new}, y_1^{new}, y_1^{new} \), the maximum value and monotonic interval of the deflection curve equation are obtained, and the deformation displacement of the whole section of the electric spindle is analyzed.
2.4.1. Electric spindle deflection curve. The MKS8318 cam electric axis has a maximum speed of 5000 rpm, and theoretically calculates a deflection deformation of the electric spindle from 5000 rpm over the entire shaft span. The Y-direction deflection curve of the gradient speed with the spindle span is plotted separately, as shown in Figure 4.

![Figure 4. Theoretical displacement curve of motorized spindle deflection curve equation](image)

2.4.2. Peak value of electric spindle deflection curve and deformation displacement of grinding wheel. For the deflection curve analysis of the electric spindle, the maximum displacement peak appears at the motor rotor near the front electromagnetic bearing on the span of the electric rod, that is, the position of the maximum displacement shape variable at the entire section of the electric axle. On the one hand, since the mass of the whole shaft is simplified to the combined force, the action point of the force will act on the middle of the main shaft, and then the electromagnetic energy is coupled before the maximum displacement position is reasonable at a spindle span of 0.6 m. The displacement variable of the grinding wheel is smaller than the maximum displacement shape variable, but because the grinding wheel directly participates in the grinding work, the displacement deformation of the grinding wheel end is also one of the consideration criteria.

3. Simulation Analysis of Electric Spindle System Deformation

3.1. Three-dimensional model of the spindle structure of the grinding machine

According to the above-mentioned grinding machine spindle structure, a three-dimensional model of the new electric spindle structure was established by using Solidworks software, as shown in Fig. 5. The three-dimensional model electric spindle part is imported into the finite element software as a finite element analysis model.

![Figure 5. Three-dimensional structure model of new electromagnetic bearing motorized spindle](image)

3.2. Simulation analysis of spindle deformation of non-magnetic bearing grinder

The ANSYS analysis software is used to analyze the deformation model of the original grinding machine spindle, as shown in Figure 6. The spindle system is subjected to grinding force, gravity and centrifugal inertia force, and is restrained by a pair of rolling bearings. The most important part of the model is the spindle, the grinding wheel, and the bearing part, and the rest is simplified accordingly. In the simulation model, the cylindrical surface constraint is applied at the front and rear mechanical bearings to limit the
displacement in the three directions of X, Y, and Z. The elastic constraint is applied to the front and rear mechanical bearings to simulate the flexible support, and the elastic stiffness value is used to express the radial stiffness. Also, a displacement constraint is applied to the right end surface of the spindle motor to limit its freedom of rotation about the Z axis. The central axis adds a gravitational field in the Y direction.

Under the normal working condition, the cam grinding machine MKS8318 has a rated power of 7.5 KW, transmission efficiency of approximately 1, a maximum spindle speed of 5000 r/min, a grinding wheel diameter of 600 mm and a radial grinding force of about 100 N. The deformation of the main shaft shows in Fig. 9. The simulation analysis results show that when the simulated NN radial grinding force is applied, it is found that the point deformation of the spindle motor is the largest, the distortion is 98.624 μm; the displacement of the section in the grinding wheel is 27.628 μm.

3.3. Simulation analysis of spindle deformation of electromagnetic bearing grinder

3.3.1. Simulation results of spindle deformation of electromagnetic bearing grinding machine. The simulation of the spindle deformation of the electromagnetic bearing grinding machine is established. The spindle structure of the electromagnetic bearing grinding machine is shown in Fig. 7. The simulation model of the spindle bearing deformation of the electromagnetic bearing grinding machine is shown in Figure 8. In the model, the spindle system is subjected to the electromagnetic force in addition to the effects of crushing force, gravity, and centrifugal inertia. The other conditions are the same as those of the non-magnetic bearing spindle system.

3.3.2. Analysis of simulation results of spindle deformation of electromagnetic bearing grinding machine. The deformation data shows in Figure 10. It shows that the maximum deformation of the main shaft changes with the electromagnetic energy under the condition that the grinding force is 100N. When the electromagnetic force is in the range of 0-3500N, the spindle deformation decreases with the increase of the electromagnetic force; when the electromagnetic force is in the range of 3500-4000N, the spindle deformation is minimum; when the electromagnetic force continues to increase from 4000N, the deformation of the main shaft is no longer reduced, but it is increasing. Therefore, when designing the
electromagnetic spindle, the control range of the electromagnetic force should be appropriately selected to improve the deformation performance of the spindle.

3.4. Comparative analysis of simulation results of two kinds of spindle structures

Due to the high speed of loading, it is essential to study the effect of loading electromagnetic force on the improvement of the electric spindle. In this paper, by setting different rotation speeds, it is verified that the degree of deflection of the electric spindle is improved under the application of electromagnetic force. In the theoretical model, the excellent compensation electromagnetic force at the corresponding speed can be obtained. The maximum deflection value of the traditional electric spindle and the maximum deformation value of the electric spindle to which the optimum electromagnetic force is applied are longitudinally compared at the same speed. The simulation results are extracted as shown in Figure 10.

![Figure 10. New mechanism and traditional structure displacement with speed change diagram](image)

The suppression rate is introduced to indicate the improvement of the electromagnetic bearing's flexural deformation of the electric spindle. That is, during the rotation of the electric spindle, at the same speed, the symbol η expresses the maximum displacement difference between the deflection of the non-magnetic bearing spindle and the deviation of the pivot of the electromagnetic bearing and the maximum displacement of the spindle without the electromagnetic bearing. In the range of 0 rpm to 8000 rpm, from the low-speed range to the high-speed range, the inhibition rate of 13.39% from 500 rpm to the inhibition rate of 41.8% when the rotation speed reaches 8000 rpm. The inhibition rate of different rotation speeds shows in Table 1. Table 1 shows that as the rotation speed increases, the inhibition rate also becomes higher, and the higher the rotation speed, the more obvious the suppression effect.

| Rotate speed \( N \) (r/min) | 500  | 1000 | 2000 | 3000 | 4000 | 5000 | 6000 | 7000 | 8000 |
|-----------------------------|------|------|------|------|------|------|------|------|------|
| Inhibition ratio \( \eta \) (%) | 13.39| 25.54| 34.32| 36.4 | 37.5 | 38.1 | 38.9 | 40.1 | 41.8 |

4. Conclusion

(1) The mechanical model of the electric spindle of the camshaft grinder is established, and the equation of the spindle axis deflection curve is derived. Under the condition of certain rotation speed and grinding force, the electromagnetic force and the electromagnetic force are added to the main shaft respectively.
Calculate the maximum deflection of the spindle axis and the vertical displacement at the grinding head. The results show that the addition of electromagnetic force on the main shaft significantly reduces the maximum deformation of the main shaft and the vertical displacement of the grinding wheel end.

(2) Three-dimensional modeling of the electric spindle with electromagnetic bearing was established. The ANSYS Workbench finite element software was used to simulate the electric rod. The simulation results of the electromagnetic force and electromagnetic force were compared and analyzed. It shows that the electromagnetic force has a significant inhibitory effect on the deformation of the electric spindle, which significantly reduces the displacement of the spindle wheel end.

(3) Through the theoretical calculation of the deflection and finite element simulation results, the numerical results show that the theoretical maximum Y-direction deflection and the end displacement of the grinding wheel are basically consistent with the finite element analysis results. It shows that the theoretical model and the simulation model are basically correctly, the derivation of the camshaft grinding machine with the electromagnetic bearing is basically correct.

(4) The characteristic of this paper is to consider the influence of electromagnetic force and centrifugal inertial force on the deflection of the camshaft grinding machine spindle when deriving the calculation formula of the spindle deformation. The calculation results have certain application value for the modification of the existing camshaft grinding machine.

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