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AUTOMATIC THERMAL EXPANSION COMPENSATION OF THE AMB SPINDLE IN PRECISION GRINDING MACHINE

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ABSTRACT

The application of AMB spindle in precision grinding is an important direction in the research of magnetic bearing. In the process of grinding, thermal expansion of the magnetic bearings will lead to the posture drift of the grinding head, which can seriously affect the precision of the grinding. In this paper, the module of the relationship between temperature rise and the spindle posture is established based on the detection of the temperature rise. The relationship between the controller's five reference inputs and the spindle posture is ascertained. The controller's five reference inputs are corrected according to the sample value of the temperatures in the system, so the inline adjustment of the grinding head posture and the automatic thermal expansion compensation of the system can be realized. The compensation algorithm is implemented on TI's DSP. Experiment proved that this algorithm could successfully compensate the thermal expansion and ensure the precision of the high-speed AMB spindle used in precision grinding machine.

INTRODUCTION

The application of AMB spindles to precision grinding is an important direction in the research of magnetic bearings. An AMB spindle can offer many advantages not available with conventional spindles: no friction, no wear, theoretically infinite life; no need of maintenance, no need of lubrication, no contamination; high speed, low power consumption; adjustable stiffness and damping; etc [1]. The AMB is an intelligent component by itself; therefore it can be used as a sensor to measure the system process characteristics, and also an actuator to affect the system behavior, which creates opportunities to further expand the AMB's role in this application.

Magnetic bearings have already been successfully applied to high-speed grinding processes and significantly improves the performance of the grinding machine. At present, the temperature rise is a key problem for high-speed precision grinding spindles using either magnetic or conventional bearings [2-4]. In the process of grinding, because of the rise of temperature, thermal expansion inevitably affects the position of the grinding head. Specifically in magnetic bearings, copper loss in the bearing and motor coils, as well as iron loss due to eddy currents and hysteresis all will cause heating. A significant portion of this heat is absorbed by the AMB spindle system, leading to temperature rise. This thermal problem is exacerbated by the sealed construction of AMB spindles. In high-speed operation, a specific opportunity created by application of magnetic bearings, the temperature rise problem of magnetic bearings is particularly significant, so compensation of the grinding head position error due to this temperature rise is particularly important. In contrast to a traditional mechanical spindle, a very attractive feature of a magnetic bearing spindle is that the spindle's posture is adjustable so that the grinding head posture can be controlled actively. Temperature data may be used to adjust the relative position between the grinding head

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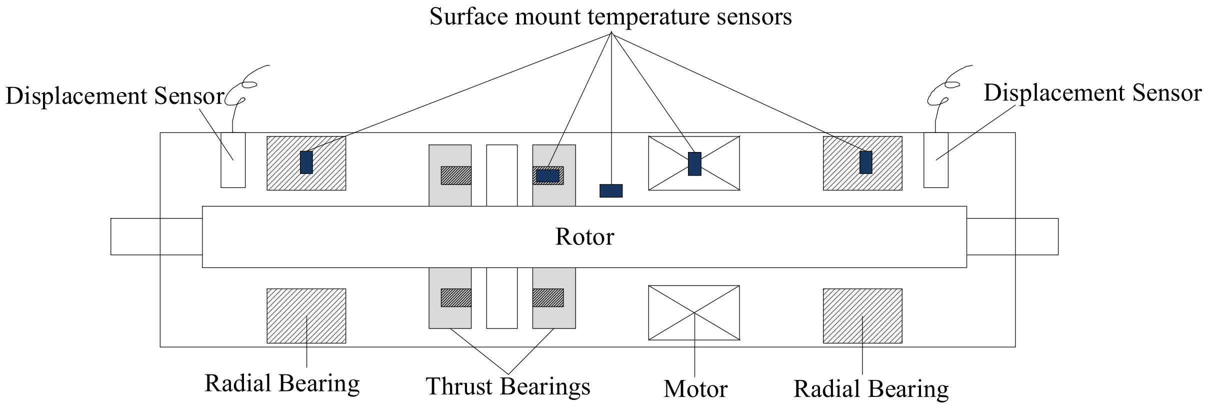
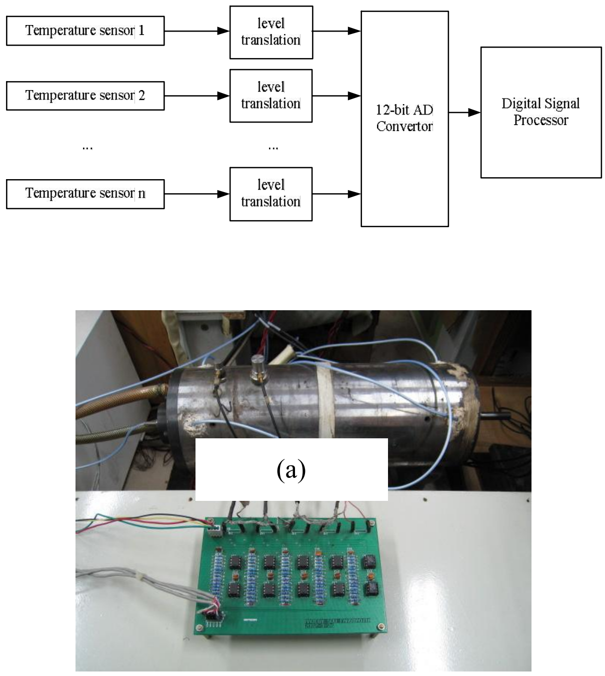


FIGURE 1: The five temperature detection points.

and the workpiece to minimize the impact of temperature rise.

First, this paper chooses five locations for temperature measurement which most strongly indicate system thermal expansion, and designs the temperature detection circuit. Next, the mapping from temperature rise to the change of spindle posture is established and corrected using a neural network approach. Finally, the relationship between the controller's five reference inputs and the spindle posture is ascertained. Through the detection of temperature rise, changes of the controller's reference inputs are realized, thereby achieving compensation of the grinding head posture drift.

In high-speed precision grinding machines, magnetic bearings must provide a precise, highly repeatable location of the rotor. The temperature rise of the magnetic bearing system will cause the grinding head posture to drift in space, thus affecting the static precision of the magnetic bearing system, violating the basic requirements of high-precision applications. Therefore, the repeatable locating precision of magnetic bearing, that is the rotor posture in relation to a fixed reference system (the base) remains unchanged, is very important. The compensation of the spindle system thermal expansion due to temperature is necessary and prerequisite for the magnetic bearing spindle in precision applications.



(b)

FIGURE 2: The schematic diagram (a) of the temperature data acquisition and the actual circuit (b).

DESIGN OF THE TEMPERATURE DETECTION COMPONENT

In a magnetic bearing spindle system, the copper loss in the bearing coils and the motor coils, along with the iron loss due to eddy currents and hysteresis are the main sources of heat. The spindle in high-speed rotation has no physical contact with stationary components, so the temperature sensors cannot be placed directly on the rotor. Therefore we chose the temperature detection points at: two radial bearings' and the axial bearing's stator core, the motor's stator core and the center of the housing near the inner surface, as shown in Figure 1. The temperature sensor used in this work is the SMD NTC surface-mount thermistor. The sensors' analog outputs were converted by a 12-bit AD converter to provide inputs to the DSP processor. The schematic diagram of the temperature data acquisition and the actual circuit are provided in Figure 2 (a) and Figure 2 (b), respectively.

MODELING AND ANALYZING THE RELATIONSHIP BETWEEN TEMPERATURE RISE AND ROTOR POSTURE

There is a complex non-linear relationship between the change of the thermal field and the change of the grinding head posture, governed by thermal distortion of the housing and internal components. A neural network was applied to solve this problem because it offers the advantages of: (1) the full approximation of an arbitrary complex nonlinear relationship, (2) distribution of large-scale parallel processing, which facilitates fast compution, (3) ability to learn and adjust to the dynamic nature of substantially uncertain systems, (4) all quantitative and qualitative information is distributed in the neurons of the network, which gives it high robustness and fault-tolerant capabilities.

The neural network has the five temperature sensor signals T_1, T_2, T_3, T_4, T_5 as inputs and the changes of the spindle posture's five degrees of freedom Δx_c, Δy_c, Δz_c, $\Delta\theta_x$, and $\Delta\theta_y$ as outputs. The non-linear relationship between the inputs and outputs is determined through the BP algorithm of neural network theory [6]. The main idea of the BP algorithm is to propagate the output layer's error layer by layer from the back to the front, so as to correct the weight of each neural unit in each layer. The algorithm is divided into two phases: In phase I (the positive process), input information propagates positively from the input layers through the hidden layers to calculate the export value of each unit. In phase II (back propagation process), output errors propagate in reverse to calculate the error of each unit in hidden layers, which is used to correct the weight of the upper layer [5]. In the back-propagation algorithm, a gradient method is commonly used to correct the weights, which requires a differentiable output function. A sigmoid function is usually used as the output function. The neural network is structured as indicated in Figure 3.

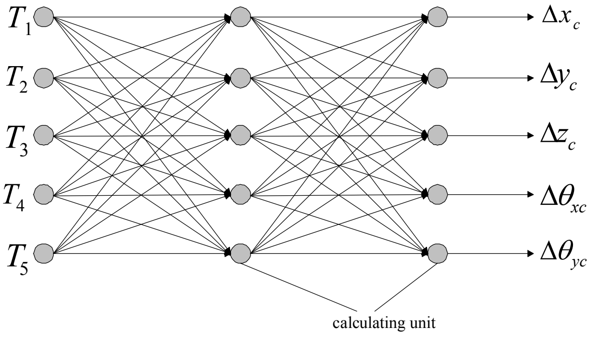


FIGURE 3: The schematic diagram of the parameter compensation neural network

The initialization, study and training of the BP neural network was realized using MATLAB's neural network toolbox. 300 groups of system temperature and changes of spindle posture collected in the actual operation of the magnetic bearing were used as the training sample set to train the linear network model, and gradually correct the weights until the errors are within the allowed range. Figure 4 shows the training error curve of the neural network. As can be seen in this figure, in the early training steps, the error oscillation margin is relatively large, but when the training step number exceeds 100, the error stabilizes to the target range.

Finally, the neural network algorithm itself can be constructed by retrieving each of the two layers' thresholds and weights as produced by this training process.

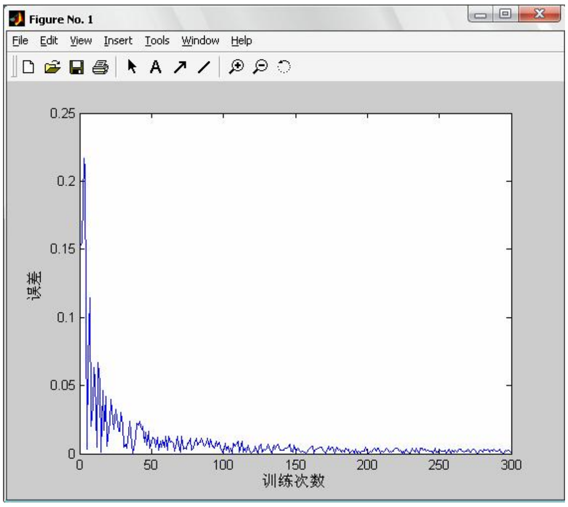


FIGURE 4: The training error curve of neural network.

ADJUSTMENT OF THE GRINDING HEAD POSTURE

Adjust ment of the grinding head posture can be realized through change of the five AMB degrees of freedom (excluding the magnetic bearing spindle's axis rotation freedom.) Because the grinding head is fixed rigidly to the spindle, changes in grinding head posture depend entirely on changes in spindle pose. Therefore, adjustment of the spindle posture is the same as adjustment of the grinding head posture. The rotor position coordinates are shown in Figure 5.

Using the coordinate transform of (1), the five center of gravity degrees of freedom of the AMB spindle x_c, y_c, z_c, θ_x, θ_y may be obtained from the coordinates of the five displacement sensors x_a, y_a, x_b, y_b,

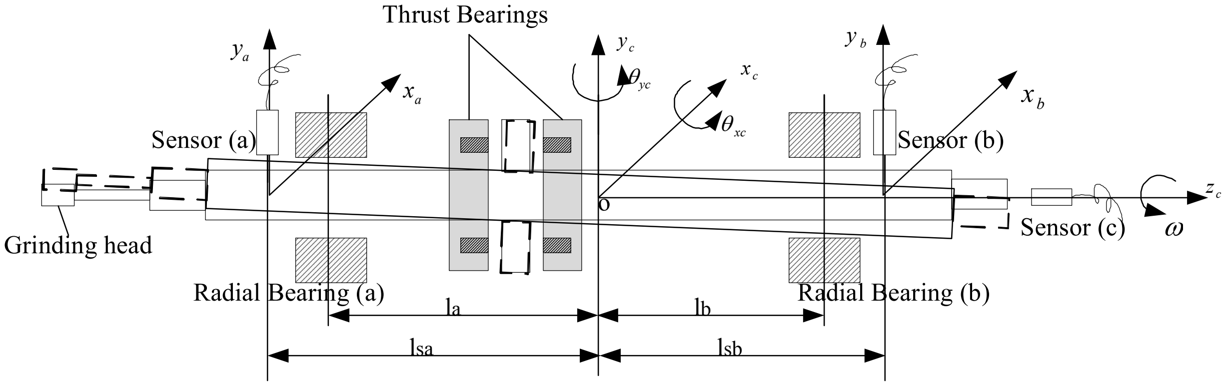


FIGURE 5: Change of rotor position in magnetic bearing spindle.

and z_c.

$$\begin{cases} x_c = \frac{l_b}{l} x_a + \frac{l_a}{l} x_b \\ y_c = \frac{l_b}{l} y_a + \frac{l_a}{l} y_b \\ z_c = z_c \\ \theta_x = \frac{1}{l} y_a - \frac{1}{l} y_b \\ \theta_y = -\frac{1}{l} x_a + \frac{1}{l} x_b \end{cases} \tag{1}$$

in which $l=l_a+l_b$. The relationships of the coordinates' changes are computed from (1):

$$\begin{aligned} \Delta x_a &= \Delta x_c - l_a \Delta\theta_y \\ \Delta x_b &= \Delta x_c + l_b \Delta\theta_y \\ \Delta y_a &= \Delta y_c + l_a \Delta\theta_x \\ \Delta y_b &= \Delta y_c - l_b \Delta\theta_x \\ \Delta z_c &= \Delta z_c \end{aligned} \tag{2}$$

The five coordinates in the displacement sensors reference frame x_a, y_a, x_b, y_b, and z_c are set via the controller's reference inputs, so the posture of the grinding wheels can be automatically adjusted through the change of the controller's five reference inputs. By applying the outputs of the neural network: the required changes of the spindle posture's five degrees of freedom Δx_c, Δy_c, Δz_c, $\Delta\theta_x$, and $\Delta\theta_y$ to (2), the adjustment values for the controller's five reference inputs are obtained to realize automatic real-time compensation of the grinding head posture affected by the temperature rise.

CONCLUSION

The automatic compensation of rotor position error due to temperature rise proposed in this paper includes three steps: temperature acquisition, computation of the spindle posture change using a neural network and correction of the controller reference (s)signals to accomplish the compensation. All three of the steps were implemented on a TI DSP TMS320F2812. Experiments demonstrated that this algorithm could compensate the thermal expansion of the AMB spindle successfully. When the spindle temperature rises from 20°C to 80°C, the radial thermal shift of the grinding head reduces from 17μm to 0.3μm, which meets the needs of precision grinding.

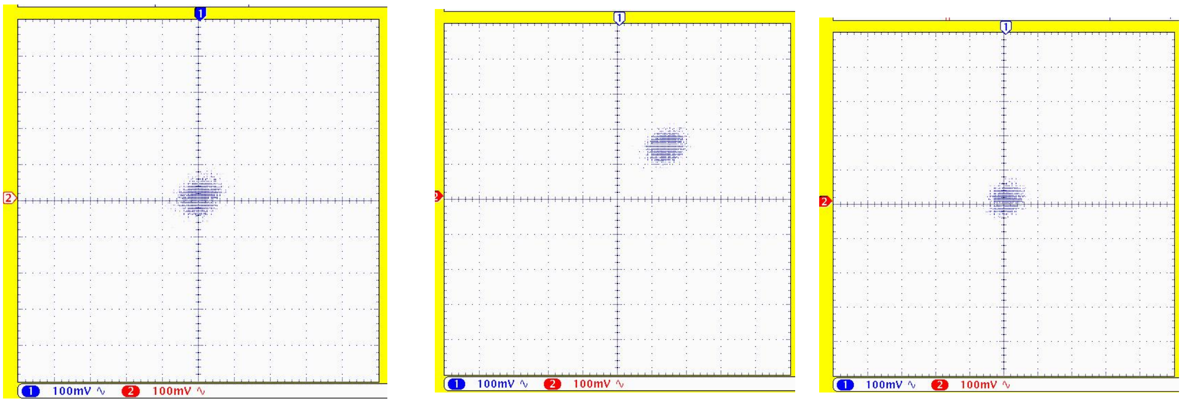
REFERENCES

[1] G. Schweitzer, H. Bleuler, A. Traxler, Active Magnetic Bearings, vdf Hoschulverlag AG, ETH Zurich, 1994

[2] Seung-Kook Ro, Jin-Ho Kyung, Jong-Kweon Park, Study On the Thermal Characteristics of a Magnetically Suspended High Speed Machine Tool Spindle, Ninth International Symposium on Magnetic Bearings, August 3-6, 2004, Lexington, Kentucky, USA

[3] Shuqin Liu, Chris Mi, Coupled Electro-thermal Modeling of Magnetic Bearing Systems, Tenth International Symposium on Magnetic Bearings, August 21-23, 2006, Martigny Switzerland

[4] Siegwart R, Bleuler H, and Traxler A, Industrial Magnetic Bearings - Basics and Application, Gordon and Breach Science Publisher, Amsterdam, 2000



(a) 20℃ **(b) 80℃without compensation** **(c) 80℃with compensation**

FIGURE 6: Position of the grinding wheel

[5] Li De-guang, "Algorithm of the Image Process and its Application in Path Planning of the Battlefield Scout Robot", Ph.D Thesis, Beijing Institute of Technology, 2005

[6] Leonard, J. and Kramer, M. A., "Improvement of the Back Propagation Algorithm for Training Neural Networks," Comp. Chem. Eng., Vol. 14, No. 3, pp. 337-341, 1990.