Thermal Error Test and Intelligent Modeling Research on the Spindle of High Speed CNC Machine Tools

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Abstract. Thermal error is the main factor affecting the accuracy of precision machining. Through experiments, this paper studies the thermal error test and intelligent modeling for the spindle of vertical high speed CNC machine tools in respect of current research focuses on thermal error of machine tool. Several testing devices for thermal error are designed, of which 7 temperature sensors are used to measure the temperature of machine tool spindle system and 2 displacement sensors are used to detect the thermal error displacement. A thermal error compensation model, which has a good ability in inversion prediction, is established by applying the principal component analysis technology, optimizing the temperature measuring points, extracting the characteristic values closely associated with the thermal error displacement, and using the artificial neural network technology.

1. Introduction

The machine tool is the mother machine of all mechanical equipment, and its processing accuracy is the competition focus of all CNC machine tool products. In recent years, the CNC machine tool technology has become one of the important areas of international scientific and technology competition and has also become an important symbol of the development level of machinery industry[1]. In addition, the precision machining center plays a decisive role in precision manufacturing[2]. Statistics from Professor J. Peclenik of University of Birmingham and Professor Hosano Yoshiaki of Kyoto University indicate that: In precision machining, manufacturing errors caused by the machine tool thermal error accounts for 40% - 70% of the total manufacturing errors[3].

Therefore, the research and control of machine tool thermal error will be the key factor that can help improve the machining accuracy.

At present, there are two basic methods to improve the machining accuracy by controlling the thermal deformation error: error prevention method and error compensation method[4]. (1) Error prevention method mainly improves the manufacturing accuracy of machine tool parts by eliminating or reducing the thermal error sources through the design and manufacturing process and therefore is known as hard compensation, and it is clear that the hard compensation is subject to higher costs. (2) Error compensation method mainly feeds back errors to the CNC system for error correction by testing and analyzing thermal errors in the machining process and establishing the thermal error model and therefore is known as soft compensation. Obviously, this method features lower cost and remarkable economic benefit. At present, the thermal error compensation method has become a research focus in
the precision assembly manufacturing[5,6]. More heat sources, heat stagnation caused by friction and deformation caused by complex thermal stress on the contact surface lead to the thermal error subject to characteristics of time delay, time varying, coupling and non-linearity, thus making it difficult to express accurately with the traditional mathematical model the complexity of thermal error changes. This paper studies the optimization of temperature measuring points, the relationship between thermal errors and temperature of each measuring point, and the key problem of intelligent modeling for the machine tool error.

2. Hardware Design for Machine Tool Thermal Error Testing System
The testing system hardware mainly consists of the temperature detection components, displacement detection components and data acquisition cards. The Swedish INOR thermal resistance PT100 and temperature transmitter APAQ-3HPT are attached to the machine tool surface as the temperature detection sensors, with the temperature measuring range: 0 - 100°C, and transmitting output: 4 - 20mA.

Keyence EX-305V eddy current displacement sensors are used as the thermal error displacement detection components, which features non-contact, high linearity and high accuracy; measuring range: 0 - 1.0mm; transmitting output: 0 - 5V; and resolution: 0.4 um.

Multi-channel synchronous data acquisition cards are used as the data acquisition cards: NIPCI6024E multifunction data acquisition card (DAQ).

A 250Ω high precision resistance LR is connected in parallel to both output ends of the temperature sensor, to transform the analog current signal into the 1 - 5V analog voltage signal; the π-type RC passive low-pass filter is used to eliminate high-frequency noise interference and improve SNR; in order to protect the data acquisition cards, voltage-regulator tubes are applied in the rear end of filter for voltage limit. The signal conditioning module features signal conversion, filtering and voltage limiting.

3. System Software Design
The program for thermal displacement and temperature data acquisition is designed in the LabVIEW8.0 environment. The Data collection flow chart is shown as Figure 1, mainly including: parameter setting module, data analysis module, continuous acquisition module, data storage module, data display module, etc.

4. Testing Experiment of Spindle Thermal Error
The temperature and thermal displacement testing system is used for measurement of the spindle thermal deformation of a vertical CNC machining center, so as to study the temperature and heat displacement required for thermal deformation compensation modeling. The temperature measuring points are mainly selected on the electrical spindle and the spindle box; the displacement sensor is arranged at the lower end face and side face of the toolholder at end of the spindle, i.e., the Y-axis and Z-axis thermal displacement errors of the spindle toolholder.
4.1. Determination of temperature measuring points
During real-time thermal error compensation, the layout of temperature measuring points shall accurately temperature field distribution of the spindle. In general, more temperature measuring points are more helpful, but too many points not only increase the cost of temperature measuring equipment, but also increase the difficulty of mathematical modeling and computing time, affecting the real-time compensation of CNC system, therefore, temperature measuring points shall be properly determined. According to relevant documentation, this paper preliminarily set seven measuring points with serial numbers from T1 to T7 as shown in Figure 2.

4.2. Determination of displacement measuring points
Based on the relevant document[6] for the spindle of the vertical machining center, the thermal error in the Z-axis direction is larger, followed by the Y-axis direction, while the thermal error in the X-axis direction is usually small due to high rigidity of the slide guide. Therefore, this experiment only measures the thermal error displacement in the Z-axis and Y-axis, as shown in Figure 3, and mainly includes: machine tool spindle, tool holder and eddy current sensor.

4.3. Analysis of correlation between temperature and thermal error
The machine tool spindle is operated at 2,000 rpm and is measured every 6 minutes until the temperature reaches the highest value and remains stable. As a measurement cycle, data of 20 samples are obtained in this paper. After obtaining the measured data, the mathematical model of thermal error, which can accurately reflect the relationship between temperature change and thermal error, is established by various modeling methods. Some test data are listed, as shown in Table 1, due to space limitations.

Seven temperature sensors are located in different positions of the machine tool spindle box. To have an in-depth analysis of the influence of temperature of each sampling point of the thermal error, correlation analysis and regression analysis of temperature and the thermal error data have been done.

Figure 4 shows the relationship of the temperature of T7 and the thermal error in the Z-axis, Figure 6 shows the relationship of the temperature of T7 and the thermal error in the Y-axis. It can be seen from Figure 4 and Figure 5 that the temperature of T7 is highly correlated with the thermal errors in the Z-axis and Y-axis, and the correlation coefficients are 0.9483 and 0.9894, respectively. According to the correlation coefficients of each temperature sampling points calculated with the Matlab software, the data of temperature sampling points are also highly correlated.
According to the principal component analysis theory[7], figure out eigenvalues and eigenvectors of relevant coefficient matrixes, as shown in Table 3. The eigenvalues are denoted as r1=6.7625, r2=0.1371…r7=0.0027, and (r1+r2)/(r1+r2+…r7)=98.56%.

This means that two principal components can express 98.56% of all information. Therefore, two principal components are used in this article, and the products of the corresponding eigenvectors of the eigenvalues and the original data are used as the input parameters of the neural network modeling, denoted as F1 and F2.

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\begin{align*}
F_1 &= 0.3729T1 + 0.3761T2 + 0.3834T3 + 0.3746T4 + 0.3834T3 + 0.3761T2 + 0.3729T1 \\
F_2 &= -0.6003T1 + 0.3799T2 + 0.0862T3 - 0.5380T4 + 0.0600T5 + 0.2154T6 + 0.3852T7
\end{align*}
\]

Among numerous neural network models, the BP neural network model is the most widely used and the most effective one. It is a one-way communication multilayer feedforward network. The first layer of the network is the input layer, the last layer is the output layer, and the middle layers are all hidden layers. There is no coupling between the neuron nodes on the same layer, and the neurons on adjacent layers are connected with connection weight coefficients. The input information is transmitted from the input layer to the output layer in turn, and the output of each layer affects only the input of the next layer. This paper uses a more mature 3-layer BP network model, refer to document for details[8].

5. Conclusion
In this paper, This paper presents a method for building intelligent thermal error model on the spindle of high speed CNC machine tools. Using the 20 pieces of temperature and error data collected from the experiment as samples to calculate the values of the above two principal components, train the BP network with the principal component value, and then test the generalization ability of the network. Figure 7 shows the curve of neural network training process, and it can be seen that the convergence speed is very fast and the effect is good. To test the prediction capability of the trained network, test the input samples with the trained network. The test results showed that the error range is [-2.0543~1.8942], and the corresponding relative error is less than 2%, showing a good effect.

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