Thermal Deformation Test and Modeling of Main Spindle of Numerical Control Vertical Machining Center

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Abstract. Thermal error is the main factor affecting the manufacturing accuracy of the numerical control vertical machining center. The thermal deformation of the machine spindle is the main source of machine tool thermal error. In view of the deficiency of single factor modeling of thermal deformation of spindle of traditional machine tools, it is measured in this paper the temperature rise and Z-axis thermal deformation of a vertical machining center under several rotating speed conditions, the test data is analyzed and processed, and the relationship curves of thermal deformation of the spindle relative to time and temperature rise under several working conditions are drawn. Binary linear regression analysis model and artificial neural network model for thermal deformation of the spindle are presented. By comparing the residual error of these two modeling methods, the error for binary regression modeling is from -7.5\,\mu m to 10\,\mu m, however, the error for neural network modeling is from -5.5\,\mu m to 8.1\,\mu m, it is shown that neural network modeling is superior to binary regression modeling.

1. Introduction

Machine tool is the machine tool of all mechanical equipment, and the machining accuracy is the focus of the competition of CNC (Computerized Numerical Control) machine tool products. In recent years, the CNC machine tool technology has become one of the essential areas of international scientific and technological level competition, and it has become an important symbol of the level of development of the mechanical equipment industry, precision machining center in precision manufacturing plays a crucial and decisive role. According to the statistics of professor J. Peclenik of the University of Birmingham and professor Yoshiaki Higano of Kyoto University, the manufacturing error caused by a thermal error of machine tools accounts for 40-70\% of the total manufacturing error in precision machining. Therefore, the control of thermal deformation error of the machine tool will be a key factor to improve the machining accuracy of the machine tool [1-5].

Currently, there are two main ways to reduce thermal error: one is to adopt the active error reduction method, and the other is the error compensation method [6].

(1) The active error reduction method is to eliminate or reduce the thermal error source through the design and manufacturing links, improve the machining accuracy of the machine tool, or control the temperature to meet the accuracy requirements. The cost of this method is very high, and there exist limitations of processing conditions and processing capacity.

(2) Error compensation method is to realize error correction through the software compensation function of the numerical control system by applying some control strategy, using monitoring devices,
actuators, and computer technology. This method has significant economic benefits. At present, thermal error compensation technology has become a research hotspot in precision equipment manufacturing [7]. At present, many scholars do a lot of research work around the CNC machine tool thermal error detection and compensation, mainly reflected in the following areas of study as temperature field and heat transfer mechanism of machine tool as well as precision detection method of thermal error, machine tool of temperature measuring point layout and optimization and thermal error modeling and so on, in that identification of the thermal deformation and thermal error modeling are the critical technology of machine tool thermal error compensation, it directly affects the effect of thermal error compensation. At present, thermal error compensation is mainly based on the establishment of the single-factor function relationship between thermal deformation and temperature. It adopts mostly such artificial intelligence technologies as linear regression, nonlinear fitting, expert system, fuzzy control, and neural network. After many years of theoretical and practical research, it is considered in this paper that the establishment of a single-factor model of thermal error and temperature has shortcomings. In the practice of thermal error testing, it is noted that the spindle temperature rises at different speeds, and the thermal deformation of the spindle is related to the temperature rise, as well as the working conditions of the machine, such as the rotational speed.

2. Test system composition

The hardware composition of the temperature and thermal error acquisition and analysis system is shown in Fig.1. It is composed of a temperature sensor and a transmitter to form a temperature acquisition part, an eddy current displacement sensor, and a controller to create a thermal displacement acquisition part, a data acquisition card, and a computer.

![Machine tool spindle thermal error test system.](image)

According to the precision requirements and temperature range of the temperature acquisition of the CNC machine tool [9], the temperature sensor is measured by the SMT PT100 platinum thermal resistance temperature sensor produced by the INOR of Sweden, and the components are attached to the surface of the machine tool. The thermal deformation detection sensor is made of KEYENCE named EX-416 type eddy current sensor and EX-205 eddy current signal transmitter. The eddy current sensor has the characteristics of non-contact, high accuracy, and high linearity with measuring range from 0mm to 5mm; The output of the controller is standard voltage type signal from 0V to 5V. The data acquisition card is a USB1252 multi-channel asynchronous data acquisition card produced by Smacq Technologies. Co., Ltd. with 12-bit analog input resolution and up to 500kS/s analog input sampling rate and up to 200kS/s analog input sampling rate when the multi-channel is opened. The data acquisition card is equipped with data collection and analysis software, which has some essential data analysis functions. It can also save the data in text form, which is convenient for other data analysis software to call.

3. Measurement method and data analysis

Through reading and analyzing a large number of documents, it is found that the thermal deformation of the vertical machining center spindle along the guide rail direction has the most significant impact
on the machining, that is, the thermal deformation of the Z-axis has the most significant effect on the machining accuracy, and the temperature rise of the spindle is closely related to the thermal deformation of the spindle. The arrangement of temperature measurement points and thermal deformation measurement points in this paper are shown in Fig. 2 [8-9].

![Figure 2. Arrangement of temperature and displacement measurement points.](image)

According to the working speed range of the machine tool, it operates at 2500rpm, 3000rpm, 3500rpm, 4000rpm, 4500rpm, 5500rpm, 6000rpm rotating speeds, respectively, and is labeled as working condition 1 to 7 respectively. With room temperature as the initial temperature, measure the corresponding temperature T and thermal deformation δ every 15 minutes. With the measured time as the abscissa and the thermal deformation of the machine tool spindle as the ordinate, the curve of the relationship between thermal deformation and time was made with Matlab software, as shown in Fig.3. It can be seen from Fig.3 that at different rotational speeds, the maximum temperature that the spindle can finally rise is also different, the lower the rotational speed, the lower the maximum temperature that can increase, the higher the rotational speed, the higher the maximum temperature that can arise. As can be seen in Fig.4, the spindle of the machine tool operates at different rates, and the speed of thermal deformation is not the same, the higher the rotating speed, the faster the thermal deformation rises, the lower the speed, the lower the thermal deformation increases. The change in thermal deformation is non-linear. In the early stage, it changes rapidly, but in the later stage, it turns slowly, and finally reaches the thermal equilibrium state.

Take the temperature rise as the abscissa and the thermal deformation as the ordinate, use Matlab software to make the temperature rise and thermal deformation curve of the machine tool spindle, as shown in Fig. 5.

![Figure 3. The temperature rise under different rotation speeds.](image) ![Figure 4. The thermal deformation under different rotation speeds.](image)

As can be seen from Fig. 5, at each rotating speed, thermal deformation and temperature rise are positively linearly correlated, and the slope of each curve is different, indicating that the velocity of
thermal deformation is different. When the spindle of the machine tool rises to the same temperature, the thermal deformation is different in different rotating speeds.

![Graph showing thermal deformation under temperature rise](image)

**Figure 5.** The thermal deformation under temperature rise.

The analysis of Fig.4 and Fig.5 shows that the thermal deformation of the spindle of the machine tool is not only related to the rotating speed but also related to its temperature rise. Therefore, in the establishment of a machine tool spindle thermal deformation model, not only the the rotating speed factor to be considered, but also temperature rise should be considered.

4. Thermal deformation modeling

4.1. Multiple regression modeling

According to the above analysis, the thermal deformation of machine tool spindle $\delta$ is positively correlated with temperature rise $T$ and rotating speed $v$. Therefore, it is established in this paper the thermal deformation model of machine tool spindle based on binary parameters.

Set the temperature rise $t$, rotational speed $v$ as independent variables, and thermal deformation $\delta$ as function, then the set of seven experimental rotational speed vectors named $v$ is denoted as \{v1, v2, v3, v4, v5, v6, v7\}, the set of temperature vectors named $T$ measured at each rotational speed is denoted as \{T1, T2, T3, T4, T5, T6, T7\}, the set of thermal deformation vectors named $Y$ measured at each rotational speed is denoted as \{δ1, δ2, δ3, δ5, δ6, δ7\}. By using the multiple linear regression function program provided by Matlab software, the regression coefficient $b$ was calculated as \[-8.854, 5.4865, 0.2559\]. Thus, the binary linear regression equation of thermal deformation of the spindle of the machine tool is expressed as:

$$y = -8.854 + 5.4865T + 0.2559v$$

(1)

As shown in Fig.6, the residual error is calculated, and the error for binary regression modeling is from -7.5µm to 10µm. The relative error is from -9.1% to 12.1%.

![Graph showing residual error of binary regression modeling](image)

**Figure 6.** Residual error of binary regression modelling.
4.2. Neural network modeling
For the high stiffness of the spindle structure of numerical control machining center, the bearing is fixed with pre-tightening treatment, from the perspective of mechanical deformation analysis, it has non-linear characteristics. Therefore, the use of multiple linear regression method has defects. Consequently, it is adopted in this paper the neural network intelligent modeling technology. According to the literature, a radial basis network (PNN) is characterized by a simple structure and fast training speed, which is especially suitable for solving pattern classification problems [10-12]. The structural model of the 3-layer neural network is shown in Fig.7. In this paper, the input of neural network training samples is two; one is the machine tool of spindle temperature rise of vector set T named as \{T_1, T_2, T_3, T_4, T_5, T_6, T_7\}, the other is the speed vector set V named as \{v_1, v_2, v_3, v_4, v_5, v_6, v_7\}. The training sample of neural network has only one output, which is the set of thermal deformation vectors Y named as \{δ_1, δ_2, δ_3, δ_5, δ_6, δ_7\}. The training process of the neural network is shown in Fig.8. As can be seen from Fig.8, after 16 iterations, the predetermined accuracy is achieved.

\[ \begin{align*}
   \hat{y}_1 &= \alpha_{11} s_1 + \alpha_{12} s_2 + \alpha_{13} s_3 + \alpha_{14} s_4 + \alpha_{15} s_5 + \alpha_{16} s_6 + \alpha_{17} s_7 \\
   \hat{y}_2 &= \alpha_{21} s_1 + \alpha_{22} s_2 + \alpha_{23} s_3 + \alpha_{24} s_4 + \alpha_{25} s_5 + \alpha_{26} s_6 + \alpha_{27} s_7 \\
   \hat{y}_3 &= \alpha_{31} s_1 + \alpha_{32} s_2 + \alpha_{33} s_3 + \alpha_{34} s_4 + \alpha_{35} s_5 + \alpha_{36} s_6 + \alpha_{37} s_7 \\
\end{align*} \]

Figure 7. Model of neural network.

Figure 8. Neural network training iterative process.

The error calculated by the model is shown in Fig.9. Fig.9 shows that the error range of the model is from -5.5µm to 8.1µm, and the relative error range is from -6.7% to 9.8%.

![Error of neural network modeling](image)

Figure 9. The error of neural network modelling.

5. Conclusion
Through data analysis, the factors that affect the thermal deformation of the numerical control vertical machining center spindle are not only the speed but also the spindle speed. Therefore, in order to improve the accuracy of spindle thermal deformation prediction, it is necessary to establish a multivariate error prediction model. Because of the non-linear characteristics of the machine tool spindle thermal deformation, artificial neural network modeling has higher accuracy than binary linear regression modeling to deal with the problem of spindle deformation prediction.

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7. References

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