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Thermal Error Measurement and Real Time Compensation System for the CNC Machine Tools Incorporating the Spindle Thermal Error and the Feed Axis Thermal Error

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Thermally induced errors have been significant factors affecting machine tool accuracy. In this paper, the thermal spindle error and thermal feed axis error have been considered, and a measurement/compensation system for thermal error is introduced. Several modelling techniques for thermal errors are also implemented for the thermal error prediction; i.e. multiple linear regression, neural network, and the system identification methods, etc. The performances of the thermal error modelling techniques are evaluated and compared, showing that the system identification method is the optimum model having the least deviation. The thermal error model for the feed axis is composed of geometric terms and thermal terms. The volumetric errors are calculated, combining the spindle thermal error and feed axis thermal error. In order to compensate for the thermal error in real-time, the coordinates of the CNC controller are modified in the PMC program. After real-time compensation, the machine tool accuracy improved about 4–5 times.

Keywords: Accuracy; CNC; Error compensation; Machine tools; Thermal error

1. Introduction

Thermally induced errors are significant factors affecting machine tool accuracy. The thermal errors generally come from the thermal deformations of the machine elements caused by heat sources which exist within the structure, i.e. ball screws, bearings, nuts, axis drive motors, friction on the surfaces, cutting processes, the flow of coolant/lubricating oil, and the ambient temperature [1–5]. Those thermal errors have been reported to be about 70% of the total positioning error of the machine tool (e.g. [1]), and spindle thermal errors or spindle drift has been considered to be the dominant error component among them (e.g. [2]). In this paper, a measurement system for spindle thermal error and feed axis thermal error is developed and three methods of thermal error modelling are implemented, i.e. multiple linear regression, neural network, and system identification. The error modelling for a feed axis is composed of geometric error terms and thermal error terms. In order to obtain the compensation value, the algorithm for volumetric error mapping is programmed using the models for thermal spindle error and feed axis error. The coordinate data of the machine tool controller are modified for compensation in real-time using the PMC program. After the compensation, the machine tool accuracy was improved about 4–5 times.

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2. Spindle Thermal Error Measurement / Modelling

2.1 Measurement System for the 5 DOF Spindle Thermal Errors

There are 6 degrees of freedom (6 DOF) components in the spindle error motion in machine tools [6], i.e. two radial error motions, one axial motion, two tilting motions, and one indexing error motion. From the point of view of machine tool accuracy, the indexing error motion of the spindle can be ignored and thus only 5 DOF spindle thermal errors are considered in this paper.

Figure 1 shows the measurement set-up for the 5 DOF spindle errors, in which the jig for the two master balls and 5 gap sensors are arranged around the spindle and interfaced to a PC. Temperature variations are measured with the thermocouples around the machine tool structure.

Figure 2 shows the thermocouples located around the machine tool structure. Eight sensors are located around the spindle and spindle housing, 8 sensors around the frame, 2 sensors for the ambient air temperature, and 1 sensor around the gap sensor jig. An on-line measurement procedure has

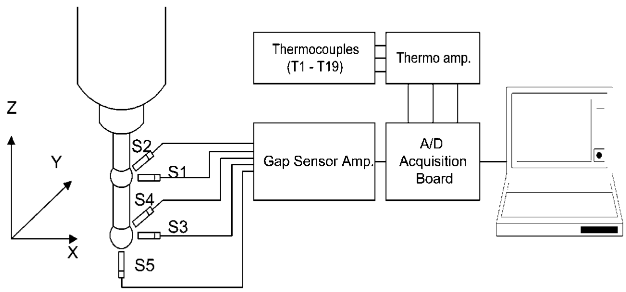

Fig. 1. Sensors for measuring spindle drift errors.

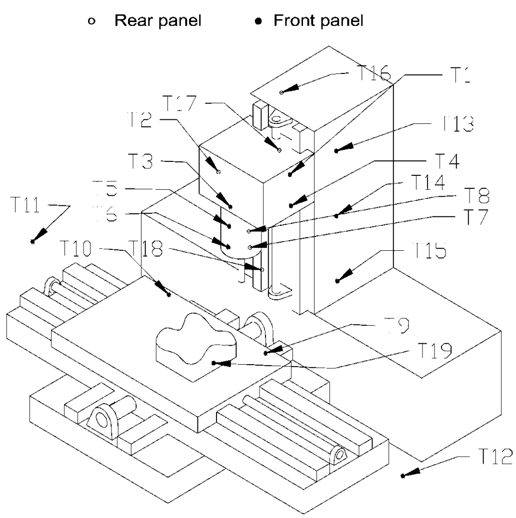

Fig. 2. Thermal sensor location.

been implemented, in order to measure the spindle thermal error efficiently. When the total measurement time and the measurement interval are input, the PC controls the CNC machine to operate according to the programmed speed via the interface between the machine and the PC. At the time of measurement, the PC sends the command "M19"(for the FANUC controller) to the machine tool so that the machine spindle stops at an angle set by the reference pulse signal, which is the zero degree location of the spindle encoder. Then the machine spindle stops, and the spindle error measurements as well as the temperature measurements are performed. After the measurement operation, the PC sends a command for spindle rotation to the machine tool, then the machine spindle keeps rotating until the next command of measurement is given.

2.2 Spindle Thermal Error Measurement and Modelling

The developed thermal error measurement system has been applied to the three operating conditions of the CNC machine tool:

1. Constant running condition (running at constant 3000 r.p.m.).
2. Progressive running condition (progressively increasing/decreasing r.p.m. at 10 min interval).
3. Random running condition (running at random r.p.m.).

For the constant running condition, the machine tool runs at 3000 r.p.m. for 4 h, then the machine stops for another 4 h. For the progressive running condition, the spindle rotation is progressively increased in steps, i.e. 0, 1000, 2000, and 3000 r.p.m.; then, the spindle rotation is progressively decreased, i.e. 3000, 2000, 1000, and 0 r.p.m. For the random running condition, the machine tool runs at a random r.p.m., whose running speed is assigned from a random number generator. In Fig. 3, temperature variations around machine tool and thermal spindle errors are shown over time in each spindle running condition. From the above spindle thermal error measurement conditions at the three typical running conditions of the machine tool, a strong relationship can thus be observed between the temperature data and the spindle thermal error data. A relationship can therefore be obtained by thermal error modelling procedures which will be explained in the next section.

2.3 Spindle Thermal Error Modelling

There are several methods for thermal error modelling for a machine tool, and three different methods for thermal error modelling are implemented and tested in this paper; i.e. the multiple linear regression model, the neural network model, and the system identification model.

Multiple Linear Regression Model

The relationship between the temperature data and the spindle error can be modelled as a multiple linear regression model. Let $t_I (I = 1, 2, \ldots, N)$ be the temperature data at several locations around the machine tool, then the thermal error component, y_1 ,can be modelled as a linear relationship as follows.

$$y_1 = a_{11}t_1 + a_{12}t_2 + a_{13}t_3 + a_{14}t_4 + \ldots + a_{1n}t_n + b_1 \quad (1)$$

where $a_{11}, a_{12}, a_{13}, a_{14} \ldots a_{1n}$ are coefficients for temperature, b_1 is the constant for the thermal error model. Equation (1) can be extended to the 5 DOF spindle thermal errors, and thus can be represented in a matrix form as follows

$$Y = AT \quad (2)$$

where,

$$Y = [y_1\ y_2\ y_3\ y_4\ y_5]^T$$

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1n} & b_1 \\ a_{21} & a_{22} & a_{23} & \cdots & a_{2n} & b_2 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ a_{51} & a_{52} & a_{53} & \ldots & a_{5n} & b_5 \end{bmatrix}$$

$$T = [t_1\ t_2\ t_3 \ldots t_n\ 1]^T$$

Therefore, the relationship between the thermal error and the temperature data can be found from Eq. (2), and the multiple linear regression model is completed.

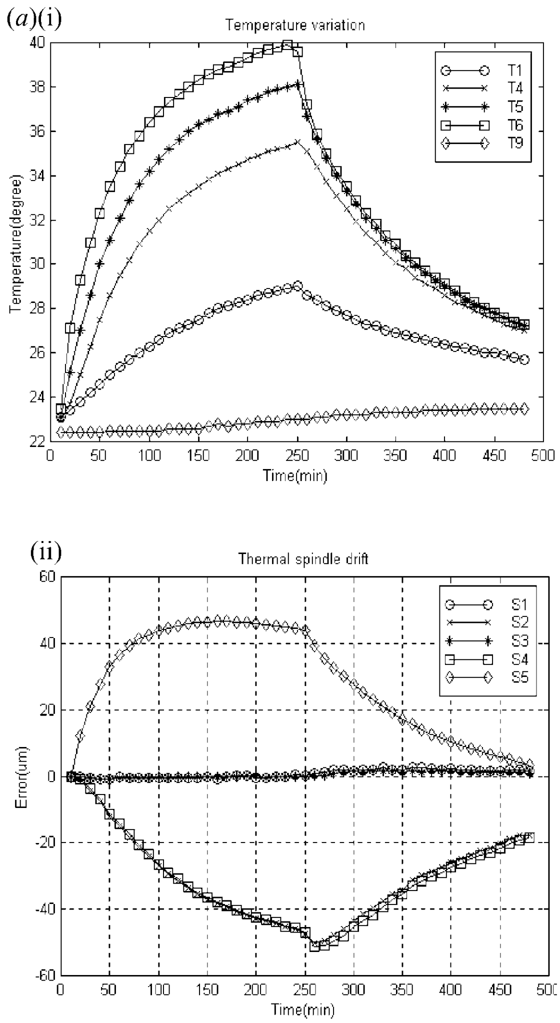

Fig. 3. (*a*)(i–ii) Temperature variations and thermal spindle variation in constant running condition.

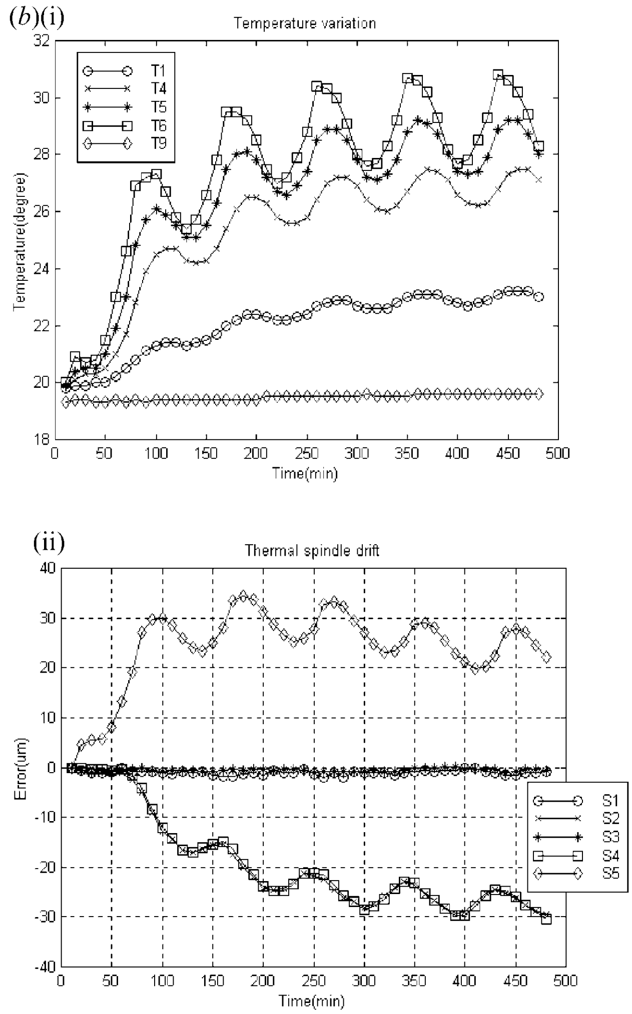

Fig. 3. (*b*)(i–ii) Temperature variations and thermal spindle variation in progressive running condition.

Neural Network

The neural network is a kind of multiple nonlinear model in which the coefficients are called weights which are evaluated by training with an iterative technique called back-propagation. Thus, a neural network is appropriate for a system having a nonlinear relationship between multiple inputs and multiple outputs. There are three types of layer for the neural network, i.e. input layer, hidden layer, and output layer, as shown in Fig. 4. For the thermal error application, the input layer is designed to consist of temperature data, and the output layer of the 5 DOF spindle thermal errors.

The hidden layers represent intermediate nodes, which are determined so that the neural model has the least errors. After the hidden layers are determined by testing the output layers, the output, O, can be calculated and the cost function, E, can be defined as follows.

$$O_i^\mu = g\left(\sum_k (w_{ik}\xi_k^\mu)\right)$$

and

$$E(w) = \sum_{i\mu} (\zeta_i^\mu - O_i^\mu)^2 = \sum_{i\mu} [\zeta_i^\mu - g\,(\sum_k w_{ik}\xi_k^\mu)]^2 \qquad (3)$$

where O_i^μ is the μth pattern of the ith model of output, g is the nonlinear thresholding sigmoid function, such as

$$g(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}} \text{ for variance } x$$

where w_{ik} is the weight value of the kth node of the ith layer, ξ_k^μ is the value of the μth pattern of the kth node in the previous layer, and ζ_i^μ is the μth pattern of ith measured data. Thus, a relationship is formed between the thermal error and the temperature data, based on the neural network.

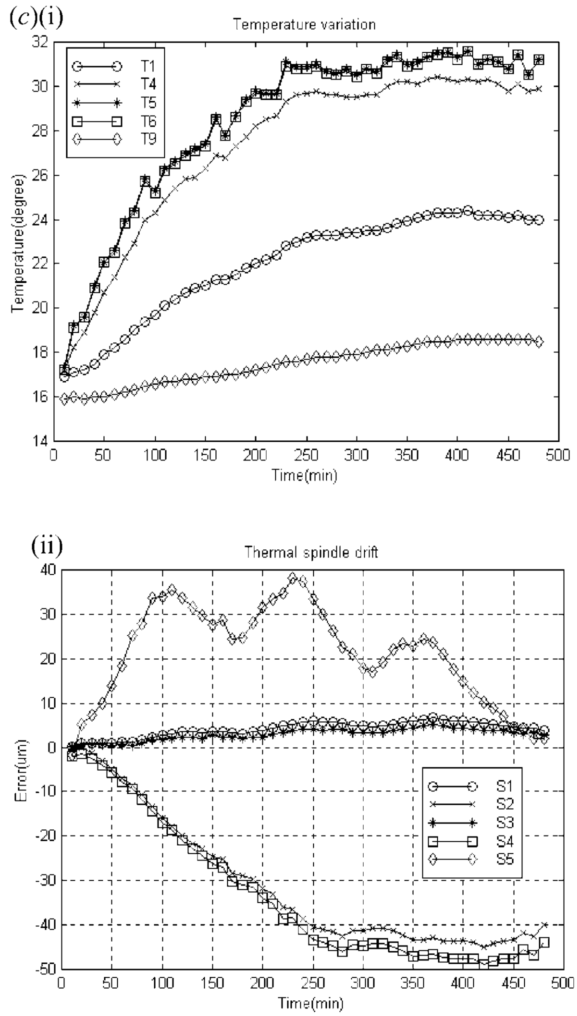

Fig. 3. (*c*)(i–ii) Temperature variations and thermal spindle variation in random running condition.

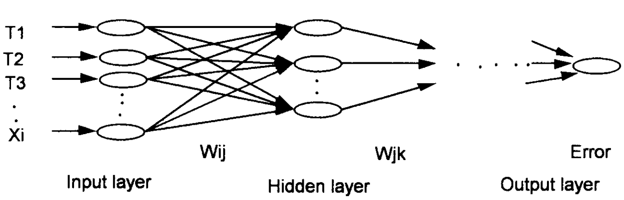

Fig. 4. The components of the neural network.

System Identification

In the system indentification model, the present thermal errors (at time *t*) are influenced by the present temperature data, the past temperature data, and the past thermal errors.

Let X_t, X_{t-1}, X_{t-2}, … X_{t-n} be the thermal errors at time *t*, $t-1$, $t-2$, …, $t-n$, respectively, and let a_t, a_{t-1}, …, a_{t-n+1} be the temperature data at time *t*, $t-1$, …, $t-n+1$, respectively. Then, the thermal errors X_t, X_{t-1}, X_{t-2}, …, X_{t-n} can be related to the temperature data a_t, a_{t-1}, …, a_{t-n+1}. That is,

$$X_t - \phi_1 X_{t-1} - \phi_2 X_{t-2} \cdots - \phi_n X_{t-n} = \theta_1 a_t - \theta_2 a_{t-1} - \theta_3 a_{t-2} \cdots - \theta_m a_{t-m+1} \quad (4)$$

where, ϕ_n and θ_m are the model coefficients, and the integers *n* and *m* are heuristically chosen as 3 and 2, respectively.

Equation (4) can be rewritten in the matrix form as follows.

$$Y = XA$$

where $Y = [X_t\ X_{t-1}\ X_{t-2}\ X_{t-3}]^T$, which is the column vector of thermal error, and $A = [\phi_1\ \phi_2\ \phi_3\ \theta_1\ \theta_2]^T$, which is the column vector of coefficients, and *X* is the matrix of thermal errors–temperature data.

$$X = \begin{bmatrix} X_{t-1} & X_{t-2} & X_{t-3} & -a_t & -a_{t-1} \\ X_{t-2} & X_{t-3} & X_{t-4} & -a_{t-1} & -a_{t-2} \\ X_{t-3} & X_{t-4} & X_{t-5} & -a_{t-2} & -a_{t-3} \\ X_{t-4} & X_{t-5} & X_{t-6} & -a_{t-3} & -a_{t-4} \end{bmatrix}$$

Therefore, the relationship between the thermal error and the temperature data can be formed.

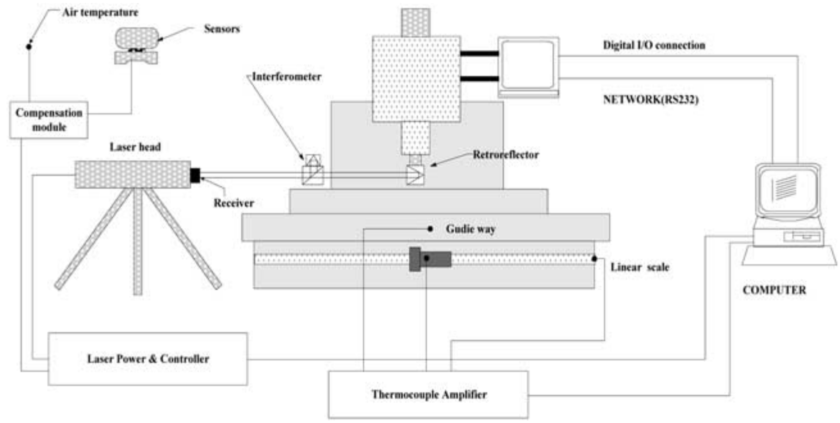

Fig. 5. The set-up for the thermal feed axis error.

3. Feed Axis Thermal Error Measurement/Modelling

3.1 Feed Axis Thermal Error measurement

For the feed axis thermal error, 3 translational errors (including 1 postional error and 2 straight errors) and 3 rotational errors (pitch, yaw, roll) are considered along the feed axis. The thermal translational errors, pitch, and yaw are measured using a laser interferometer over time; and at the same time the temperatures around the machine tool are measured with thermocouples. The measurement system for thermal feed axis error/temperature is shown in Figs 5 and 6. The system is composed of a PC that has a program interfacing the machine tool and the laser interferometer, and the temperarture measurement system is also implemented for data acquisition around the machine tool. Temperature locations are selected by consideration of the heat source(s) causing the thermal distortion. Therefore, temperature data can be obtained for the ball screw bearings, linear scale, environment air, and slidesways in each axis.

3.1 Feed Axis Thermal Error Modelling

The feed axis error model is composed of a geometric term and a thermal term. The geometric term is a function of the nominal position value in each axis and the thermal term is a function of temperatures around the machine tool as follows:

$$Error(P,T) = Error_g(P) + Error_t(T) \tag{5}$$

each term is defined as follows:

$$Error_g(P) = a_0 + a_1P + a_2P^2 + \ldots \tag{6}$$

$$Error_t(T) = m_1(T)P + m_2(T) \tag{7}$$

where p is the nominal position in each axis, and T is the temperature around the machine tool. Figure 7 shows the thermally induced positional error and the temperature in the X-axis, where the error data and temperature data are measured for 4 h. It is observed that the longer feed axis has the larger thermal error in the machine tool. The first term of Eq. (7) indicates that thermal error is related to the nominal position and temperatures of the machine tool. The straightness error and angular errors are also modelled; the vertical and horizontal

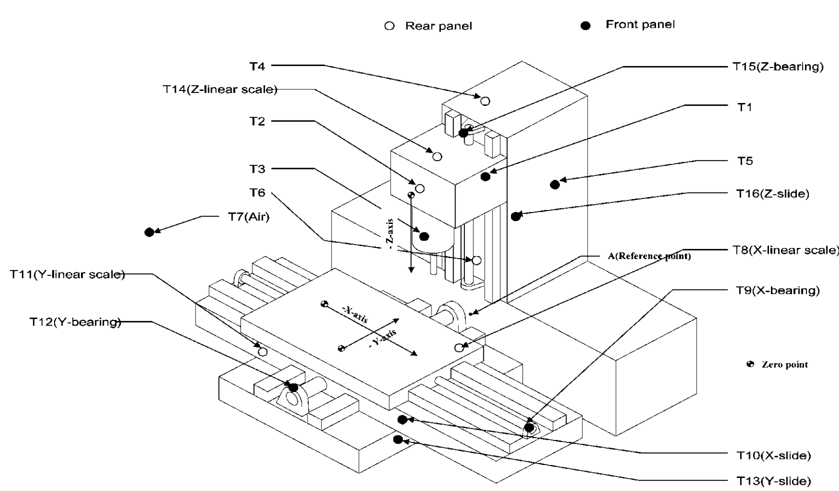

Fig. 6. Temperature sensor locations.

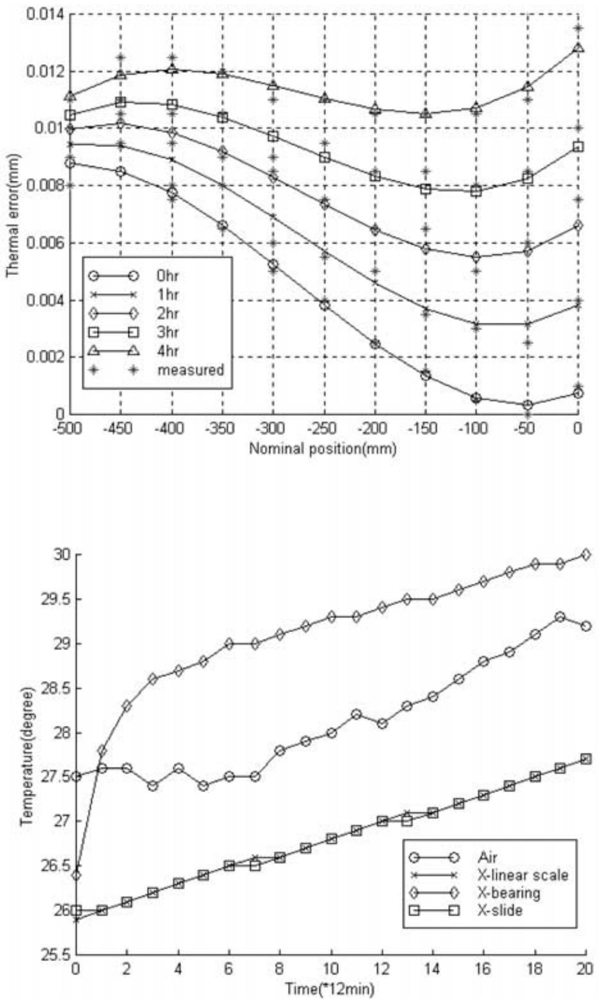

Fig. 7. Temperature variation and positional error with time in the *X*-axis.

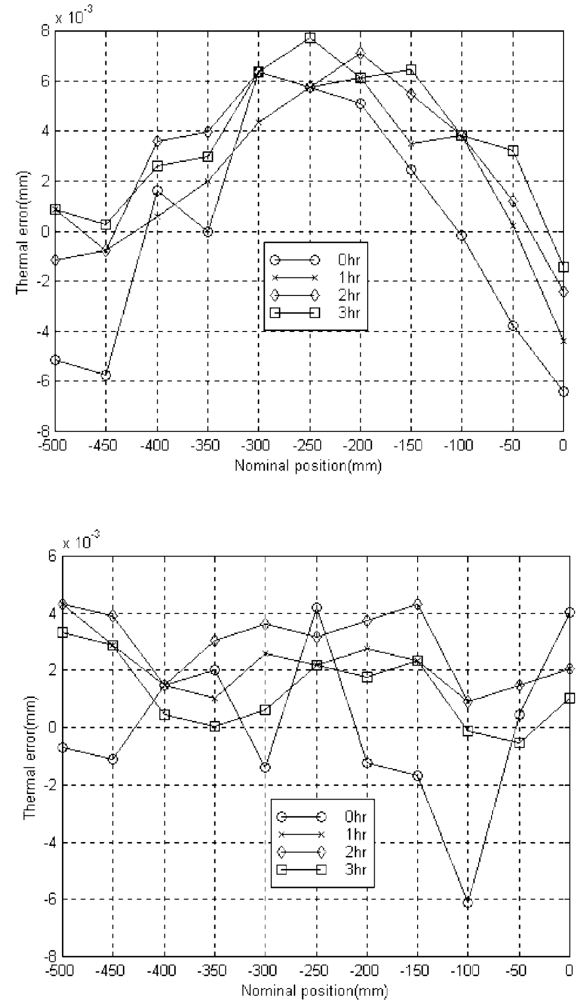

Fig. 8. Thermal error in *y*-straightness and *z*-straightness in *X*-axis with time.

straightness errors are measured and modelled for the feed axis. Figure 8 shows the vertical straightness and horizontal straightness errors along the *X*-axis. The angular pitch and yaw errors are also measured and modelled. Figure 9 shows the angular pitch and yaw errors along the *X*-axis.

3.3 Volumetric Error and Real-Time Compensation

After the thermal errors are measured and modelled for the spindle and the feed axis, those errors are combined to give the volumetric error in the machine tool. The volumetric error is calculated using a homogeneous transformation matrix (HTM), where the HTM is defined as follows:

$$T_r^n = \begin{bmatrix} O_{11} & O_{12} & O_{13} & P_x \\ O_{21} & O_{22} & O_{23} & P_y \\ O_{31} & O_{32} & O_{33} & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (8)$$

This matrix transforms the *n* reference coordinate system to the *r* reference coordinate system. **O** is related to the anglular term and **P** is related to the translational term. Thus, the volumetric error in each axis is calculated as follows:

$$S_{AP_t} = T_A^D T_D^E P_t(p),\ S_{AP_w} = T_A^C T_C^B P_w(p),\ Error = S_{AP_w} - S_{AP_t} \quad (9)$$

where D, A, E, B, C, and P_w refer to the coordinate system as shown in Fig. 10. The real-time compensation system is developed with a modified programmable logic control (PLC) program in the CNC controller. The compensation data are calculated in each axis, and then sent to the machine tool controller. The real-time error compensation system is implemented and tested using the diagonal measurements in the measurement volume by a laser interferometer. Figure 11 shows the diagonal measurement data before and after the real-time compensation system is implemented. The diagonal error is observed to be 40 μm before compensation, and it is reduced to 15 μm after compensation.

The efficiency and performance of the developed system as demonstrated should have a very high potential for the error compensation of CNC machine tools.

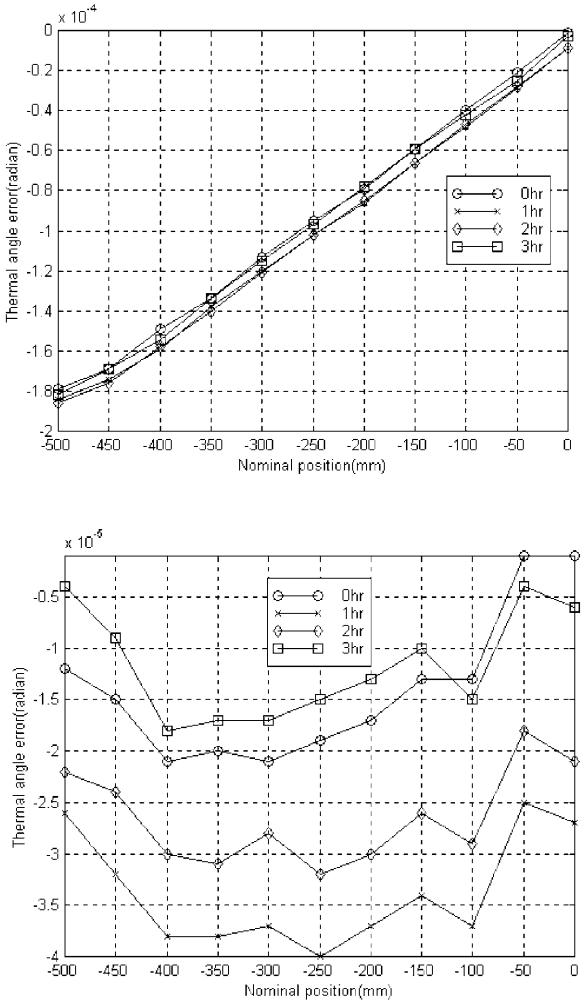

Fig. 9. Themal pitch error and yaw error in *X*-axis with time.

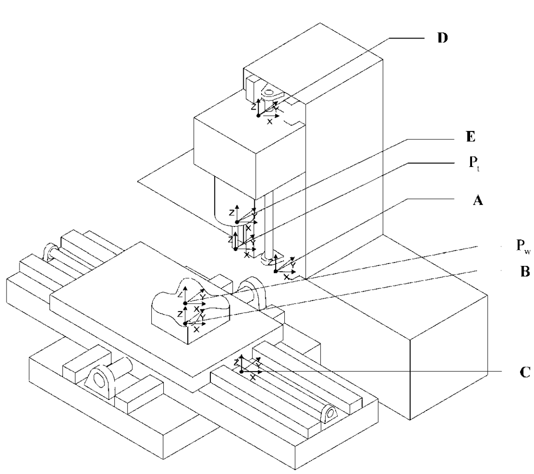

Fig. 10. Coordinate system for compensation.

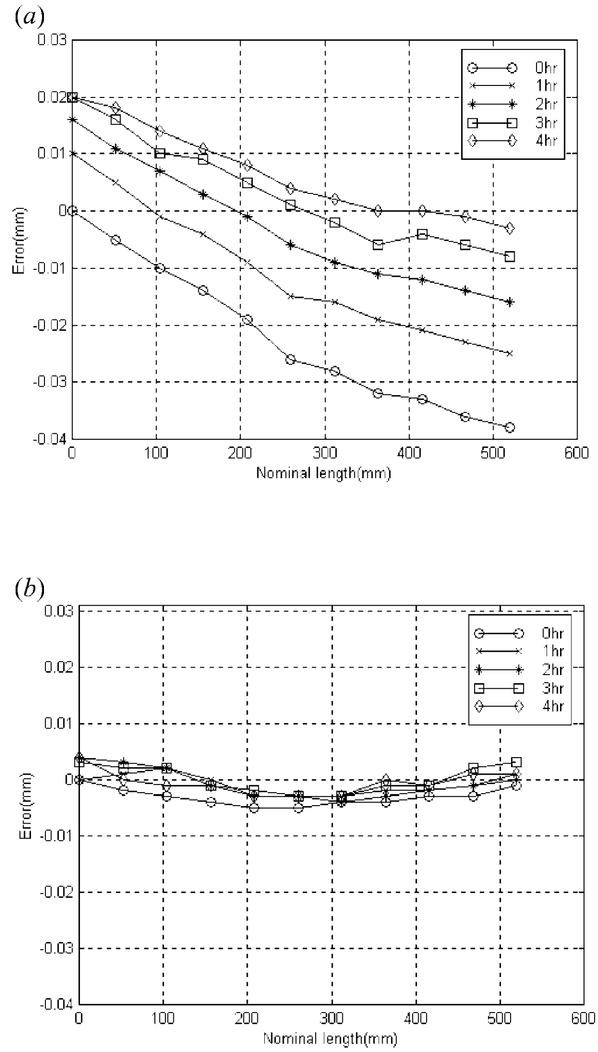

Fig. 11. The error (*a*) before and (*b*) after compensation.

4. Conclusion

Accuracy is greatly improved using the developed error compensation system. The spindle thermal error and feed axis error including the thermal and geometric errors are measured and modelled. Then, the volumetric errors are calculated using an HTM, and can then be compensated for. A real-time compensation system is implemented by modifying the PLC program in the CNC controller, and interfacing the PC and the machine tool controller. The developed system has been applied to a CNC machining centre, and the accuracy has been improved about 4–5 times after compensation, demonstrating a very high potential for the error compensation of CNC machine tools.

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