Integrated Real Time Compensation System for Thermally Induced Volumetric Errors in Commercial CNC machine tools

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1.Introduction

Thermally induced errors have been significant factors affecting the machine tool accuracy. The thermal errors generally come from the thermal deformations of the machine elements caused by heat sources that exist within the structure, ball screws, bearings, nuts, axis drive motors, friction on the way surfaces, cutting processes, the flow of coolant/lubricating oil, and the ambient temperature. Those thermal errors have been reported as much as about 70% of the total positioning error in the machine tool, and among them, the spindle thermal errors or spindle drifts have been considered as the dominant error components (e.g.[1]) In this paper, a measurement system for spindle thermal error and feed axis thermal error is developed and three methods of thermal error modeling are implemented for the spindle thermal error: multiple linear regression, neural network, and system identification; and the error modeling for feed axis thermal error is composed of geometric error and thermal error. In order to obtain the compensation values, the algorithm of the volumetric error map is programmed using the models. The coordinates of the machine tool controller are modified to compensate in real time in PC interfaced environment program. After the real tome compensation, the machine tool accuracy has been improved about 4-5 times.

2. Spindle thermal error measurement/modeling

2.1 Measurement system for the 5 DOF spindle thermal errors

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

Fig.1 shows the measurement setup of the 5 DOF spindle errors, where the jig of two master balls and 5 gap sensors are arranged around the PC interfaced environment. Temperature variations are also measured with the thermocouples around the machine tool structure.

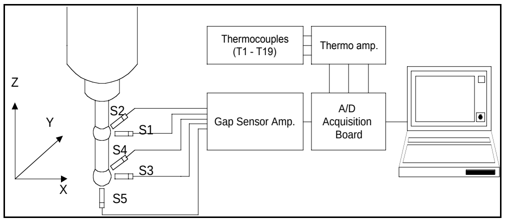

Fig.1 Sensors for measuring spindle drift errors.

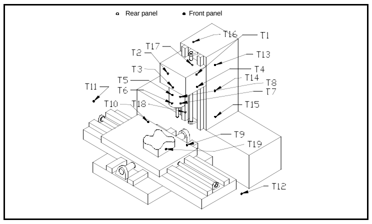

Fig.2 Thermal sensor location

Fig.2 shows the thermocouples located around the machine tool structure, where 8 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. The on line measurement feature has been implemented, in order to measure the spindle thermal error with efficiency. 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 RS232C serial interface connection. At the time of measurement, the PC sends the command “M19”(typically for the FANUC controller) to the machine tool such that the machine spindle stops at the angle of reference pulse signal(zero degree) 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 the command of spindle rotation to the machine tool, then the machine spindle rotates until the next command of measurement is given.

2.2 Spindle thermal error measurement and modeling

The developed thermal error measurement system has been applied to the three operation conditions of the CNC machine tool: (1) constant running condition (running at constant 3000 rpm) (2) progressive running condition (progressively increasing/decreasing rpm at 10 min interval) (3) random running condition (running at random rpm). The machine tool is running at 3000rpm constantly during 4 hours, then machine stops during another 4 hours in constant running condition. In progressive running condition, the spindle rotation is progressively increasing from such as 0 rpm, 1000 rpm, 2000 rpm, and 3000 rpm, then the spindle rotation is progressively decreasing from such as 3000rpm, 2000rpm, 1000rpm, and 0 rpm. In random running condition, the machine tool is running at random. In fig.3, temperature variations around machine tool and thermal spindle errors are shown over time in each spindle running condition. From the above three spindle thermal error measurement cases at the three typical running condition of machine tool, a strong relationship can thus be suggested between the temperature data and the spindle thermal error data. Therefore the relationship can be obtained by the thermal error modeling procedures which will be explained in the next section.

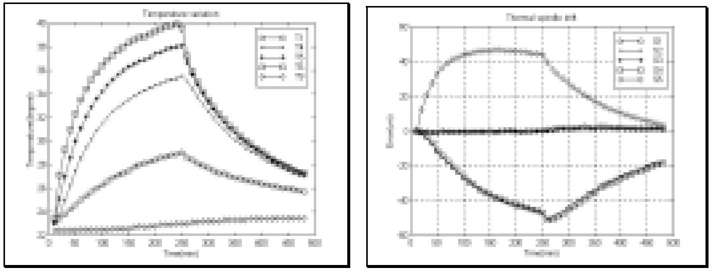

Fig.3a Temperature variations and thermal spindle variation in constant running condition

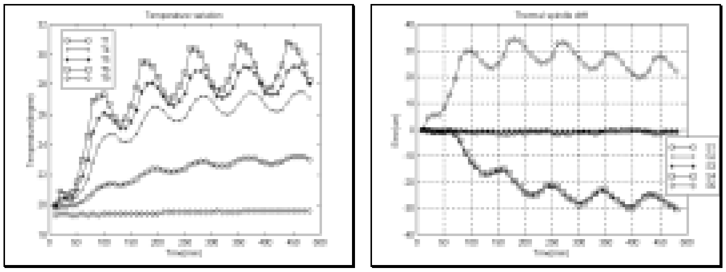

Fig.3b Temperature variations and thermal spindle variation in progressive running condition

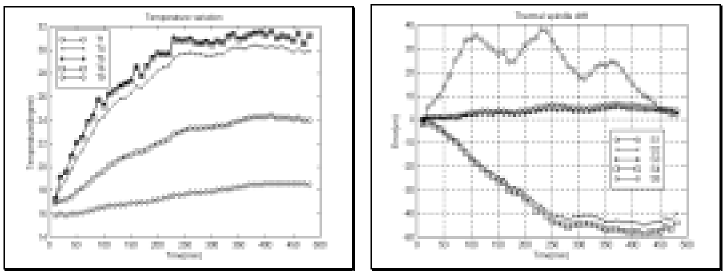

Fig.3c Temperature variations and thermal spindle variation in random running condition

2.3. Spindle thermal error modeling

There have been several methods of the thermal error modeling for the machine tool, and three different methods of thermal error modeling are implemented and tested in this paper: multiple linear regression model, neural network model, and the system identification model.

- Multiple linear regression model

The relationship between the temperature data and the spindle error can be modeled as the multiple linear regression model. Let t_l(l=1,2,….N) be the temperature data at several locations around the machine tool, then the thermal error component, y_1 can be modeled as linear relationship as follows.

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

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

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

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

- Neural network

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

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

$$X_t - \phi_1 X_{t-1} - \phi_2 X_{t-2} - \cdots - \phi_n X_{t-n} = \theta_1 a_t - \theta_2 a_{t-1} - \theta_3 a_{t-2} - \cdots - \theta_m a_{t-m+1} \qquad (3)$$

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

3. Feed axis thermal error measurement/modeling

3.1 Feed axis thermal error measurement

There are 3 translation errors(including 1 postional error and 2 straight errors) and 3 rotational errors(pitch, yaw, roll) along feed axis. The thermally induced translational errors, pitch, yaw errors are measured using the laser interferometer over time; and temperatures around machine tool are simultaneously measured with thermocouples. The measurement system for feed axis thermal error is shown in fig.5. The system is composed of PC interfaced devices such as program interfacing machine tool using RS232C and laser interferometer; and having acqusition system for temperature around machine tool. Temperature locations are selected, considering principal heat sources and associated thermal distortion; ball screw bearings, linear scale, environmental air, slide face in each axis.

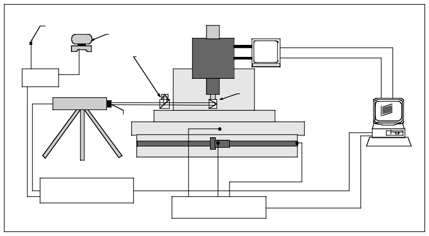

Fig.5 Setup for thermal feed axis error

3.1 Feed Axis Thermal Error Modeling

Feed axis error model is composed of geometric term and thermal term.Geometric term has factor of nominal coordinates in each axis and the thermal term has factors of temperatures around machine tool, that is,

$$Error(P,T) = Error_g(P) + Error_t(T) \qquad (4)$$

Where each term is defined as following:

$$Error_g(P) = a_0 + a_1 P + a_2 P^2 + \ldots \qquad (5)$$

$$Error_t(T) = m_1(T) * P + m_2(T) \qquad (6)$$

Temperature variation and positional error including thermal/geometric error in X axis is shown in fig.6. It has been found that the longer feed axis, the more thermal error machine tool has. The first term in equation(6) has physical meaning that thermal error is related to the length and temperature. The rest of thermally induced feed axis errors such as straightness and angular errors are also modeled similarly, however, angular error and straightness error have less variation than positional error over time, while the angular errors are usually amplified by the Abbe's offset principle.

3.2 Volumetric error map and real time compensation

The volumetric errors are calculated using the homogeneous transformation matrix(HTM) including spindle thermal error and the feed axis thermal error. The HTM is defined as follows,

$$T_r^n = \begin{bmatrix} O_{11} & O_{12} & O_{13} & P_x \\ O_{21} & O_{22} & O_{23} & P_y \\ O_{31} & O_{32} & O_{33} & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (7)$$

where **O** is related to angular terms and **P** is related translational terms. The actual errors at every nominal position are calculated in each axis as follows:

$$S_{AP_t} = T_A^D T_D^E P_t(p) \quad S_{AP_w} = T_A^C T_C^B P_w(p) \quad Error = S_{AP_w} - S_{AP_t} \qquad (8)$$

Real time compensation system is developed using the modified PLC program in CNC controller. The compensation data in each axis calculated using the HTM, and are sent to the controller. The developed system has been applied to a practical CNC machine tool, and the diagonal error is measured with laser interferometer for verification. The result is shown in fig.7 where the error was greatly reduced typically about 4-5 times.

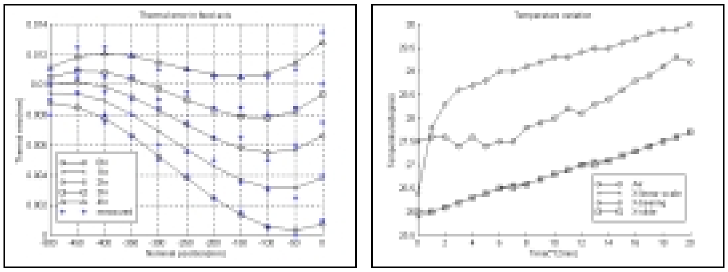

Fig.6 Temperature variation and positional error with time in X-axis

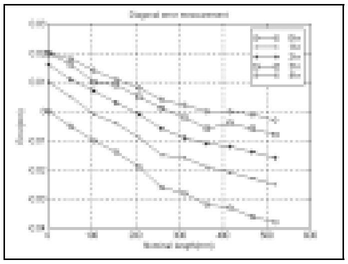

Fig.7a The error before compensation

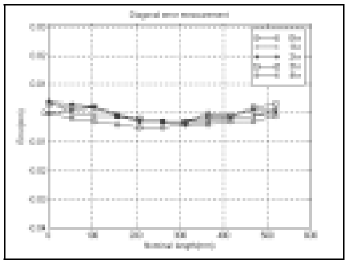

Fig.7b The error after compensation

4. Conclusion

Thermal error measurement and real tome compensation system has been successfully developed. The spindle thermal error and feed axis error including thermal and geometric error are modeled respectively. The real time compensation system is developed modifying the PLC program in CNC controller interfacing the PC which has algorithm calculating the volumetric error. After compensation, about 85% of error is removed. This result shows that the error modelings suggested have good performance.

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