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ORIGINAL ARTICLE

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Testing, variable selecting and modeling of thermal errors on an INDEX-G200 turning center

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Abstract The purpose of this research is to enhance the accuracy of an INDEX-G200 turning center through real-time compensation for the thermal errors. This paper presents the whole process of thermal error testing, temperature variable selecting by grouping approach, thermal error modeling, etc. The analysis results show that the thermal error range for radius direction on the machine is approximately 18 μm larger than expected, the model set by this method is more accurate and robust, and the thermal error is the major error sources for the machine and should be considered seriously by machine builders and users.

Keywords CNC machine tool · Error testing · Optimal modeling · Thermal error

1 Introduction

Due to the thermal deformation of machine tools when machining, the relative distance between the cutting tool and the part being machined, by which the machine accuracy is defined, is changed, so the machining error was made. And the thermally induced error is the biggest contributor to the whole machine errors. There are two main solutions for reducing thermal errors: by improving the machine tool design and by error compensation techniques. Recently, by the help of the development of sensing, modeling, and computer techniques, real-time error compensation based on software approach has received wide attention to further improve the machine accuracy cost effectively [1–7]. One of the main difficult issues in a thermal error compensation is to select appropriate temperature variables as well as to obtain an accurate thermal model. For solving this problem, the grouping approach is put forward to determine the best combination of temperature variables [8–10], in which the Mallows' Cp or the residual mean square were used as the criterion for selecting the temperature variables so that the high accuracy model of thermal error could be obtained and the computational time is reduced greatly.

In this paper, a computer controlled testing set-up was first built to collect the data of temperature field and thermal drift or errors of an INDEX-G200 turning center, which is a kind of new and precision machine (Fig. 1). Then, the optimal temperature variable selected using the grouping approach for thermal error modeling was presented in which the R_p^2-value (the coefficient of determination) was used as the criterion because of easy computation. Finally, the thermal error optimal model was set by the multiple regression analysis (MRA) in the general linear form. And the modeling result analysis shows that the model is more accurate and robust, and the machining accuracy of the NC machine tools can be improved largely with low cost by real-time error compensation.

2 Thermal error testing

2.1 Sensor locations and experimental setup

Because the machining accuracy is decided by the accuracy of the relative movement between the cutting tool and the part, as Fig. 2 shows, a displacement sensor mounted on the cutter rest are used for the measurement of thermal drifts of the spindle and the axis origins, that is, measuring the errors of the relative movement between the cutting tool and the part in the x, y and z directions induced by temperature changes of the machine, here just taking the main dimension of the x direction as an example. There are scalar errors that change only with temperature and no relation with the position of the slides. These thermal errors or drifts include the spindle drift and all origin shifts that can be affected by the leadscrew expansion, the column distortion, the spindle tilt, etc.

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Fig. 1. INDEX-G200 turning center

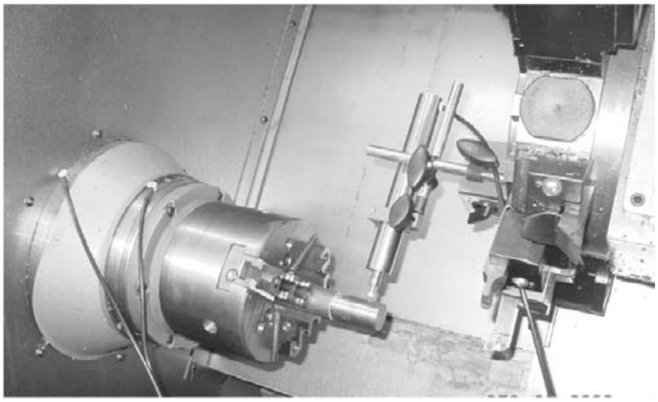

Fig. 2. Thermal error measurement

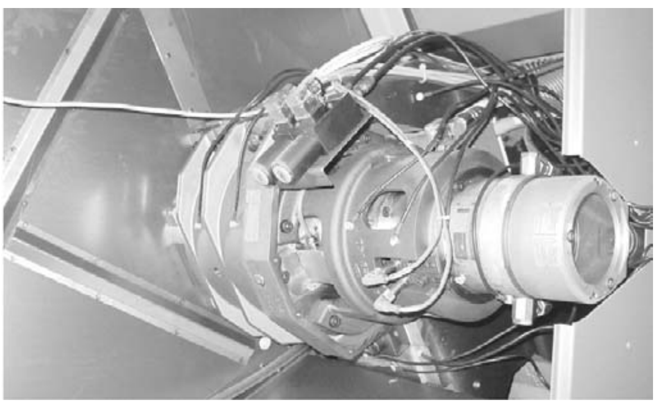

Fig. 3. Sensors on the back end of the spindle

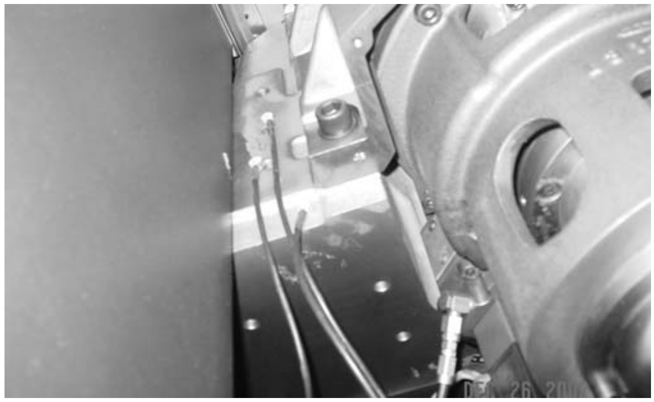

Fig. 4. Sensors on the spindle rest

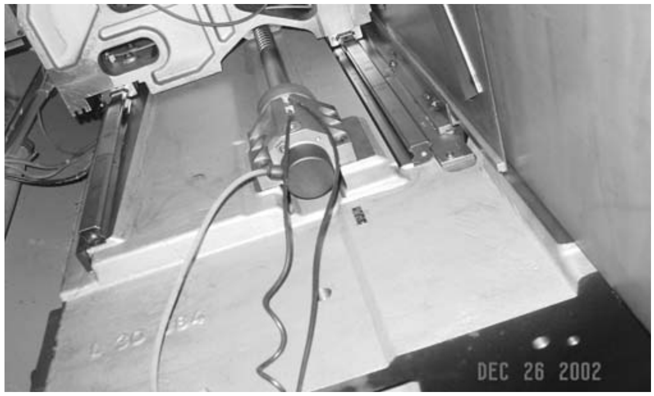

Fig. 5. Sensor on the x nut and leadscrew

In any system for thermal error compensation, thermal sensor location is critical. Whenever possible, the sensors should be placed directly on the structural elements undergoing thermal expansion and contraction. Because the spindle and the nut and leadscrew are the main thermal sources and affect the machining error a lot, the sensors are positioned as close as possible to the spindle and the nut and leadscrew. Figures 3–5 show that many thermal sensors are mounted separately on the spindle, the spindle rest, the x nut and leadscrew, etc., for detecting the temperature field in the main thermal part on the machine.

There are a total of fourteen thermal sensors installed on the machine. The locations of the thermal sensors can be divided into four groups as shown in Fig. 6:

1. Eight thermal sensors (numbers 1-6,13,14) for measuring the temperatures of the spindle
2. Four thermal sensors (numbers 7-10) for measuring the temperatures of the spindle rest
3. One thermal sensor (number 11) for measuring the temperatures of the x nut and leadscrew
4. One thermal sensor (number 12) for measuring the environment temperature

2.2 Thermal error experiment

First, an experiment was conducted to simulate the cycle of cutting parts. Initially the machine was run at working cycle for 1 h. Then the machine was cooled down for 10 min. After that, the machine was run for another 1 h, cooled down for 20 min, and again run for 1 h and cooled down for 30 min. A set of data was collected and recorded for every 2 min.

The thermal error and temperature histories measured by the sensors under working cycles are shown in Fig. 7a,b. Results disclose that:

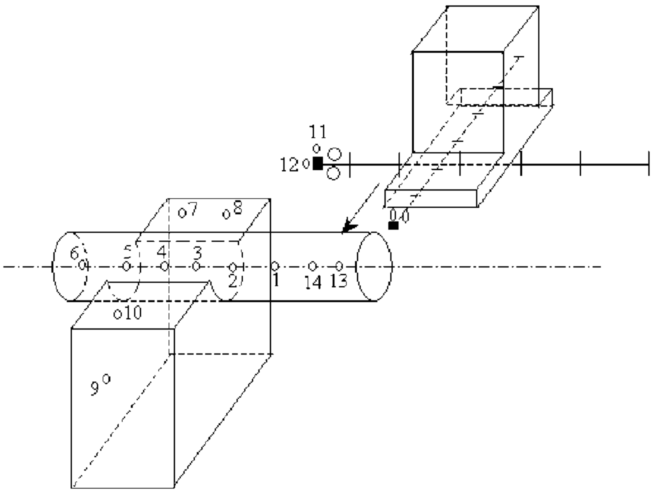

Fig. 6. Sketch map of the sensor locations of the thermal sensing system

1. Generally, the part radius increases with the machine temperatures decrease
2. The part radius changes with the machine temperature changing, but having some delaying
3. The thermal error range for radius direction is approximately within 18 μm, and larger than expected
4. The thermal error changes occur more and more slowly and become smaller and smaller over time because of near the period of the thermal balance. Based on these experiments, the correlation between each temperature readings at a measuring point and thermal error become clearer.

3 Optimal temperature variable selecting by grouping approach

3.1 Criterion for selecting the variables

A system output Y (thermal error) can be expressed as a function of system inputs T (temperature variables) with coefficients $\beta: Y = T\beta + \varepsilon$. In this study, the R_p^2-value (the coefficient of determination) shown in Eq. 1 is used as the criterion for selecting the variables in the thermal model:

$$R_p^2 = \frac{SSR}{SSTO} = 1 - \frac{SSE}{SSTO}\,, \tag{1}$$

where p is the number of independent variables, SSR is the squared sum of regression, $SSTO$ is the squared sum of total, SSE is the squared sum of residual, and they can be calculated as:

$$SSR = \sum (\hat{Y}_i - \bar{Y})^2\,, \tag{2}$$

$$SSTO = \sum (Y_i - \bar{Y})^2\,, \tag{3}$$

$$SSE = \sum (Y_i - \hat{Y}_i)^2\,. \tag{4}$$

3.2 Criterion for selecting the variables

By setting the threshold of the correlation coefficient as 0.95, a correlation grouping result is obtained and is listed in Table 1. Six temperature groups are constructed, and the temperature variables in the same group show similar thermal behaviors and are considered as dependent variables. The temperature variables in the different groups are independent variables.

The error model is assumed to be a linear function of rises from the environment temperature (T_{12}), and all the temperature variables used in the optimization searches are the temperature differences from the environment temperature. One variable is chosen in each group according to its correlation with the thermal error, which is measured by the displacement sensor, and

Table 1. Correlation grouping result

Group	1	2	3	4	5
Temp. variable	ΔT_1, ΔT_2, ΔT_3, ΔT_{13}	ΔT_4, ΔT_5, ΔT_6	ΔT_7, ΔT_8, ΔT_9, ΔT_{10}	ΔT_{11}	ΔT_{14}

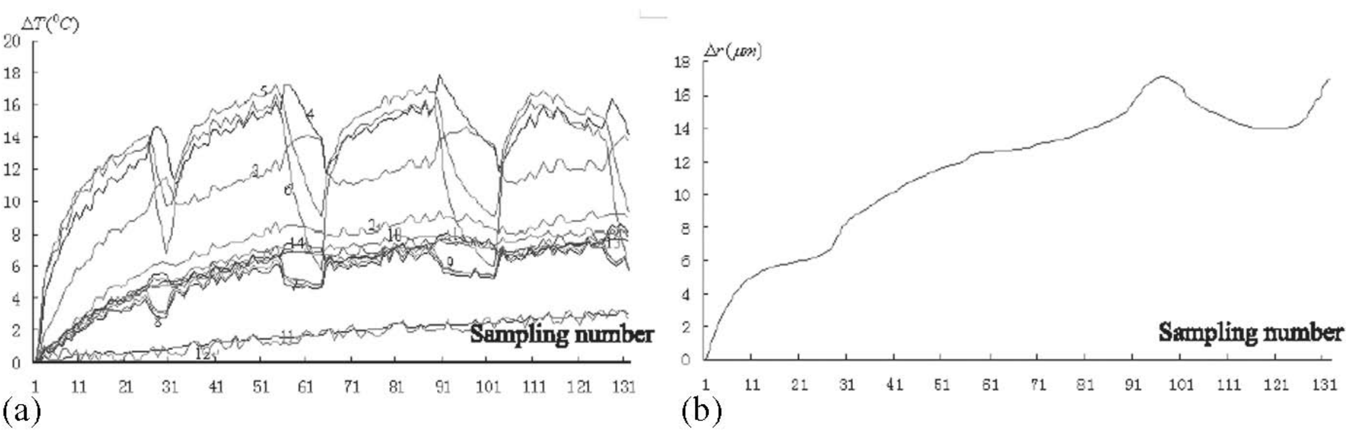

Fig. 7a,b. Testing of air cutting in working cycles **a** Temperature reading from 14 sensors **b** Thermal error between spindle and cutter rest

Table 2. Variation in coefficient of determination R_p^2

p	Variable grouping	R_p^2
1	ΔT_2, ΔT_4, ΔT_{10}, ΔT_{11}, ΔT_{14}	0.959, 0.832, **0.974**, 0.785, 0.791
2	ΔT_2, ΔT_2 & ΔT_{10}, ΔT_2 & ΔT_{11}, ΔT_2 & ΔT_{14}, ΔT_4 & ΔT_{10}, ΔT_4 & ΔT_{11}, ΔT_4 & ΔT_{14}, ΔT_{10} & ΔT_{11}, ΔT_{10} & ΔT_{14}, ΔT_{11} & ΔT_{14}, ΔT_{12} & ΔT_{14}	0.959, 0.974, 0.959, 0.969, 0.974, 0.914,0.872, 0.974, **0.977**, 0.877, 0.894
3	ΔT_2 & ΔT_{10}, ΔT_2 & ΔT_{11}, ΔT_2 & ΔT_{14}, ΔT_2 & ΔT_{10} & ΔT_{11}, ΔT_2 & ΔT_{10} & ΔT_{14}, ΔT_2 & ΔT_{11} & ΔT_{14}, ΔT_4 & ΔT_{10} & ΔT_{11}, ΔT_4 & ΔT_{10} & ΔT_{14}, ΔT_4 & ΔT_{11} & ΔT_{14}, ΔT_{10} & ΔT_{11} & ΔT_{14}	0.974, 0.959, 0.969, 0.975, **0.980**, 0.970, 0.975, 0.978,0.923, 0.977
4	ΔT_2 & ΔT_{10} & ΔT_{11}, ΔT_2 & ΔT_{10} & ΔT_{14}, ΔT_2 & ΔT_{11} & ΔT_{14}, ΔT_2 & ΔT_{10} & ΔT_{11} & ΔT_{14}, ΔT_4 & ΔT_{10} & ΔT_{11} & ΔT_{14}	0.975, 0.980, 0.974, **0.981**, 0.978
5	ΔT_2 & ΔT_{10} & ΔT_{11} & ΔT_{14}	**0.981**

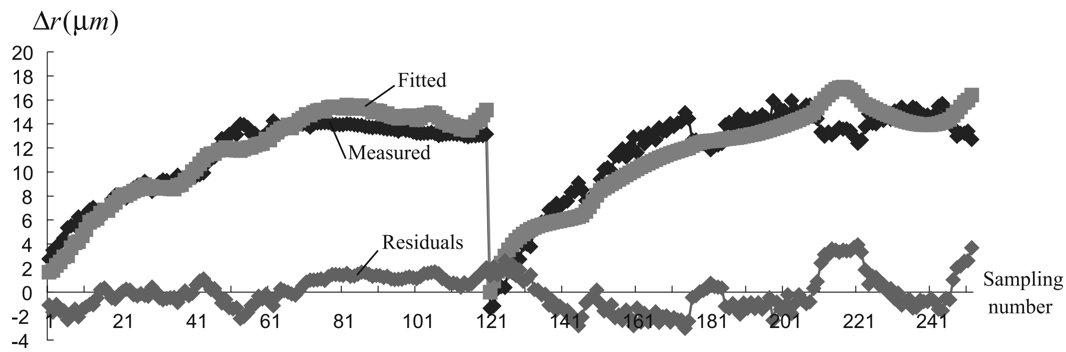

Fig. 8. Model result of the thermal error

they are ΔT_2 (the temperature change at middle of spindle), ΔT_4 (the temperature change at back of spindle), ΔT_{10} (the temperature change at spindle rest), ΔT_{11} (the temperature change at x nut and leadscrew) and ΔT_{14} (the temperature change at front of spindle). All the combinations of the temperature variables in the five candidate groups are scanned. The variation of R_p^2 for each case is represented in Table 2. From the table, it can be seen that the best combination of temperature variables for the optimal thermal error model is ΔT_2, ΔT_{10}, ΔT_{11}, and ΔT_{14} because the combination has the least number of the temperature variables under the condition of the biggest value of R_p^2.

4 Thermal error modeling

After the appropriate temperature variables of ΔT_2, ΔT_{10}, ΔT_{11}, and ΔT_{14} are found, the optimal thermal error model is given as below:

$$\Delta r = 1.157\Delta T_2 + 2.867\Delta T_{10} - 0.927\Delta T_{11} - 1.959\Delta T_{14} - 1.353\,. \quad (5)$$

A comparison between the measured error data and the predicted values using the model is represented in Fig. 8. It can be observed that the model describes the error very well, and the modeling error is smaller than 5 μm, so a more accurate thermal model is obtained.

5 Conclusions

1. The thermal error range for radius direction on this precision INDEX-G200 turning center is approximately 18 μm, which is much larger than we expected. The thermal error is the major error source for the machine and should be considered seriously by machine builders and users.
2. The R_p^2-value method is one of the grouping approaches for selecting the best combination of temperature variables, by which the thermal error model can be set accurately and quickly with fewer temperature variables.
3. The machining accuracy of the machine can be improved largely by real-time error compensation.

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