

# COMPENSATORY CONTROL OF THERMAL ERRORS FOR HIGH-SPEED MACHINE TOOLS

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**Abstract:** Objective of this paper is the development of a real-time thermal error compensator for high-speed machine tools. A vertical type high-speed machine tool having a slant column with lightweight moving slides is used to investigate thermal characteristics. The high-speed machine tool has a large thermal drift error within a few minutes. The thermal time constant is only 3~4 minutes at the spindle speed of 25000rpm. Due to tooling problems of the high-speed spindle, the axial offset errors are also appeared in machined specimens. If-Then rules and thermal mode approaches are applied to remove defects of test specimens. The developed real-time thermal error compensator has the compensation period that is adequate for thermal characteristics of high-speed machine tools. The accuracy of machined surface is improved from  $70\mu\text{m}$  to less than  $10\mu\text{m}$ .

**Keywords:** Accuracy, Axial offset, Compensatory control, High-speed machine tool, Thermal error, Thermal mode, Thermal time constant.

## 1. Introduction

High-speed machining (HSM) has been attracting interests for many years. Recently, the demand of HSM is increasing in the aircraft industry, automotive industry, die and mold makers, etc. Objectives of the HSM are improvement of surface quality and machining accuracy as well as achieving higher productivity. For these purposes, researches have been continued mainly on the viewpoint of cutting mechanics, cutting tools and machine tools [1-4]. However, there are still many problems to be resolved in the application of the HSM. Current problems include issues of tooling, balancing, thermal behaviors, and reliability of machine tools.

In this paper, thermal characteristics of a high-speed machine tool (HSMT) are investigated through cutting performance tests. The machined specimen has two features that can't be found in conventional machine tools. If-Then rules and thermal mode approaches are applied to remove defects of the test specimen. A real-time thermal error compensator is implemented on an industrial computer. Compensation period of the error compensator is determined to be adequate for thermal characteristics of the HSMT. The accuracy of machined surface is improved from  $70\mu\text{m}$  to less than  $10\mu\text{m}$  with the compensatory control action.

## 2. Thermal characteristics of the HSMT

As shown in Fig. 1, the vertical type HSMT having a slant column with lightweight moving slides is used for experiments. Its maximum feed rate is 60 m/min. A spindle with ceramic ball bearings is directly connected to the spindle motor through a coupling. The spindle speeds up to 25,000 rpm.

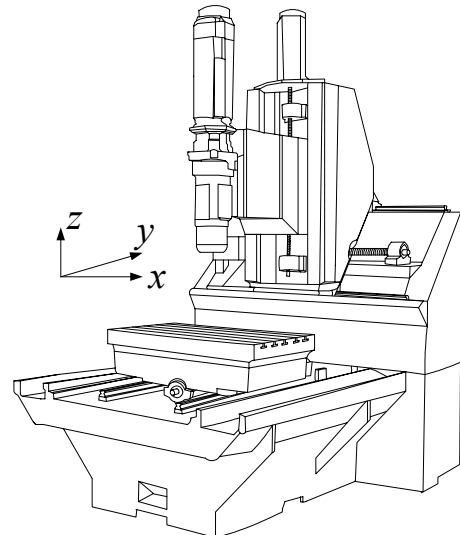
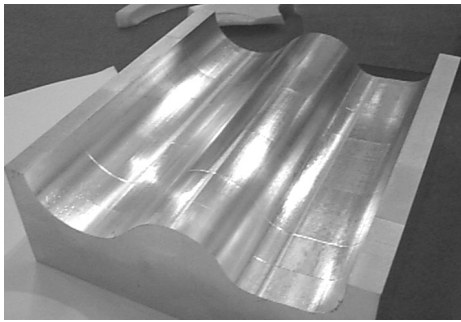


Fig. 1 Vertical high-speed machine tool.

Machining tests with various spindle speeds are performed to investigate thermal characteristics of the HSMT. Table 1 shows the cutting conditions.

Table 1 Cutting conditions.

No.	Spindle speed [rpm]	Cutting width [mm]	Cutting time [min]	Cutting feed [mm/min]
1	5,000	5	11.8	1000
2	20,000	30	30.6	4000
3	10,000	20	29.4	2000
4	25,000	35	32.5	5000
5	15,000	30	35.1	3000
6	5,000	15	35.5	1000
7	20,000	15	15.3	4000
Total		150	190.2	-
Material		Al6061		
Cutting tool		R3.0 ball-endmill 2-teeth, TiAlN coating		
Coolant		Oil Mist		
Cusp		0.42 $\mu$ m		



(a) Machined specimen



(b) Z-axis

Fig. 2 Result of machining test.

As shown in Fig. 2, the machined specimen has two features that can't be found in conventional machine tools: (1) Discontinuous marks like steps are produced where the spindle speeds are changed. This feature is related with tooling problems of the HSMT adopting the National Taper shank. Centrifugal forces resulted from the high-speeds cause radial expansion of the spindle cone, so that the tool axially displaces itself by the clamping force. The maximum axial offset error is about 40  $\mu$ m at the spindle speed of 25,000 rpm. There are nonlinear and hysteretic relationships between the spindle speed and the axial offset. In order to eliminate this discontinuity of test specimens, If-Then rules are proposed to estimate the axial offsets according to the arbitrary spindle speeds. (2) The thermal growth curve

according to the spindle speed is an exponential form. Due to the high heat dissipation of the high-speed spindle, thermal errors between two discontinuous points are over 80  $\mu$ m at the spindle speed of 25,000 rpm. This amount of thermal error is beyond the acceptable range of the precision machining. However, the high power cooling units quickly stabilizes the thermal drift errors. It is noted that 95% of thermal drift errors are occurred within 8 minutes at the spindle speed of 25000rpm. Therefore, the HSMT has larger thermal drift errors and much shorter thermal time constants than conventional machine tools. In order to predict thermal drifts of the cutting tool edge, the thermal mode analysis method is applied to the HSMT.

### 3. Thermal error modeling

#### 3.1 Modeling of axial offset errors

Fig. 3 shows the axial offsets with respect to various spindle speeds.

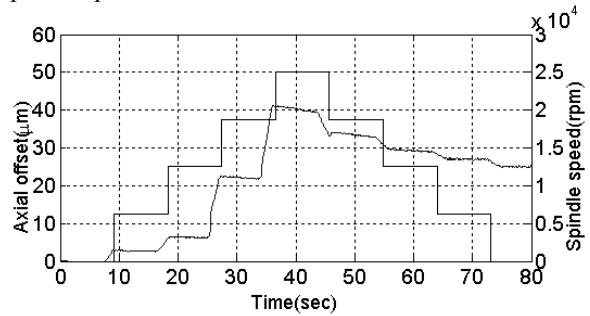


Fig. 3 Example of axial offset errors.

As shown in Fig. 3, there is a residual offset error even if the spindle is stopped. The residual offset is closely related with the maximum spindle speed. The axial offset errors can be modeled with the following If-Then rules.

Rule 0: The maximum spindle speed  $r_{max}$  is continuously updated according to the change of spindle speed.

Rule 1: The axial offset error corresponding to the maximum spindle speed,  $\delta_{max}$ , can be expressed as an second order polynomial function.

Rule 2: The residual offset  $\delta_{rsd}$  can also be expressed as an second order polynomial function.

Rule 3: The axial offset error according to the spindle speed between the maximum and the zero spindle speed,  $\delta_c$ , can be calculated by using the linear interpolation method between  $\delta_{max}$  and  $\delta_{rsd}$ .

Fig. 4 shows the flow chart for estimating the axial offset errors based on the above rules.

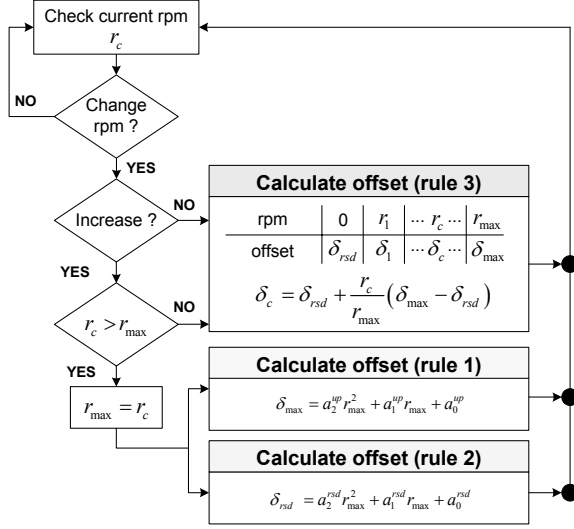


Fig. 4 Flow chart to estimate axial offsets.

### 3.2 Modeling of thermal drift errors

Thermal mode analysis method [5,6] is applied to the vertical type HSMT. Fig. 5 shows the considered thermal modes for modeling Z-axis thermal drifts.

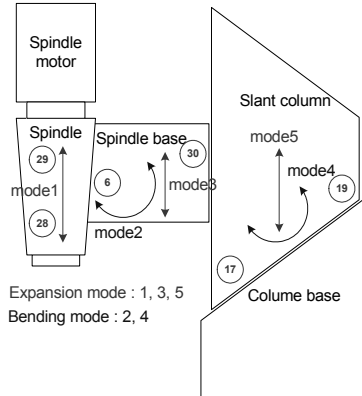


Fig. 5 Thermal modes in Z-axis thermal drifts.

Thermal drifts at the cutting tool edge are modeled as the superposition of thermal expansion and bending modes of each machine component such as a spindle, spindle base and slant column. And, each thermal mode is correlated with temperatures of the corresponding component through a thermal mode gain as follows:

$$\delta_z = G_{\text{exp}}^{\text{spindle}} T_{\text{avg}}^{\text{spindle}} + G_{\text{exp}}^{\text{s.base}} T_{\text{avg}}^{\text{s.base}} + G_{\text{bend}}^{\text{s.base}} T_{\text{diff}}^{\text{s.base}} + G_{\text{exp}}^{\text{column}} T_{\text{avg}}^{\text{column}} + G_{\text{bend}}^{\text{column}} T_{\text{diff}}^{\text{column}} \quad (1)$$

where, the subscripts *avg* and *diff* mean the average and difference values of two thermocouples, respectively.

In order to determine thermal mode gains, the air cutting tests with various spindle speeds are performed and the non-linear least square fitting method is applied.

## 4. Implementation of real-time error compensator

The thermal behavior for a specific spindle speed is exponential in nature. As shown in Fig. 6, the compensation process is performed periodically based on a compensation period. If the compensation amount per each compensation period is large, the compensatory control action will leave defects on machined surface such as a scratch or steps.

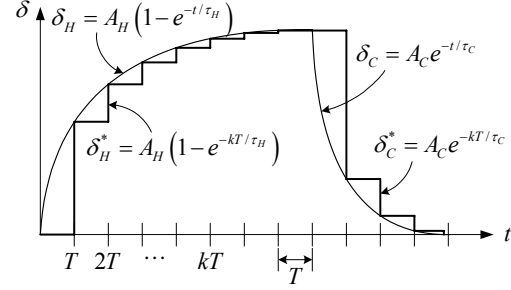


Fig. 6 Periodic compensation processes.

Therefore, in order to prevent deterioration of surface quality due to the compensatory control, the compensation amount per each period must be less than 1 BLU. In this paper, the compensation period of the real-time thermal error compensator is determined from the maximum amount of thermal errors and time constants as follows:

$$T = \min \left\{ -\tau_H \ln \left( 1 - \frac{1}{A_H} \right), -\tau_C \ln \left( 1 - \frac{1}{A_C} \right) \right\} \quad (2)$$

Since the thermal time constant is small and the maximum amount of thermal error is large, the compensation period for high-speed machine tools is very small relative to that for conventional machine tools.

The estimation model for calculating thermal drift errors is directly related to the sampled temperatures as shown in Eq. (1). Therefore, noises included in temperature data will be amplified by thermal mode gains and significantly deteriorate the surface roughness. The moving average method and digital filter theory are applied to eliminate this phenomenon.

Developed real-time thermal error compensator is realized on an industrial computer. Fig. 7 shows a flow chart for compensatory control of thermal errors. Compensation signals generated on the basis of spindle speeds and temperatures of machine components are transferred to the PLC of the machine tool. The CNC recognizes the compensation signal as the change of the work origin and modifies the current position.

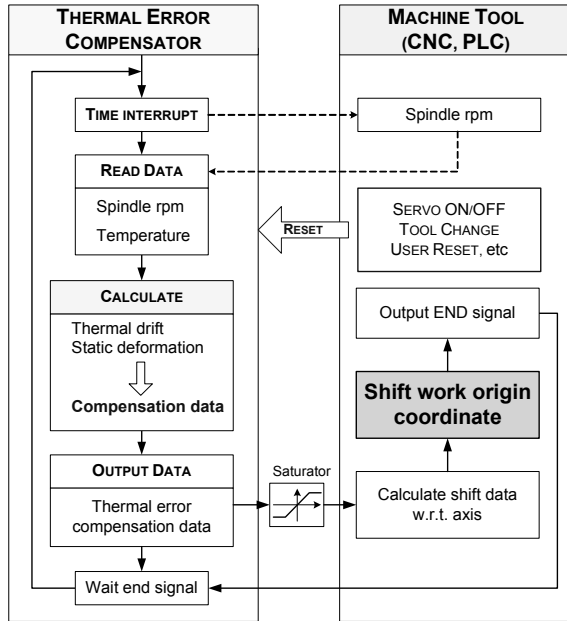


Fig. 7 Flow chart for compensatory control.

## 5. Cutting performance tests

The efficiency and validity of the developed system are verified through the machining of free-form surfaces with and without compensation. The cutting conditions are equal to the machining test described in Section 2. Fig. 8 shows the results. The accuracy of the specimen is improved from 70  $\mu\text{m}$  to less than 10  $\mu\text{m}$ .

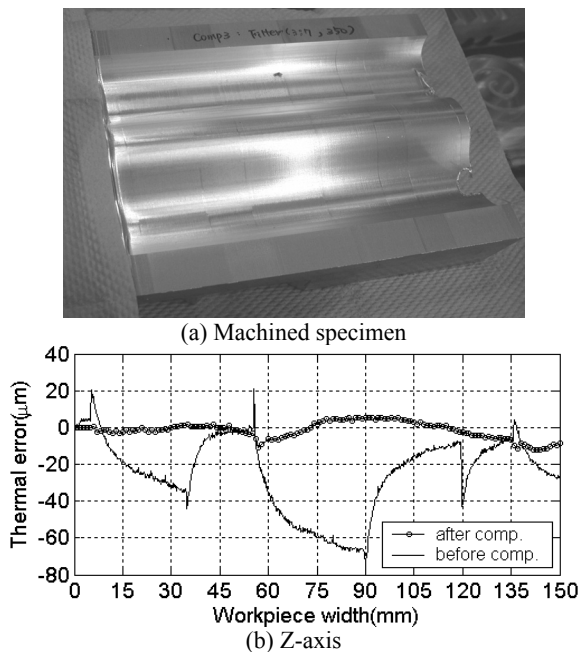


Fig. 8 Compensation result.

## 6. Conclusions

A vertical type HSMT having a slant column with lightweight moving slides is used to investigate thermal characteristics. Following conclusions are obtained:

1. Due to the high heat dissipation of a spindle and the use of high power cooling units, the HSMT has a large thermal drift error within a few minutes. The thermal time constant is only 3~4 minutes at the maximum spindle speed.
2. The axial offset errors resulted from the tooling problem of the HSMT produce defects like steps on the machined surface. There are nonlinear and hysteretic relationships between the spindle speed and the axial offset.
3. If-Then rules and thermal mode approaches are applied to predict axial offsets and thermal drifts. Thermal drifts at the cutting tool edge are modeled as the superposition of thermal expansion and bending modes of each machine component.
4. The developed real-time thermal error compensator has the compensation period that is adequate for thermal characteristics of the HSMT. The accuracy of machined surface is improved from 70  $\mu\text{m}$  to less than 10  $\mu\text{m}$  with the compensatory control.

## Acknowledgement

The authors would like to acknowledge the financial supports of the HWACHEON Machinery Works, LTD.

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