Development of Real-Time Thermal Displacement Compensation System for Machining Centers[*1]

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The thermal displacement of machine tools due to environmental temperature change causes machining errors. To compensate thermal displacement, we have developed a fast and accurate method for estimating thermal displacement based on FEM using the temperature obtained by the sensors attached to the machine tool. Machining errors due to the thermal displacement on horizontal machining centers equipped with this system were able to be reduced by 80% or more in an environment where the room temperature varies by 20°C.

***Key Words**: machine tool, thermal displacement, displacement compensation, real-time, FEM*

1. Introduction

In recent years, players in the manufacturing industry have been expanding their production in global bases and there is a demand for production technologies enabling the same quality to be obtained anywhere in the world. One major factor inhibiting stable machining quality is the thermal displacement of processing machines. The mechanical structures of machining centers and other machine tools undergo thermal deformation when the room temperature of the environment in which they are installed changes. As a result, the relative position between the tool and workpiece changes and machining accuracy deteriorates. Various measures exist in order to prevent deterioration of machining accuracy caused by thermal displacement, such as installing the machine tool in a thermostatic chamber, making the temperature distribution of the machine's mechanical structures constant by using coolant, etc. or fabricating the mechanical structures out of low-thermal expansion material. However, such measures to suppress thermal displacement all lead to an increase in manufacturing and running costs and are also not ideal from the perspective of energy conservation.

Meanwhile, there is a method to secure machining accuracy by allowing a certain extent of thermal displacement and compensating it with NC control. This measure requires an evaluation of the thermal displacement amount at the machining point and comprises two techniques; one based on actual measurement1) and another based on estimation. **Figure 1** summaries the method for assessing thermal displacement. Making a measurement of actual thermal displacement cannot be considered realistic as it is difficult to stabilize thermal displacement and continue measurement during the machining process. Although normally an additional sensors are required to estimate thermal displacement, it is possible to implement a function to estimate thermal displacement primarily using software. For this reason, the method of compensating thermal displacement based on estimating the thermal displacement at the machining point is able to suppress an increase in manufacturing and running costs compared to methods involving suppression of heat displacement and, as such, can be considered an ideal method.

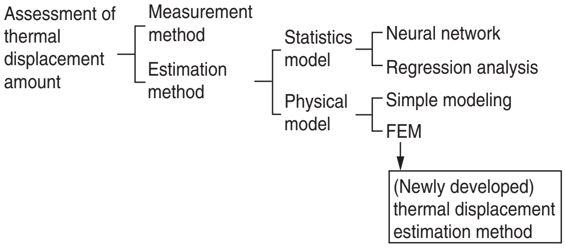

Fig. 1 Acquisition method of thermal displacement

There are two methods for estimating thermal displacement; the method that uses a statistics model and the method that uses a physical model. A typical example of the statistics model is to use the temperature data and displacement data collected in advance to build a model in accordance with the methods known as neural network and regression analysis and estimate thermal displacement

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based on this model[2-5]. The method of estimating thermal displacement using the physical model consists of performing simple modeling of mechanical structures and analytically estimating thermal displacement[6]. Although thermal displacement can be estimated with good accuracy using either of these methods for specific conditions and environments, they cannot necessarily guarantee a thermal displacement estimation with good accuracy under any circumstances.

Other methods that have been proposed for estimating thermal displacement using the physical model include using finite element method (FEM) to measure the actual ambient temperature of the environment in which a machine tool is located then use thermal analysis to find the temperature distribution of the mechanical structure and hence analyze deformation[7] as well as the method of actually measuring the mechanical structure to find the temperature at a representative point, interpolating this to find temperature distribution then analyzing deformation[8]. These methods, however, are not suitable for practical application due to the difficulty of setting thermal analysis conditions and the tremendous amount of FEM calculation that would be required.

As such, the authors devised a method of estimating thermal displacement based on FEM but at the same time equipping a machine tool's CNC with the ability to compensate thermal displacement in real-time, thus building a real-time thermal displacement compensation system. A horizontal machining center equipped with the developed system was installed in an environmental test chamber and an evaluation of machining with a room temperature varying by 20℃ was performed. As a result, we confirmed that the developed system makes it possible to reduce machining error in the Z direction by 80% or more.

2. Thermal Displacement Estimation Method

Generally-speaking, the mechanical structure of a machine tool is a complex shape, therefore in order to find thermal displacement with good accuracy through deformation analysis using FEM, many nodes must be established in the FEM model which increases the time it takes to perform analysis. Meanwhile, in order to compensate the relative displacement of tools and workpieces which varies due to the gradual change in room temperature, it is necessary to update the compensation value at a regular interval. For this reason, even for FEM models which require a high number of nodes, thermal displacement must be calculated in a short period of time. Moreover, it is difficult to find the temperature distribution of a mechanical structure using thermal analysis from the ambient temperature, however in order to use the measured temperature of the mechanical structure it is necessary to measure the temperature at all nodes of the FEM model and this is not realistic. Furthermore, the system must be compact in order to fit into a CNC with limited memory. As such, the authors devised the two below methods as solutions to these issues.

2. 1 Estimation method using measured temperature through area temperature equalization

As mentioned above, in order to compute the thermal deformation of a structure using FEM it is necessary to collect temperature information for model nodes numbering between tens of thousands and hundreds of thousands, therefore it is realistically impossible to measure this by using tens of thousands of temperature sensors on an actual machine. As such, there is a need for a technology that can compute the thermal deformation of the processing machine overall even with a limited number of sensors.

In light of this, we devised an analysis method whereby the structure is partitioned into several areas considering thermal characteristics and the nodal temperature within each area is treated as being equal. The nodal temperature of each zone is set based on actual measurement using a temperature sensor. Area partitioning and temperature sensor arrangement is determined by referring to the transient thermal analysis. **Figure 2** shows the basic concept of this method using the simplified model of a horizontal machining center column as an example.

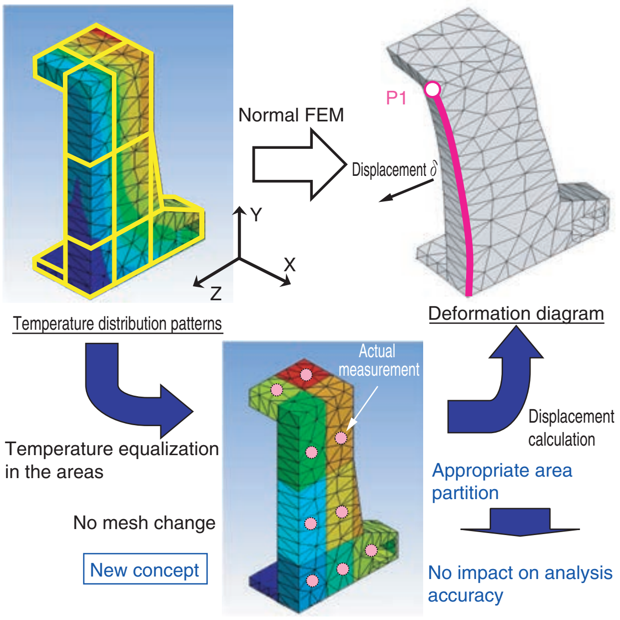
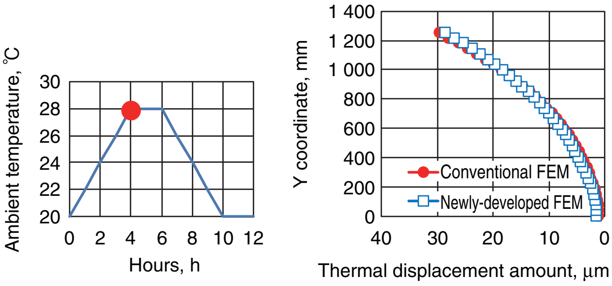


Fig. 2 Basic concept of thermal displacement estimation logic

Under a condition of the ambient temperature of the simplified model for the machining center column shown in **Fig. 2** changing by 8℃ over four hours, **Fig. 3** is a graph which takes the results of a deformation analysis with the temperature distribution obtained in a normal transient thermal analysis and the results of calculation with the newly-developed method of area temperature equalization to compare the Z-direction displacement of point P1 in **Fig. 2**. The graph shows that there is practically no difference even when making a comparison of the amount of thermal displacement at each node when four hours has passed, which is when thermal deformation is greatest. Moreover, the data itself is omitted, but over the entire time, it was confirmed that calculation was possible with a difference of ±1 μm.



(a) Ambient temperature

(b) Estimated value of thermal displacement

Fig. 3 Comparison of thermal displacement estimated values

In this way, actual thermal distribution is complicated, but it was confirmed as a result of finding the appropriate minimal area partitioning and sensor arrangement to maintain estimation accuracy, that estimation accuracy could be maintained even if temperature distribution was significantly simplified.

Using this method, not only is it possible to estimate thermal displacement with good accuracy while using a limited number of temperatures actually measured but, as explained in the following section, it is also possible to significantly reduce data capacity and calculation time using thermal displacement calculation.

2. 2 High-speed, high-accuracy thermal displacement calculation program

In order to calculate the thermal displacement of a machine tool that changes gradually over time then compensating this in real-time using the CNC of a machining center, it is necessary to maintain the abovementioned calculation accuracy at the same time as using a technology to significantly reduce the data capacity required for calculation and calculation time.

When utilizing FEM for structural analysis, etc. based on the obtained results, the model shape, etc. is corrected, then the analysis is repeated until satisfactory performance is obtained. For this reason, rather than seeking the inverse stiffness matrix which would require large-scale calculation, it is commonplace to find the displacement amount at each node from the Gaussian elimination method as a simultaneous linear equation.

In contrast, we have developed the below new technique for continuous high-speed calculation specifically customized to thermal deformation analysis. **Figure 4** shows the actual calculation method using an FEM model with around 20 000 nodes (approx. 60 000 degrees of freedom) partitioned into 26 areas.

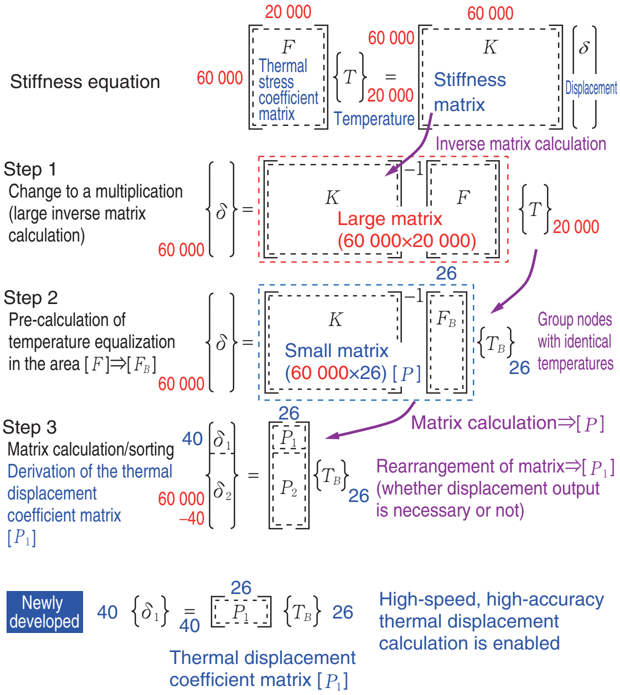


Fig. 4 Developed method for enabling high-speed calculation

[Step 1]

In the deformation analysis using FEM, nodal displacement is found by solving the following stiffness equation.

$$\{f\} = [K]\{\delta\} \tag{1}$$

However, $\{f\}$ is the external force vector, $[K]$ is the stiffness matrix and $\{\delta\}$ is the nodal displacement vector. External force other than thermal stress caused by nodal temperature change is not taken into consideration therefore the external force vector $\{f\}$ is the product of the thermal stress coefficient matrix $[F]$ and nodal temperature vector $\{T\}$, and Equation (1) is expressed by the following type of equation.

$$[F]\{T\} = [K]\{\delta\} \tag{2}$$

Calculation of the thermal displacement amount in the thermal displacement compensation system involves repeating calculation using the same FEM model as the mechanical structure does not change. Here, it is possible to calculate in advance the stiffness matrix $[K]$ and inverse matrix $[K]^{-1}$, which are determined by the shape and material of the structure alone, as well as the thermal stress coefficient matrix $[F]$, and Equation (2) is expressed by the following type of equation.

$$\{\delta\}=[K]^{-1}[F]\{T\} \tag{3}$$

As a method to find displacement from measured temperature using Equation (3), though prior research[9)10)] does exist, this research succeeds at finding thermal displacement through Step 2 and 3 below even if there are a significantly lower number of temperature measurement points than the number of nodes on an FEM model.

[Step 2]

The nodal temperature within the partitioned areas is equalized, therefore the area temperature vector $\{T_B\}$ is used to substitute the nodal temperature vector $\{T\}$. By doing this, of the components of the thermal stress coefficient matrix $[F]$, it is possible to find the components which correspond to the nodes within identical areas. As a result, the number of rows for the thermal stress coefficient matrix $[F]$ is the same as the number of lines for the area $[F_B]$, and Equation (3) is expressed by the following equation.

$$\{\delta\}=[K]^{-1}[F_B]\{T_B\} \tag{4}$$

For this example, the number of components $\{T_B\}$ and number of rows $[F_B]$ are both 26. If the thermal displacement coefficient matrix $[P]$ is made

$$[P]=[K]^{-1}[F_B] \tag{5}$$

then Equation (4) would be expressed by the following equation.

$$\{\delta\}=[P]\{T_B\} \tag{6}$$

[Step 3]

According to Equation (6), the nodal displacement is found by multiplying the thermal displacement coefficient matrix $[P]$ and area temperature vector $\{T_B\}$. In Equation (6), the displacement amount for the X, Y and Z directions of all nodes is obtained however only a small portion of the nodal displacement is necessary to estimate the thermal displacement amount at the machining point. Here, the following equation is used to express the necessary nodal displacement as $\{\delta_1\}$ and the unnecessary nodal displacement as $\{\delta_2\}$, thus sorting the components of Equation (6),

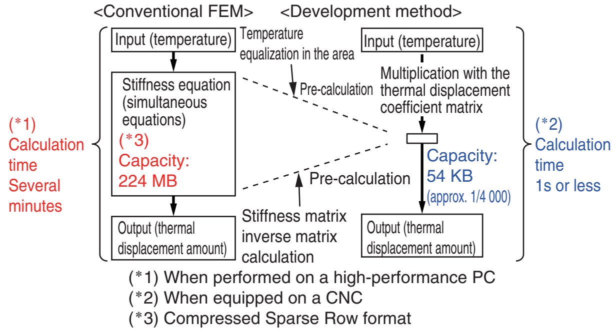
$$\begin{Bmatrix}\delta_1\\ \delta_2\end{Bmatrix}=\begin{bmatrix}P_1\\ P_2\end{bmatrix}\{T_B\} \tag{7}$$

When the components related to the necessary nodal displacement are extracted from this equation then,

$$\{\delta_1\}=[P_1]\{T_B\} \tag{8}$$

is established. In the example used here, thermal displacement coefficient matrix $[P_1]$ is a compact matrix of 40 multiplied by 26, and the area temperature vector $\{T_B\}$ is 26 components therefore the nodal displacement necessary to estimate the thermal displacement at the machining point $\{\delta_1\}$ can be found using an extremely minimal calculation in accordance with Equation (8).

As shown in **Fig. 5**, if this method is used, it is possible to calculate the relationship between temperature change and thermal displacement in advance despite using a large model therefore a calculation using the conventional FEM that would take several minutes to process even on a high-performance PC can be processed instantly in a CNC.



(*1) When performed on a high-performance PC
(*2) When equipped on a CNC
(*3) Compressed Sparse Row format

Fig. 5 Comparison between developed method and conventional FEM

3. Experimental Verification

3. 1 Equipping on actual machine

Figure 6 shows the configuration of a real-time thermal displacement compensation system.

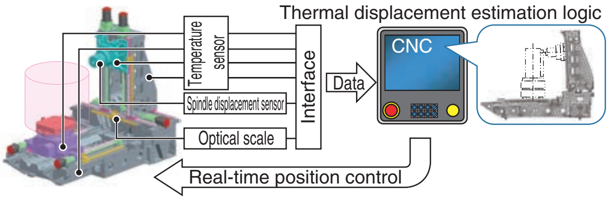


Fig. 6 Real-Time thermal displacement compensation system

Based on the temperature data measured with the temperature sensors located on various parts of the machine and an FEM model of the machine, the amount of thermal displacement is calculated in the CNC and the relative thermal displacement for the tool and workpiece at each coordinate within the axial travel space is found. The axial travel amount is compensated to account for this as the static special error of the linear axis. The amount of compensation is updated at a set interval.

The developed real-time thermal displacement compensation system was equipped on FH630SX-i horizontal machining center[11).

3. 2 Machining evaluation

The FH630SX-i equipped with the developed system was installed in an environmental test chamber and a machining evaluation was performed. Temperature in an average plant in Japan varies by 5℃ to 10℃ throughout the duration of one day but, as **Fig. 7** shows, the experiment evaluated a tough temperature pattern whereby the room temperature changed by 20℃ over four hours in order to take account of overseas plants located in severe environments where the temperature change is significantly large. The machining evaluation method was as described below.

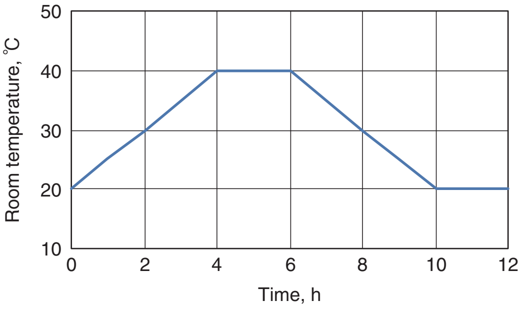
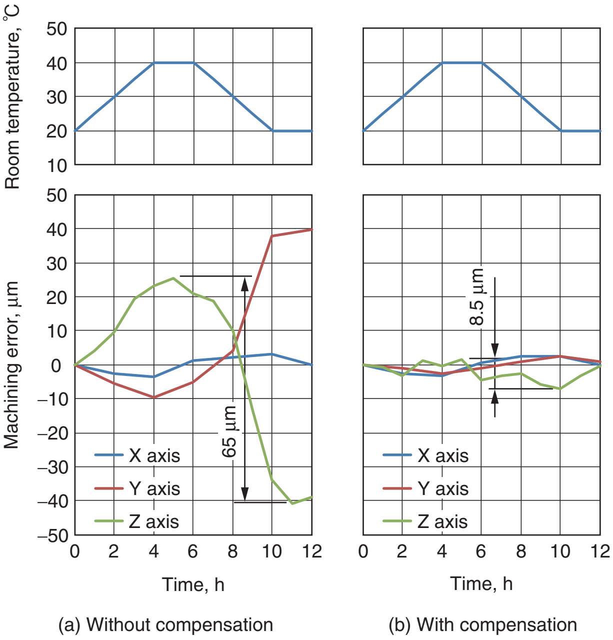


Fig. 7 Temperature change during machining evaluation

For the X and Y directions, the point where the room temperature began to change was made 0 and contouring of an ϕ8 hole was performed on a test-piece every two hours. After machining was completed and the room temperature became sufficiently stable at 20℃, the center of the machined hole in the test piece was measured on a CMM and the difference with the center of the hole machined at time increment 0 was established as the machining error due to the thermal displacement in the X and Y directions at each time increment.

For the Z direction, the point where the room temperature began to change was made 0 and plane processing was carried out in the Y direction every hour. After machining was completed and the room temperature became sufficiently stable at 20℃, the Z direction height of the machining face was measured using a non-contact displacement gauge mounted to the end of the spindle after the spindle was scanned, and the difference with the machined face height at time increment 0 was made the machining error due to the thermal displacement in the Z direction at each time increment.

Figure 8 shows the machining error in the X, Y and Z directions on the test-piece that was machined both with and without real-time thermal displacement compensation. In contrast to a maximum machining error in all directions (X, Y and Z) of 65 μm when there is no compensation, the machining error could be suppressed to 8.5 μm or less if compensation was applied, and it is possible to obtain stable machining accuracy even in an environment where the room temperature changes as much as 20℃.



(a) Without compensation (b) With compensation

Fig. 8 Comparison of machining errors

4. Conclusion

The authors devised a method to estimate thermal displacement based on FEM but with the ability to calculate displacement at high-speed when equipped on a CNC then developed a real-time thermal displacement compensation system which incorporated the said method. The FH630SX-i horizontal machining center equipped with this system was installed in an environmental test chamber and a machining evaluation was carried out under the condition of the room temperature changing 20℃ over four hours. As a result, it was confirmed that stable machining accuracy could be obtained even amidst a fluctuating room temperature.

Moving forward, we plan to gradually equip other models with this system.

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