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Thermal displacement reduction and compensation of a turning center

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ABSTRACT

Temperature variation within a machine tool structure caused by heat transfer between ambient environment and the structures thermally deforms the machine tool. Thermal sensitivity analysis was performed on a turning center to investigate how the temperature variation within the machine structure contributes to the thermal displacement. Based on the results from the sensitivity analysis, geometry of thermally sensitive section of the machine structure was improved to build more thermally robust machine. The thermal displacement compensation method using deep-learning from temperature sensors installed on the turning center and thermal displacement behavior is also presented.

Introduction

Accuracy is the most essential property of machine tool. Thermal deformation has significant effects on the machining accuracy. Under the machining operation, internal and external heat source of machine tool and its change are the main factor that degrades the accuracy. Much research has been carried out on this topic. However, not many good results were gained in practice.

In recent years, due to lack of labor force in the manufacturing industry, automation and robotized work transportation systems have been required for unmanned or reduced personnel factory. For continuous operation by this automation, it is important to suppress the deterioration of accuracy due to thermal deformation, and technique to successfully suppress thermal displacement is required. Against this issue, various thermal displacement control technics by cooling and compensation have been developed [1,2]. For example, the method using thermal sensors [3–5], prediction from the NC unit internal data [6] and prediction by neural networks [7] were developed. In the development of artificial intelligence technologies, including deep-learning in recent years, has made image recognition more accurate [8,9].

In this paper, thermal sensitivity analysis was applied to a turning center and the result is visualized to express the relationship between the temperature variation and thermal deformation of the machine structure as a transfer function. The thermal displacement due to the ambient temperature variation around the machine tool can be predicted by using the temperature sensors attached to the high thermal sensitivity places. Subsequently, convolutional neural network (CNN) was applied to predict machine tool thermal displacement. Better performance prediction was realized than ridge regression by CNN. Furthermore, to improve the performance of the model, it was possible to realize a model with good performance by measuring the temperature variation and thermal displacement of multiple turning centers and using them as learning data. The results showed that CNN thermal displacement compensation may have 76.4%–90.8% improved thermal displacement of turning center.

Thermal sensitivity analysis

Contribution to thermal displacement by temperature variation

To understand and compensate thermal displacement, it needs to know the relationship between thermal displacement and temperature variation. Conventionally, the amounts of thermal deformation and temperature have been calculated and analyzed in detail by finite element method (FEM) [10,11]. However, FEM requires many computational resources and it has been difficult to quantitatively calculate the contribution to thermal deformation and to evaluate which part of the structure affects thermal deformation. Therefore, we developed a method to obtain the relation between the temperature variation of the mechanical structure and the thermal deformation as a transfer function. By defining the transfer function as thermal sensitivity, this method can evaluate the contribution of the temperature variation of the structure to the thermal displacement.

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Mathematical modeling

When a load p_T due to a temperature variation is applied to the mechanical structure, displacement u is generated. This relationship is generally described by:

$$ku = p_T \tag{1}$$

where k is stiffness of the structure. Eq. (1) can be expressed in a matrix notation for multi degree of freedom system as:

$$\boldsymbol{Ku} = \boldsymbol{p_T} \tag{2}$$

where $\boldsymbol{K}$ is a stiffness matrix determined by the structural shape and material. Meanwhile, relationship between load $\boldsymbol{p_T}$ generated by temperature variation $\boldsymbol{\Delta t}$ can be expressed as the temperature-load transformation matrix $\boldsymbol{H}$:

$$\boldsymbol{p_T} = \boldsymbol{H\Delta t} \tag{3}$$

Therefore, the relation between the temperature variation $\boldsymbol{\Delta t}$ and the displacement $\boldsymbol{u}$ is expressed by substituting Eq. (3) into Eq. (2) as:

$$\begin{aligned}\boldsymbol{u} &= \boldsymbol{K}^{-1}\boldsymbol{H}\Delta\boldsymbol{t}\\ &= \boldsymbol{W}\Delta\boldsymbol{t}\end{aligned} \tag{4}$$

The transfer function between the displacement and the temperature variation is obtained as Eq. (5) from the stiffness matrix and the temperature-load transformation matrix [12–14]. Thermal sensitivity $\boldsymbol{W}$ can be described by inverse stiffness matrix and temperature-load transformation matrix as:

$$\boldsymbol{W} = \boldsymbol{K}^{-1}\boldsymbol{H} \tag{5}$$

Calculation of thermal sensitivity from finite element model

The stiffness matrix $\boldsymbol{K}$ is normally calculated from the finite element model. Nastran was applied to calculate $\boldsymbol{K}$. The temperature-load transformation matrix $\boldsymbol{H}$ was calculated based on Nastran's thermal load generation algorithm of solid element [15]. Based on these, the thermal sensitivity $\boldsymbol{W}$ can be obtained. The overview of this method is shown in Fig. 1.

Thermal sensitivity of a turning center

Slant bed type turning centers have asymmetric mechanical structure. So they have been difficult to clarify characteristics of thermal deformation. Thermal sensitivity analysis which was described in the previous section was carried out on a turning center. Fig. 2 shows thermal sensitivity result in the X-axis direction. The red area in the figure shows deformation that the area temperature increase causes the turret and headstock to move away from each other and the blue area moves the turret and headstock closer to each other. In addition, the color density shows the magnitude of thermal sensitivity.

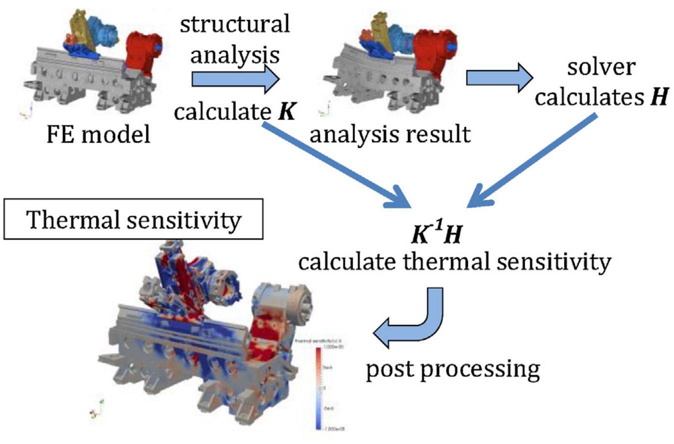

Fig. 1. Calculation method for thermal sensitivity.

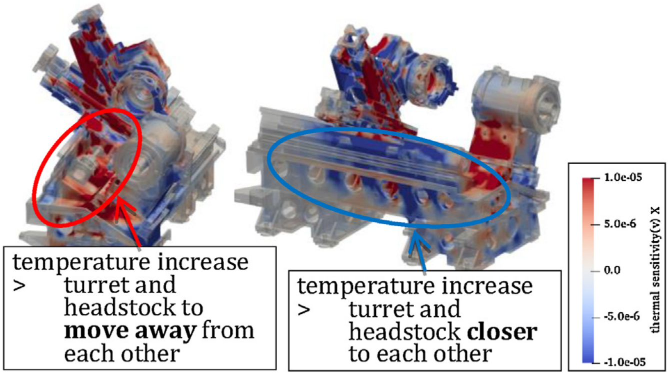

Fig. 2. Thermal sensitivity of X-axis of turning center.

Reducing thermal displacement based on thermal sensitivity analysis

A fan and covers are attached to a turning center to validate the effectiveness of thermal sensitivity analysis. To reduce the thermal deformation that makes the turret and headstock closer to each other, the fan is attached near the front upper face of the bed and the covers are attached to the rear faces of the bed as shown in Fig. 3. Upper face of the bed has high thermal sensitivity in the direction of turret and headstock moving away from each other and rear face of the d has high thermal sensitivity in the direction of turret and head stock getting closer. Fig. 4 shows the comparison of thermal displacement due to the ambient temperature variation around the machine tool. The fan and covers reduced the thermal displacement by 51.6%. The effect was significant in the negative displacement direction, meaning the displacement that makes the turret and headstock closer to each other is reduced. The fan forces quicker heat transfer at the red circled area in Fig. 2 whose temperature rise make the turret and headstock closer, and the cover make slower heat transfer at the blue circle area. The change in machine structure based on thermal sensitivity analysis realizes more thermally robust machine tool.

Thermal displacement prediction by deep-learning

Thermal displacement compensation by deep-learning

In order to make an accurate thermal displacement prediction model, deep-learning was used. Deep-learning is a technique which has made remarkable achievements in various fields in recent years, particularly in the fields of image recognition and speech recognition. The performance has exceeded human's cognitive ability [8,9].

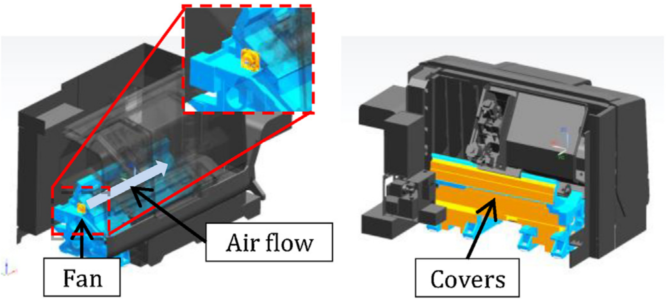

Fig. 3. Attached fan and cover.

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