

Effective Measurement Method of Thermal Deformation of Machine Tools Caused by Linear Axis Motion

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1. Introduction

The spindles speed and feed rate of machine tools increase greatly to realize high-productivity with high accuracy. This leads to exceeding increase in heat generation and then the thermal deformation of the machine tools become serious problems. Therefore it makes necessary to measure and evaluate the thermal deformation. With these points as background, measuring methods for thermal deformation of machine tools were standardized in the international standard ISO 230-3 in March 2001¹⁾. In this standard, the measurement methods of thermal deformation caused by environmental temperature variation, spindle rotation and linear axis motion were provided. For measuring thermal deformation caused by environmental temperature variation and spindle rotation, the methods to measure simultaneously five degrees of freedom components of the thermal deformation are specified in the standard. In this standard, the measurement method proposed by us for high-speed spindle is adopted as a recommended method²⁾. In addition, we have proposed more effective evaluation method with our method³⁾.

On the other hand, in ISO, for measuring thermal deformation caused by linear axis motion, the only thermal deviation in positioning direction is measured. However, it is pointed out that the thermal deviations in other five directions also occurs and influence on the machining accuracy⁴⁾. Then many measurement and compensating methods have been studied^{5,6)}. However, there are no simple and effective measurement methods for measuring the thermal deformations with linear axis motion.

Therefore, in this paper, we propose a new measurement method to measure simultaneously six degrees of freedom components of the thermal deviation caused by linear axis motion in machine tools and shows its effectiveness.

2. Proposition of an effective measurement method and device

2.1 Measurement methods under ISO230-3 and its problems

Figure 1 shows a measurement method of thermal deviations in ISO230-3¹⁾. This is a case of measurement test for X axis motion of a vertical machining center.

In this method, displacement sensors are fixed on the nose end of the spindle and two targets are located on the table. The spindle head is moved relatively to the table between the targets and only the change of the positioning accuracy is measured. However, the problems of thermal expansion of the ball screw tend to be resolved by the adoption of a linear encoder or a cooling system. Then the importance of the thermal deviations in the positioning direction shifts to the other directions to achieve the higher machining accuracy. This tendency becomes stronger with the great increase of heat generation accompanied by the speeding-up of the recent machine tools. Therefore the universal measurement and evaluation methods of thermal deviations with the six degrees of freedom are getting to be demanded.

2.2 Proposition of an effective measuring device and method

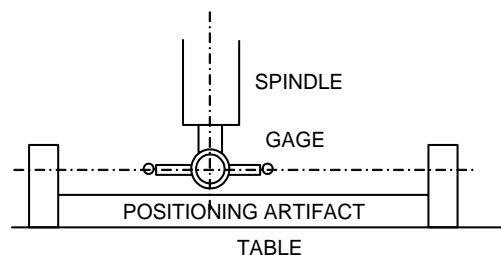


Fig.1 The measuring method of thermal deviations under ISO230-3¹⁾

(1) Measuring device

In this study, we propose a new simultaneous measuring method of six components of the thermal displacement consisting of a component in positional direction, two components orthogonal to the positioning direction, three angular components around these three directions.

Figure 2 shows the proposed measuring device. The device consists of a sensor fixture to hold seven non-contact type displacement sensors and three targets. The details of the sensor fixture and targets are shown in figure 3 and 4. The sensor fixture is fixed on the spindle nose with a tool holder. The three targets are located on the table in a straight line parallel to the feed direction. In the measurement test, the following cycles are continued for a prescribed hours. The sensor fixture moves back and forth between the target L and R several times and stops at a target, the gap changes between target and sensors are detected to measure the thermal deviations.

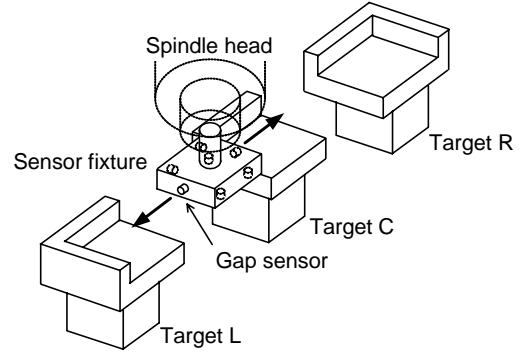


Fig.2 Setup of proposed measuring device

Equations to calculate thermal deviations are shown as follows. Δg_i ($i : 1-7$) is the gap change at sensor S_i . The direction increasing the gap to the target is the plus direction of the sensor output. L_{ij} is the distance between sensor S_i and S_j .

$$\text{Translational deviations: } X = \begin{cases} \Delta g_1 & (\text{at } L) \\ -\Delta g_2 & (\text{at } R) \end{cases}, \quad Y = -\frac{\Delta g_3 + \Delta g_4}{2}, \quad Z = \frac{\Delta g_5 + \Delta g_6}{2}$$

$$\text{Angular deviations: } \theta_x = \frac{\Delta g_5 - \Delta g_7}{L_{57}}, \quad \theta_y = \frac{\Delta g_6 - \Delta g_7}{L_{67}}, \quad \theta_z = \frac{\Delta g_3 - \Delta g_4}{L_{34}}$$

In this method, the measurement is carried out also at the center of the linear motion, unlike the method in ISO. Therefore the change of the straightness by the thermal effect can be evaluated from the measurement results of thermal translational deviations at each three targets.

Another advantage of the proposed measuring method is that the machining error can be predicted more accurately. For example, when angular deviation around Y axis occurs, the value of positioning deviation is different according to Z position. Then, if a thermal deviation for only one direction is measured, the machining error can not be estimated accurately even in its direction.

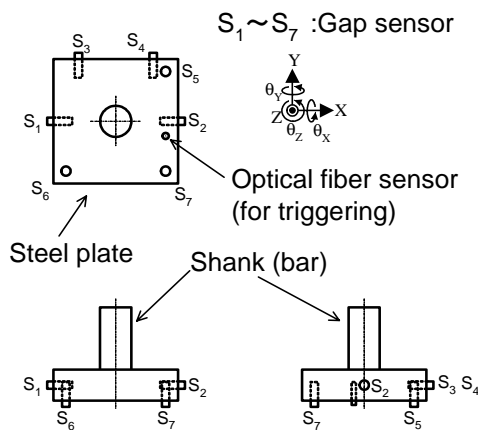


Fig.3 Sensor fixture

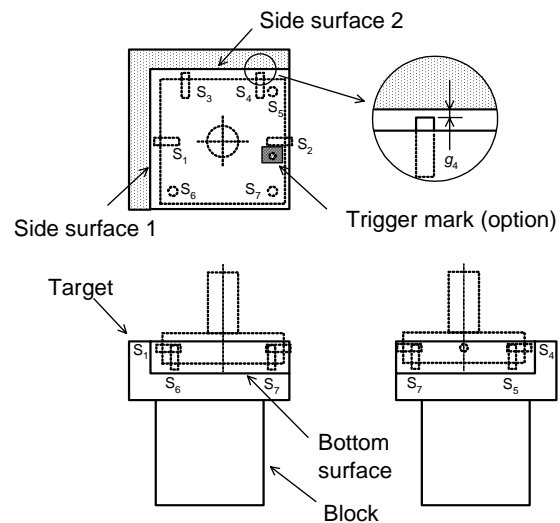


Fig.4 Target (L)

The other feature of the proposed measuring device is that all sensors are held on a sensor fixture to makes the reference point of the device determinate. For example, if the sensors are located on the table side, the deformation of the table causes to change the positions of sensors, and to shift the reference point of the device. Moreover, when the thermal drift of sensor occurs, it is easy to resolve this problem by correcting the sensors' outputs with the temperature of the fixture, since all sensors are fixed on the fixture.

In addition, the construction of the measurement system is very simple, easy to be carried and suitable to use in machine shops. Then the system proposed here can be accepted for the standardization in ISO.

A prototype measuring device based on the proposed method was made. Table 1 shows main specifications of the prototype system. Eddy current sensors are used. The mild steel is used for the material of the sensor fixture and targets. The reason for this is that the jigs and fixtures of the device should be the same material as the workpieces to evaluate the effect of the thermal deviations on the machining error. In this study, the workpieces are assumed to be made of mild steel.

(2) Measuring method

Figure 5 shows the top view of the paths of axis motion for the test of thermal deviations. After the spindle head moves back and forth for a prescribed times on the path 1, the measurement is carried out at three targets with dwell along the path 2 at a distance d from the path 1. This cycle is repeated for prescribed hours. The influence of shifting distance d to measure seams to be small, if the distance is small and the frequency of the measurement is few.

3. The measurement results of the test with the proposed measuring device and the efficiency of the device

3.1 Test method and conditions of the thermal measurement test

Figure 6 shows the setup of the experimental device to verify the effectiveness of the proposed measuring method. The measurement test was carried out on the X axis of a double column type machining center. The X axis motion of the machining center is carried out by the spindle head traverse from side to side and the table is fixed. The thermal expansion of the ball screw effects greatly on the positioning accuracy, since X axis control is a semi-closed type with a rotary encoder.

In this figure, the points of temperature measurement at the environment, the sensor fixture, the targets and the bed of machine are also drawn. Table 2 shows the conditions of the test.

3.2 The results of temperature measurement

Figure 7 shows the change of the temperature from the start of the test. From the figure, it seems that the heat generation caused by X axis motion does not effect on measurement system and the sensor fixture becomes cool down slightly by the fall of the environmental temperature. Therefore, the effects of the temperature change in the measurement test can be ignored.

Table 1 Specifications of the prototype measuring system

Type of sensors	Eddy current sensor
Angular resolution	0.1 μm
Translational resolution	1 arc-sec
Size of sisor's fixture	120 x 120 x 20 mm
Size of target	140 x 140 x 120 mm
Material of fixure & target	mild steel

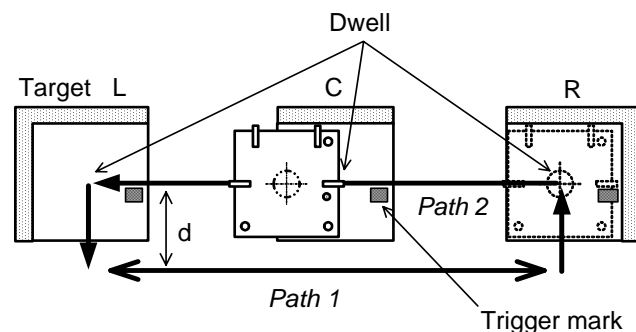


Fig.5 Paths for measurement

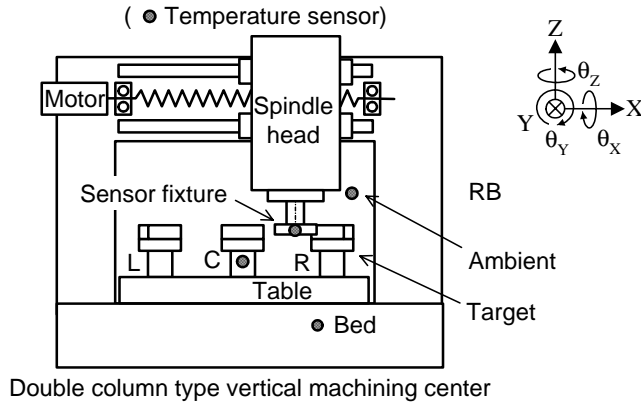


Fig.6 Experimental setup

Table 2 Conditions of the measurement test

Feed rate	1700 mm/min
Transverse length	500 mm
Offset d	5 mm
Dwell	2 s
Measuring cycle	1 / 10 round trips

3.3 The results of the positional thermal deviation measurement

Figure 8 shows the measurement results of the thermal deviation along the positioning direction. The thermal deviation X at target R tends to increase with the time passed and shows the characteristic like a first order lag system. The thermal deviation X at target L decreases slightly once, then increases gently. The difference between R and L indicates the typical characteristic of thermal deviation caused by the thermal expansion of a ball screw. This results shows that the proposed measuring method can get the equivalent results with the method standardized in ISO230-3.

3.4 The results of the translational thermal deviation measurement

The measurement results of the thermal deviations in Y and Z direction orthogonal to the positioning direction are shown in figure 9 and 10. The deviation in Y tends to decrease and in Z tends to increase monotonously. These results are smaller than in X direction, but the order can not be ignored. The thermal deviation in Y at target C is larger than the deviation at the other targets in the minus direction. The reason seems that the temperature rises on the front side of the cross-rail fixing guide ways, and then the cross-rail is warped to the operator's side like a convex curve. The difference of the deviations in Z direction at all targets can not be observed. Therefore, the result seems to originate from the thermal expansions of two columns in Z direction and/or from the angular deviation around the axis X with the warp deformations of the columns.

3.5 The results of the angular deviation

Figure 11 shows the measurement results of the thermal angular deviation θ_X . θ_X increases only just after the start of the test in plus direction and increases monotonously in minus direction. It is reasonable to think that the monotonous increasing tendency originates from column's warping caused by the temperature difference between the front and back of column as mentioned above or the thermal deformation of the spindle head or saddle. Pointing out the cause of the

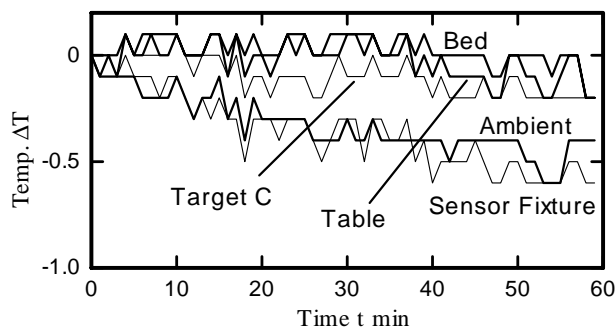


Fig.7 Temperature change

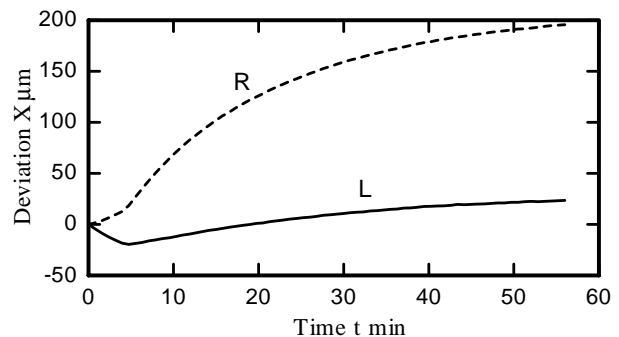


Fig.8 Thermal deviation X

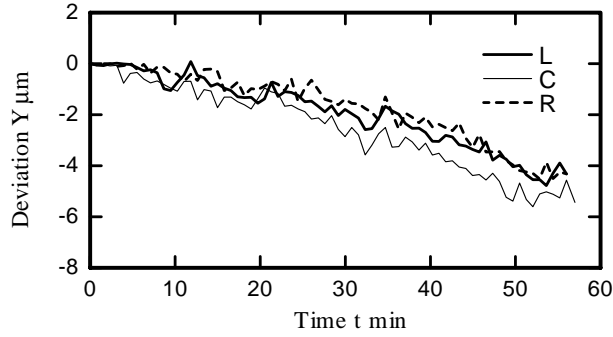


Fig.9 Thermal deviation Y

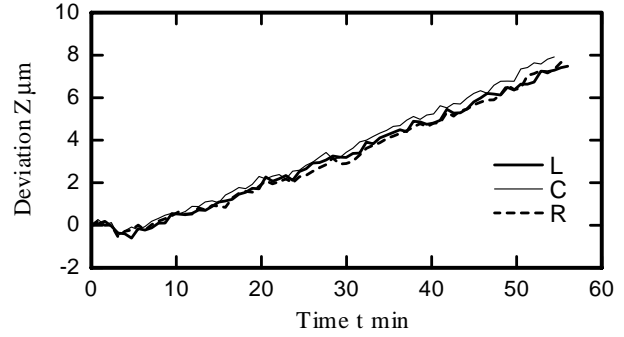


Fig.10 Thermal deviation Z

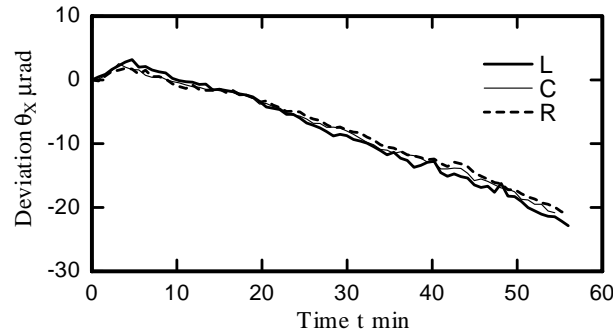


Fig.11 Thermal deviation θ_x

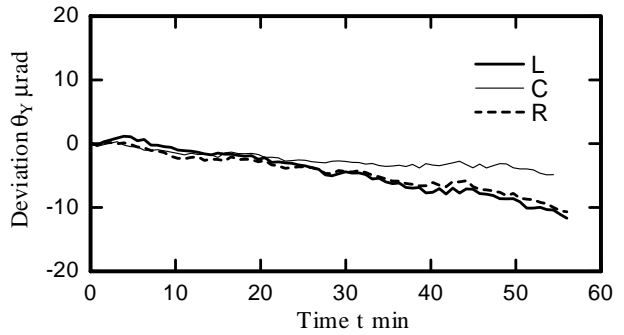


Fig.12 Thermal deviation θ_y

warping is impossible from the result of this measurement only, but it can be realized by measuring simultaneously the temperatures of the machine structures. The effect of θ_x must be included in the results shown in figure 9 and 10, since θ_x influences on the displacement in Y and Z direction,

Figure 12 shows the thermal angular deviations around axis Y (θ_y). θ_y at the target C changes a little, but tend to decrease at target L and R. From this results, it is reasonable to think that the cross-rail curves up like S character. Generally θ_y effects on X directional deviation. However, this effect can not be recognized in this results, since the deviation caused by the thermal expansion of the ball screw is the dominant cause of X directional deviation.

Figure 13 shows the measurement results of thermal angular deviation θ_z . θ_z value at right target is larger than at left one. This seems to be caused by the warping of the cross-rail as mentioned above to generate the deviation in Y direction. If the cross-rail is warped completely symmetrically, then θ_z at target C becomes zero, and θ_z at target R should displace to plus direction and θ_z at target L should displace to minus direction. However, θ_z at all targets displace actually to plus direction. The reason is this that the upper side of the machine structure than the table occurs twist deformation and/or the saddle or the spindle head deforms in this direction. The thermal deformation predicted from the above results is shown in figure 14.

3.6 Efficiency of the proposed measuring method and device

As mentioned in the above section, the five components of the thermal deviation except for the positioning are also remarkably generated in the same way as the positioning. The combination of these results enables to predict the behavior of the thermal deformation of the machine tool. Moreover, thermal deviations at any points in the work area seems to be estimated more accurately from the measurement results. In addition, the proposed method has great possibility to search the cause of the thermal deformation accurately in a short time more than in the past.

As described above, it was made clear that the proposed simpler measuring device can measure simultaneously six degrees of freedom components of thermal deviations with the compatible characteristics of ISO230-3 and can evaluate thermal deviations more effectively.

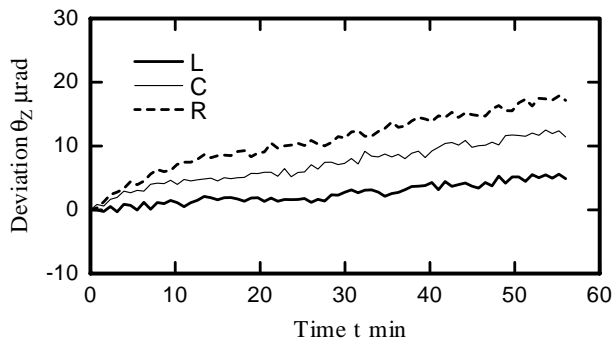


Fig.13 Thermal deviation θ_z

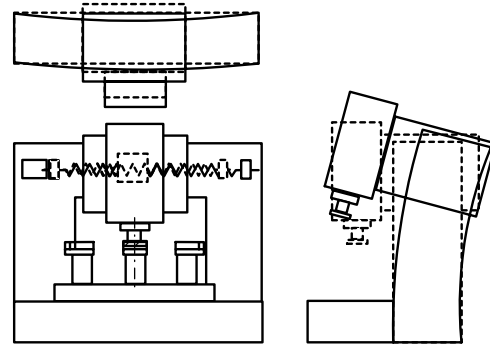


Fig.14 Deformation of machine structure

4. Conclusion

A new effective measurement method was proposed to measure simultaneously the six degrees of freedom components of the thermal deviation of machine tools caused by linear axis motion. The measurement test for the X axis motion was carried out with the prototype measurement system on the machining center. From the results, the effectiveness of the proposed measurement method was made clear.

References

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