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Prediction of thermal displacement of shaft of machine tool spindle using cooling fluid temperatures

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Abstract
A thermally-induced axial displacement, TIAD, of machine tool spindle degrades directly relative position accuracy between workpiece and cutiing/grinding tools. Accordingly, the TIAD during machining operations must be minimized. In our previous report, the temperature control of a built-in motor spindle was studied. In the study reported, temperature control system used spindle temperature as a feedback information. The experimental results indicated that the control system successibly reduce the temperature change of the spindle. However, effectiveness of the TIAD reduction was limited. A main reason is the temperature of spindle body is not same as that of the spindle shaft. The limitation comes from a difficulty such that direct measurement of TIAD is pratically difficult during machining operations. To cope with the problem, this study investigates the use of temperature change of cooling fluid to design feedback control system.

Spindle, Temperature control, Thermally induced displacement, and Cooling

1. Introduction

Machining accuracy of a machine tool is determined by the stiffness, motion accuracy, and thermal characteristics of the machine tool structure. Among these factors, thermal displacement caused by various types of heat generations has a significant influence on machining accuracy.

To cope with the issue of TIAD of machine tool spindle, forced coolings are used to reduce thermal displacement. In most conventional forced cooling systems, cooling fluid controlled at a constant temperature is supplied to the spindle. In many cases, the desirable cooling performance that follows changes in heat generation of the machine tool due to changes in spindle speed cannot be obtained. This is due to the large thermal time constant of the heat exchange between the cooler and the refrigerant.

In general, during the machining processes by a machine tool, the amount of heat generation changes with changes in spindle speed and machining loads. As a result, the temperature of the machine tool changes sequentially accordingly. Therefore, it is essential to control temperature and resultant thermal displacement appropriately.

In previous research by the authors, a temperature feedback control system that can control the temperature of the cooling fluid precisely was developed [1]. Furthermore, the developed temperature control system was applied to a built-in motor spindle [2], [3]. In the control, the TIAD was measured and fedback. As a result, it was found that this system has better thermal displacement suppression performance than conventional cooling systems.

However, it is noted that direct measurement of TIAD during machinining operations is difficult to carry out. In a previous report [3], it was verified that there is a correlation between temperature change of the cooling fluid and TIAD of spindle.

In this study, we focused on the relationship between the supply and discharge temperatures of the cooling fluid and TIAD. Specifically, we studied the prediction of TIAD based on the temperatures of the cooling fluid, which is relatively easy to measure even under actual machining conditions.

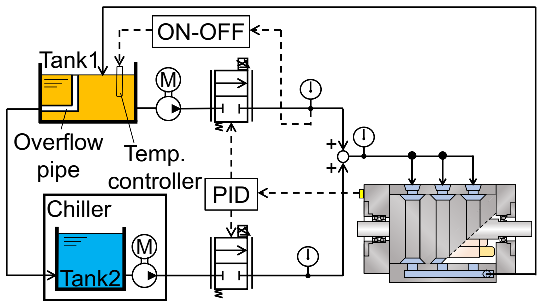

Figure 1. Developed temperature control system

2. Developed feedback control system

Figure 1 shows the configuration of the feedback temperature control system developed. The system controls and mixes fluids supplied from two fluid reserviors maintained at different temperatures. Mixing flow ratio of cooling fluids from the reservoirs controls temperature of mixed cooling fluid arbitrally and precisely. Using this system, spindle temperature and/or spindle TIAD are fedback, and the mixing ratio are controlled in real time to achieve control objective, such as zero TIAD. Each tank consists of a higher temperature tank (Tank 1) and a lower temperature tank (Tank 2), each of which is set at about room temperature and is operated by an industrial chiller. The flowrates are controlled by flow control valves. The cooling fluid temperature is controlled in real time so that the spindle temperature or spindle TIAD equals to control objective. Gains of the PID controller were chosen based on simulation studies using mathematical model. The derived gains were implemented into the controller for experimental studies. Then, further gain adjustment was made through trial-and-error procedures to achieve better performance.

3. Tested built-in motor spindle

Figure 2 shows the configuration of the built-in motor spindle used in this study. A cooling jacket of the spindle is provided around the motor periphery to suppress heat generation by supplying cooling fluid. The temperature of the cooling fluid supplied to the cooling jacket is controlled by the developed temperature control system. The TIAD of the spindle is measured at the shaft end using a laser displacement sensor fixed to a Super Invar fixture directly attached to the spindle.

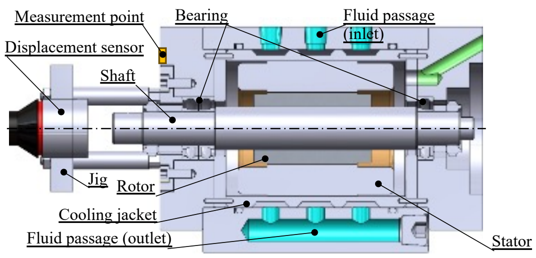

Figure 2. Structure of built-in motor spindle

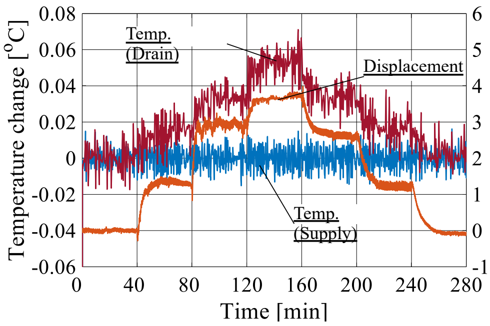

Figure 3. Relationship between temperature changes and TIAD

4. Prediction of thermally induced axial displacement

4.1. Corellation between TIAD and cooling fluid temperatures

In our previous study, the thermal displacement suppression performance of the developed temperature control system was evaluated by feeding back the measured TIAD. The results showed that the TIAD suppression performance of the developed system was higher than that of conventional cooling systems. However, it is difficult to measure directly TIAD and use it for feedback signal under actual machining conditions.

Therefore, this study examined the estimation of TIAD based on the supply and discharge temperatures of the cooling fluid supplied to the spindle. Figure 3 shows the relationship between the supply and discharge temperatures of the cooling fluid and the TIAD associated with changes in spindle speed.

Figure 3 shows that the discharge temperature of the cooling fluid supplied to the spindle increases due to the effect of changes in spindle heat generation. On the other hand, the TIAD of the spindle shaft also changes due to the heat generation change. In fact, Figure 3 shows that there is a good correlation between the discharge temperature of the cooling fluid and the TIAD.

Based on the consideration using a derived lumped parameter model, the TIAD ΔZ can be presented by the temperatures of supplied and drained cooling fluid, θ_{in} and θ_{out}, in addition to initial spindle temperature θ_0. The prediction of TIAD ΔZ is then presented by Eq. (1).

$$\Delta Z = k_1 \theta_{out} + k_2 \theta_{in} - k_s \theta_0$$

4.2. Prediction result

According to Eq. (1), thermal displacement can be estimated by measuring the supply and discharge temperatures of the cooling fluid. By controlling the system to suppress the estimated thermal displacement, it is expected to realize a system that can suppress thermal displacement with high accuracy even during machining.

The prediction accuracy of the thermal displacement prediction presented in Eq. (1) was evaluated experimentally. Specifically, in this study, cooling fluid at a constant temperature was supplied to the spindle, and the amount of heat generated was varied by changing the spindle speed. The actual thermal displacement measured by a displacement sensor was compared with the predicted thermal displacement.

Figure 4 shows that the shaft end thermal displacement was about 2.5 μm as the spindle speed changed, but the proposed method can predict the shaft end thermal displacement with high accuracy based on the coolant temperatures. Specifically, the error of the average displacement in the steady state after a change in rotation speed is 0.11 μm, which is about 4.5% of the displacement. Therefore, it is clear that the thermal displacement associated with changes in spindle speed can be estimated by measuring the supply and discharge temperatures of the measured cooling fluid.

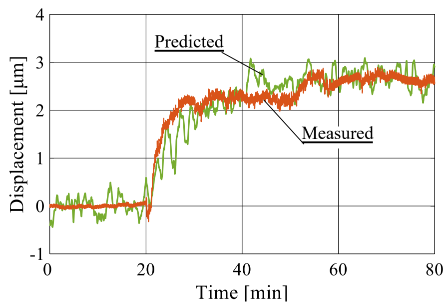

Figure 4. Comparison of measured and predicted TIADs

5. Conclusions

To develop a feedback temperature control system that can suppress thermal displacement of the spindle shaft end under actual machining conditions, we proposed a method for predicting thermal displacement of the shaft based on the relationship between the supply and discharge temperatures of cooling fluid, which is relatively easy to measure even during machining opetations. Experimental results showed that the proposed method can predict thermal displacement associated with changes in spindle speed with an accuracy of about 4.5 %. In the future our study, feedback control based on the TIAD prediction is planned.

Acknowledgment

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