euspen's 24th International Conference & Exhibition, Dublin, IE, June 2024

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Relationship between thermally induced shaft displacement and temperature measured on an outer surface of motorized spindle for developing thermal displacement feedback control system

Yohichi Nakao[1], Ryota Ishida[1], Shumon Wakiyta[1], and Jumpei Kusuyama[1]

[1]*Kanagawa University*

nakao@kanagawa-u.ac.jp

Abstract

A main objective of this study is to minimize machining error due to thermal deformation of motorized spindle. In the spindle considered in this study, water cooling structures are designed. In our previous study [1], a feedback temperature control system was developed and tested for temperature control of the spindle. A main feature of the feedback temperature control system is to mix water flows that are different temperatures from different water supply sources. The supplied water temperature can be arbitrary controlled by controlling the mixing flow rates in real time using flow control valves. Based on the control system, the temperature control of spindle body was made by designing appropriate feedback control system. An effectiveness of the control system was verified experimentally. In the previous study, the temperature of the spindle outer surface was successfully maintained even internal thermal generation of the spindle was changed. In this present study, the relation between resultant thermally induced displacement of the spindle shaft and outer surface body temperature is compared. A final goal of this study is to develop a feedback control system of thermal shaft displacement in order to achieve zero thermal displacement of spindle shaft without direct thermal displacement as well as temperature measurements of spindle shaft during cutting operations.

Spindle, Temperature control, Thermally induced displacement, and Cooling

1. Introduction

Minimization and control of thermal deformation of machine tools is a very important issue to improve machining accuracy. In particular, the machine tool spindle directly affects the relative displacement error between workpiece and cutting tool. Therefore, it is significantly important to suppress thermally induced displacement of the machine tool spindle. In particular, the thermally induced axial displacement of the spindle system has to be minimized. There are research reports and developments on the thermal deformation suppression, such as efforts through sophisticated structural design of machine tool. The use of materials with a low expansion coefficient is one of the examples. As alternative approaches, compensation technique of thermal deformation using machine tool control system can be implemented.

Another countermeasure is also being taken to suppress temperature changes through effective cooling system. In many cases of commercialized machine tool, constant temperature of cooling fluid at a constant flowrate is supplied into the heat-generating parts of the machine tool. In this case, temperature changes due to heat generation changes in the heat sources such as machine tool spindle are inevitable. Therefore, a temperature control method that can effectively minimize the temperature changes in response to heat generation changes is desired.

The authors have developed a temperature feedback control system for machine tool components and structures including spindles. In our previous study [1], it was however shown that the spindle end-shaft displacement cannot be sufficiently suppressed when the casing temperature of a spindle was kept constant using the developed temperature control system.

Therefore, alternative temperature measurement way is considered in order to control thermally induced shaft end displacement in this study. Then, we focused on the cooling water temperature supplied to the spindle as an alternative parameter for feedback. The relationship between the cooling water temperatures and shaft end displacement are presented to show strong correlation between them.

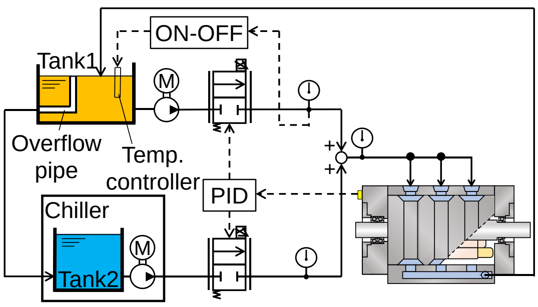

Figure 1. Developed temperature control system

2. Developed feedback control system

The temperature control principle of the developed feedback control system is based on the flowrate controls of cooling waters from two supply sources [1]. Temperature of the cooling waters with different temperatures are supplied from the sources. In Fig. 1, a basic structure of the developed control system is presented. In the control system, the tank 1 provides higher temperature fluid. Normally the water temperature in the tank 1 is the room temperature. Contrary, the tank 2 provides lower temperature fluid cooled by a commercialized chiller. Flowrate control valves that are independently controlled are used to control the flowrates from the tank 1 and tank 2. The flow ratio of the higher and lower temperature fluids is controlled in real time such that temperature control objective is achieved. In the previous our study, temperature of a surface of the spindle near spindle shaft was measured and fedback.

3. Experiments

3.1. Tested spindle

A spindle depicted in Fig. 2 was used to the experiments. Figure 2 shows a structure of the spindle. Rated power of the built-in motor is 1.1 kW. Rated rotational speed is 30050 min^{-1}. In the experiments, temperatures of cooling water at the inlet and outlet ports of the spindle were measured. Thermally induced axial displacement of the spindle shaft was measured a laser displacement sensor that was fixed at a jig made by the super invar so that thermally induced displacement of the jig can be avoided. The jig was fixed on an end surface of the spindle [2].

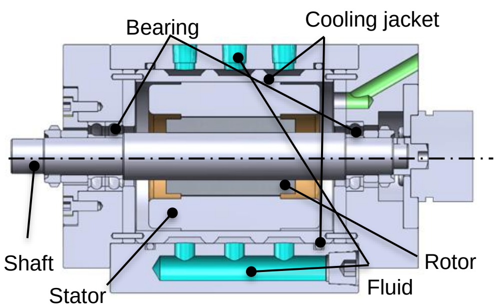

Figure 2. Structure of motorized spindle

3.2. Results and considerations

The performance of temperature control of spindle by the control system developed in previous studies was verified through experiments. In the experiments, a temperature sensor was attached to an outer surface of the spindle casing near spindle end shaft and the temperature was controlled to keep the surface temperature constant, regardless of the inner heat generation. The control results are shown in Fig. 3. In the experiment, the spindle temperature was varied by varying the spindle rotational speeds from 10000 min^{-1} to 5000 min^{-1}. In this case, if cooling water is controlled to be constant by a conventional cooling system, the spindle temperature is changed by about -1.7°C according to the change in heat generated by the spindle. In contrast, it can be confirmed that the developed temperature control system sufficiently suppresses the spindle surface temperature change though small transient change in temperature is observed.

Thermally induced axial displacement of an end surface of spindle shaft during temperature feedback control presented in Fig. 3 was evaluated as well. The experimental results indicate that if comparing the result of the conventional commercialized chiller, the shaft end displacement is slightly suppressed by the developed feedback control system, though, the effect to reduce thermal induced displacement is not sufficient.

A reason why the control effect is not sufficient is considered that temperature of the outer suface of casing and one of the shaft end is different. In fact, in our preliminary experiment, the temperature of the end surface of the shaft is higher about 5°C than that of the casing surface.

Based on the results, it is indicated that control of the spindle casing surface is not sufficient to suppress thermally induced axial displacement. In order to control the thermally induced displacement of the spindle shaft, measurement of the displacement or temperature of the shaft is desirable. However, a measurement and feedback of the displacement and/or temperature of the rotating spindle shaft itself is not adequate from a viewpoint under actual machining environments.

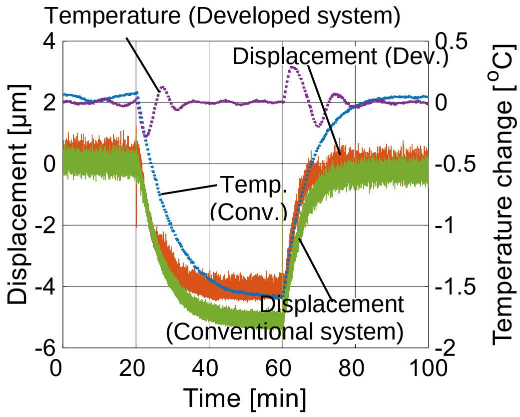

Figure 3. Thermally induced displacements

From above consideration, we focused on the cooling water temperatures measured at a supply port and a drain port of spindle, respectively. Specifically, the relationship between the temperature difference between drain water and supply water and shaft end displacement was investigated. Figure 4 indicates the experimental result.

From Figure 4, it is considered that the shaft end displacement can be predicted from the temperature difference between the cooling water supplied to and discharged from the spindle. This is because the temperature of the cooling water rises due to the amount of heat generated inside the spindle, which affects the shaft end thermally induced displacement.

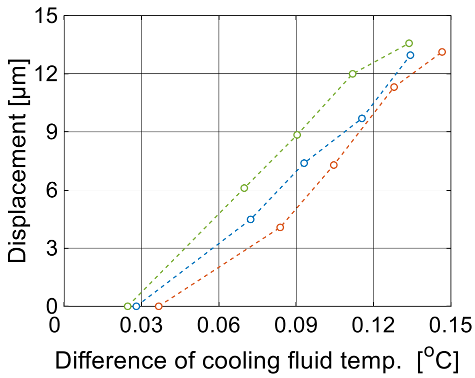

Figure 4. Relationship between difference of cooling water temperature and thermally induced displacement of end shaft

4. Conclusion

In this study, an appropriate feedback signal for the feedback temperature control system developed in our previous study was considered. From the experimental investigations in this study, it was clarified that the cooling water temperatures can be used as the feedback signal. This research was supported in part by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science and The Die and Mould Technology Promotion Foundation.

References

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