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Investigation of spindle thermal displacement and cooling unit energy consumption characteristics under various operating conditions

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Abstract
This study investigates the thermal displacement characteristics of a machine tool spindle and the energy consumption of its cooling unit under various spindle operating conditions. To reduce energy consumption during non-machining periods, the cooling unit was placed in standby mode, and the resulting changes in spindle temperature, thermal displacement, and cooling unit energy consumption were experimentally measured and analyzed. The results show that placing the cooling unit in standby mode during non-machining periods can reduce energy consumption, while also causing changes in spindle temperature and thermal displacement. Based on the experimental data, a predictive model for spindle thermal displacement was developed by incorporating the cooling unit operating state, spindle temperature, and spindle speed, and its performance under different operating conditions was examined. The results of this study suggest the potential for improving energy efficiency while maintaining thermal accuracy in machine tool spindle operation.

Machine tool, Spindle cooling unit, Thermal displacement, Energy consumption, Energy efficiency

1. Introduction

With the growing global emphasis on carbon neutrality and environmentally friendly manufacturing, improving energy efficiency has become an important research topic in the machine tool industry [1-3]. In response to this trend, leading machine tool manufacturers have introduced a variety of energy-saving technologies. Despite these efforts, reducing energy consumption during machining remains challenging, as not only servo systems but also auxiliary components must operate continuously to ensure stable machining performance. Consequently, most existing approaches focus on reducing energy consumption during non-machining periods by actively controlling auxiliary devices, for example by turning them off or placing them in standby mode during setup or idle states.

However, such energy-saving strategies may negatively affect machine tool accuracy, particularly due to thermal displacement caused by changes in the operating conditions of auxiliary systems. Therefore, it is necessary to consider both energy consumption and machining accuracy simultaneously and to investigate strategies that can effectively reduce energy consumption while maintaining accuracy. In this study, the thermal displacement behavior of a machine tool spindle and the energy consumption characteristics of its cooling unit are investigated under different operating conditions of the spindle and cooling unit. During non-machining periods, the spindle cooling unit is switched to standby mode, and the spindle temperature, thermal displacement, and cooling unit energy consumption are measured and analyzed to identify their relationships.

Based on the experimental data, a predictive model for spindle thermal displacement is developed by considering the operating state of the cooling unit, spindle temperature, and spindle speed. The applicability of the proposed model under different operating conditions is briefly examined.

2. Experiment

2.1. Experiment setup

Figure 1 shows photographs of the measurement setup for the thermal displacement of the spindle and power consumption of the cooling unit in a three-axis machining center. Temperature sensors were installed on the spindle head and the structural components of the machine tool, and a master pin was mounted on the spindle. Displacements in the X-, Y-, and Z-directions were measured using capacitive displacement sensors. To measure the power consumption of the cooling unit, power meters were installed. The spindle cooling unit employs an inverter-type cooler, and the spindle thermal displacement is effectively controlled using an oil-jet cooling method.

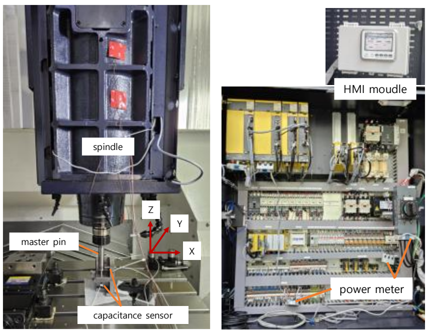

Figure 1. Experimental setup for spindle thermal displacement and cooling unit power consumption

2.2. Measurement of energy consumption and temperature

Two different spindle operating cycles were prepared: one cycle was used for modeling, and the other was used for validation. Figure 2 shows, as an example, the spindle operating condition, Cycle I used for modeling. The spindle was operated under both constant-speed and variable-speed conditions. The cooling unit was always operated when the spindle was running, however, during periods when the spindle was not in operation, the spindle cooling unit was placed in standby mode to reduce energy consumption. For spindle safety, the cooling unit was switched to standby mode after a sufficient thermal stabilization period of 30 minutes after the spindle stopped, and was reactivated 30 minutes prior to spindle restart.

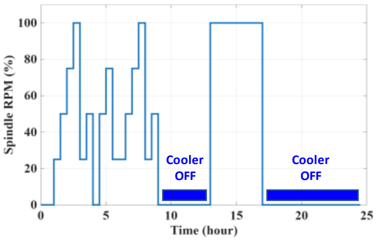

Figure 2. Spindle and cooling unit operating conditions in Cycle I

Figure 3 shows the measured power consumption of the cooling unit. When the cooling unit is operation, it consumes a baseline power of approximately 0.7 kW. After the spindle stops, when the cooling unit is placed in standby mode (the black-shaded region), the power consumption decreases to a very low standby level as the motor is turned off and only the control panel remains powered.

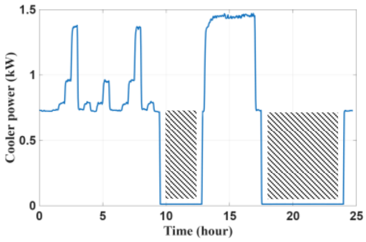

Figure 3. Measured cooling unit power and energy-saving region (black-shaded) in Cycle I

Temperatures were acquired at multiple locations, and the spindle displacement was simultaneously measured to model thermal displacement. Figure 4 shows several representative temperature measurement results for Cycle I. The temperature of the spindle head (T4-head2) increases during periods when the cooling unit is in standby mode. When the cooling unit is reactivated before the spindle starts operating, these temperatures decrease accordingly. It can also be observed that, while the temperature of the spindle head (T4-head2) increases during spindle operation, the temperature at the cooling unit outlet (T6-coolerO) and in the region of the spindle (T2-spindle2), where the cooling oil channel supplied from the cooling unit is located, decreases, indicating effective control of spindle thermal displacement. T8-envirl denotes the ambient temperature.

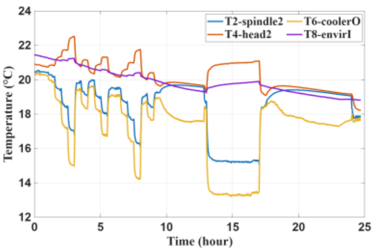

Figure 4. A few representative temperature measurement results

3. Modeling and validation of the thermal displacemenet of the spindle

Figure 5 shows the measured and modeled thermal displacement of the spindle in the Z-axis direction for Cycle I. For the thermal displacement modeling method, a widely used regression model was employed to facilitate practical implementation for compensation purposes, even though AI-based modelling methods generally show better performance. Overall, the predicted model (red line) shows good agreement with the measured thermal displacement (blue line) under various operating conditions.

After 9:30 and after 17:30, when the cooling unit was placed in standby mode, the thermal displacement increased, whereas after 24:00, when the cooling unit was reactivated, it decreased rapidly. As shown in Fig. 5, large spikes in thermal displacement were associated with variations in spindle speed. However, the residual error shows that the proposed model still tracks the experimental data well in these regions.

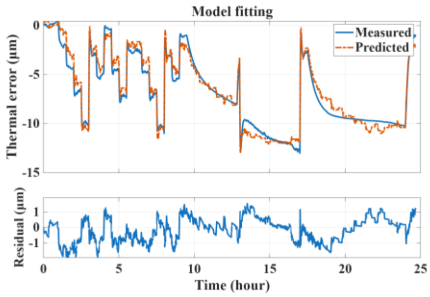

Figure 5. Modeling of thermal error in the Z-direction

To validate the developed model, experiments were conducted under an operating pattern different from Cycle I, denoted as Cycle II, which is omitted here due to limited space. When the prediction model derived from Cycle I was applied to Cycle II, the predicted results showed good agreement with the measured results. As a result, energy consumption can be reduced by placing the cooling unit in standby mode when it is unnecessary during non-operating periods of the spindle. Moreover, by modeling and compensating for the thermal displacement of the spindle that occurs during these periods, it is possible to maintain spindle accuracy while achieving energy savings.

4. Summary and future work

In this paper, a modeling method is proposed to reduce energy consumption by placing the cooling unit in standby mode when it is unnecessary during spindle non-operating periods, while maintaining machining accuracy by compensating for the resulting thermal displacement of the spindle.

Future work will focus on applying the proposed model to an actual machine tool system to compensate for spindle thermal displacement, aiming to reduce energy consumption while maintaining machining accuracy.

Acknowledgement

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