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Temperature characteristics of spindle supported with water-lubricated hydrostatic bearings

Yohichi Nakao [1], Rei Kirigaya [1], Tsubasa Yaguchi [1] and Akio Hayashi [2]

[1] *Kanagawa University, Japan*
[2] *Kanazawa Institute of Technology, Japan*

nakao@kanagawa-u.ac.jp

Abstract
Temperature characteristics of spindle supported with water-lubricated hydrostatic bearings are considered. Water as a lubricating fluid is advantageous to achieve higher thermal stability of the spindle due to the higher specific heat and heat conductivity of water. In order to investigate temperature characteristics of the spindle, the water temperatures at the upstream and downstream of the spindle and the temperature of the spindle body are measured. Then the cooling efficiency of the water flow as lubricating fluid for the hydrostatic bearings are discussed.

Keywords: Thermal stability, Hydrostatic bearings, Machine tool spindle, Ultra-precision machine tools, Water hydraulics

1. Introduction

An advantage of the machine tool spindle supported by hydrostatic bearings is a capability of non-contact support of the rotor. This achieves better rotational motion with low friction. Recently, there are strong demands of the spindle operation with higher rotational speed for the micro milling applications.

However, if the spindle speed becomes very fast, heat generations due to the viscosity of the lubricating fluid becomes significant. In addition, the pressurized lubricating fluid for the hydrostatic bearings is released into the atmosphere, thus, large pressure drop of the lubricating fluid cannot be avoided. The pressure drop occurs at the bearing restrictors and the small gaps of the bearings. The power losses of the lubricating fluid cause heat generation of the spindle.

Thermal characteristics of the water driven spindle was investigated [1]. The results showed that water as the lubricating fluid is advantageous to achieve higher thermal stability of the spindle due to the higher specific heat and heat conductivity of water.

An objective of this research is to investigate the thermal stability of the spindle supported by water-lubricated hydrostatic bearings. In order to investigate temperature characteristics of the spindle, the water temperatures at the upstream and downstream of the spindle and the temperature of the spindle body are measured. The cooling effects of the water flow as lubricating fluid for the hydrostatic bearings are then discussed.

2. Spindle supported with water-lubricated hydrostatic bearings

In Fig. 1, the structure of the spindle [2] with water-lubricated hydrostatic bearings considered is presented. The rated rotational speed of the spindle is 5,000 min^{-1}. The spindle was designed so that the stiffness of the thrust and radial bearings becomes 1,000 N/μm and 500 N/μm, respectively.

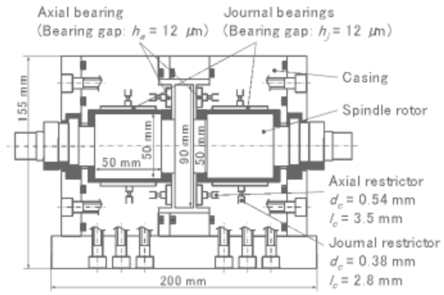

Figure 1. Spindle with water-lubricated hydrostatic bearings [2]

3. Heat generation mechanism

Now, mechanisms of the heat generation of the spindle with hydrostatic bearings are considered. There are two main causes of the heat generation in the spindle. One of them is due to the power loss of the lubricating fluid due to pressure drops. The pressure drops of the lubricating fluid generated at the restrictors and the bearing surfaces cause the power losses. In particular, the power losses increase if higher supply pressure is used in order to increase the bearing stiffness. Another cause of the heat generation is due to the viscous friction of lubricating fluid. Thickness of the lubricating fluid film is particularly small. Accordingly, the influence of the viscous torque due to the lubricating fluid on the heat generation becomes significant especially in the higher speeds.

4. Experimental setup

The experimental rig used in this study is illustrated in Fig. 2. An AC servo motor was used to drive the motor. The driving torque of the motor transmits to the spindle via a magnet coupling in order to avoid thermal effect of the motor to the spindle. The driving torque was measured indirectly via electric current signal.

In the tank A, the temperature of the lubricating fluid was controlled by a chiller equipment. The lubricating fluid was supplied from the tank to the spindle by a water hydraulic piston pump. The temperatures of the water upstream and downstream of the spindle were measured using thermistor type of the temperature sensors. Furthermore, the temperature of the outer surface of the spindle was measured as well.

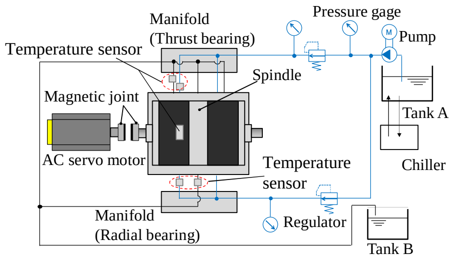

Figure 2. Experimental setup

5. Results

Power losses of the spindle against the spindle speeds are presented in Fig. 3. In Fig. 3, the power loss due to the pressure drop of water flow is denoted by P_f. In addition, the power loss due to the viscous torque of water film at the small gaps of the hydrostatic bearings is indicated by P_v.

In Fig. 4, the temperature increases of the water via thrust and radial bearings are presented separately. In Fig. 4, the temperature difference is defined as T_d–T_s: T_d and T_s are the temperatures of the drained and supply waters, respectively. It should be noted that the water temperature increases by passing through the spindle. Furthermore, the water temperature increases even zero spindle speed. The temperature increase is due to the power loss P_f as depicted in Fig. 3. In addition, the water temperature increases as increase of the spindle speed, because of the viscous torque of water.

In the experiments, flowrates of the water flow passing through the thrust bearings and radial bearings q_{th} and q_r were measured, separately. Accordingly, the power loss contributing the temperature increases of the water flow can be expressed by Eq. (1) and Eq. (2), respectively.

$$P_{ra} = c_w \rho_w q_{ra} \left(T_{d\_ra} - T_{s\_ra} \right) \tag{1}$$

$$P_{th} = c_w \rho_w q_{th} \left(T_{d\_th} - T_{s\_th} \right) \tag{2}$$

Here, c_w, ρ_w, q_{ra} and q_{th} are the heat capacity, the density of water, flowrates in the radial and thrust bearings, respectively. In addition, the subscriptions *ra* and *th* for T_d and T_s stand for radial bearing and thrust bearing, respectively.

Accordingly, the total power contributing the temperature increase of the water flow can be represented by Eq. (3).

$$P = P_{ra} + P_{th} \tag{3}$$

The total power loss defined by P_v+P_f and the power P defined in Eq. (3) are compared in Fig. 5. It can be considered that the water flow as the lubricating fluid takes away a part of the influence of the power loss from spindle. If all of the power loss can be taken by water flow out of the spindle, the spindle temperature can be constant regardless of the power loss. Consequently, the cooling efficiency η is now defined as Eq. (4).

$$\eta = \frac{P}{P_{ra} + P_{th}} \times 100 \tag{4}$$

As presented in Fig. 5, the cooling efficiency is over 80 %. In Fig. 5, the difference between P_v+P_f and P denoted by ΔP indicates the power loss that makes the temperature increase of the spindle. For instance, ΔP is about 64 W at the spindle speed of 3,000 min^{-1}.

Rate of temperature increase of the spindle was measured as presented in Fig. 6. In the experiment, a step input was applied so that the spindle speed changes 0 to 3,000 min^{-1}. The rate of temperature increase can be measured as dT_c/t. Furthermore, the power P_c that increases the temperature of the spindle casing can be estimated by Eq. (5).

$$P_c = \frac{c_s M_c dT_c}{t} \tag{5}$$

In Eq. (5), c_s and M_c are the heat capacity of stainless steel and the mass of the casing. The power P_c was estimated to be 11.7 W and 17.9 W for the different spindle speeds of 2,000 min^{-1} and 3,000 min^{-1}. The estimated power P_c is about 25 % and 28 % of ΔP.

6. Summary

Temperature characteristics of spindle supported with water-lubricated hydrostatic bearings were experimentally investigated. Water temperatures at the upstream and downstream of the spindle and the temperature of the spindle body were measured. Then the cooling efficiency of the water flow as lubricating fluid for the hydrostatic bearings was defined and it was shown to be over 80 % in the spindle studied.

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References

[1] Hayashi A and Nakao Y 2017 Evaluation of thermal stability of water-driven spindle *Transactions of the JSME*, **83**, 856, 17-00268 (in Japanese)

[2] Nagasaka K, Hayashi A and Nakao Y 2015 Design of spindle supported by water hydrostatic bearings, *Proc. of ASPE Annual Meeting*, 348-352

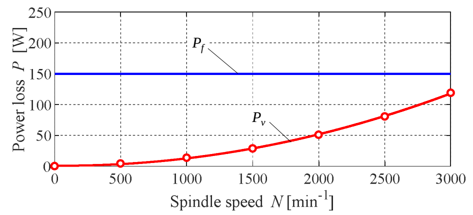

Figure 3. Power losses of water hydrostatic bearings

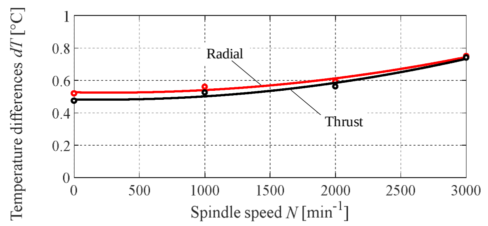

Figure 4. Temperature increase in lubricating fluid

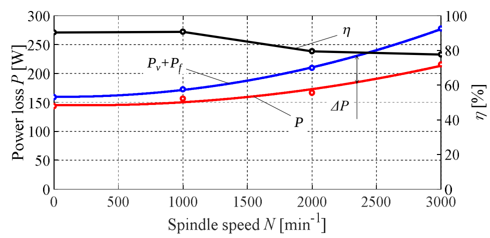

Figure 5. Cooling efficiency of lubricating fluid

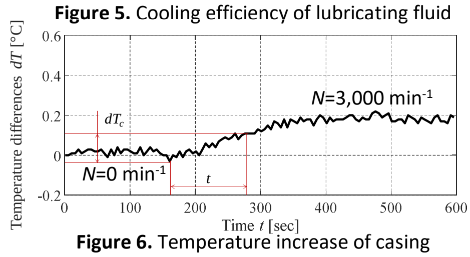

Figure 6. Temperature increase of casing