PERFORMANCE OF WATER ENERGY DRIVE SPINDLE SUPPORTED BY WATER HYDROSTATIC BEARING

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1. Introduction

Spindles used for recent diamond turning machines are typically supported by hydrostatic bearings. Especially, air hydrostatic bearings are the most common because of low viscosity of air. Low viscosity of lubricant fluid is an important requirement for operating the spindle in a range of higher rotational speeds. However, from a stiffness viewpoint of the bearings, higher compressibility of the air can be a disadvantage. From viewpoints of stiffness and stable operation of the hydrostatic bearing, incompressible fluid is desirable. Oil hydrostatic bearings may be an alternative for such case. However, higher viscosity of the oil makes it difficult to operate the spindle in a range of higher rotational speeds. A spindle supported by water hydrostatic bearing would be a better alternative.

An electrically driven built-in type motor is recently designed for the most of the spindles for diamond turning machines. In this case, heat generation at the electric motor can deform the spindle, which must cause serious problems during the spindle operation. In order to attain higher bearing stiffness of the air hydrostatic bearing, the gap between spindle body and housing is usually designed to be very small. Hence, the deformation may cause metal contacts between the two parts. To cope with these problems, a water-driven spindle supported by water hydrostatic bearings has been proposed and developed[1]-[3].

2. Developed Spindle

Figure 1 shows the spindle structure. The spindle driven by pressurized water flow can effectively use the water for three spindle functions, i.e., motor, bearing and cooling functions.

(1) Motor function

In the spindle body, simple bend channels, named flow-out channels, are designed in order that pressurized water flow in the bend channels can generate torque for rotating the spindle. Therefore, the flow channels can be used as a motor. An advantage of the motor is that it can be easily fabricated inside the spindle body. As an additional advantage, the motor structure allows us to design compact spindle.

(2) Bearing function

Water hydrostatic bearings are designed to support the spindle, which makes it possible to
design both higher spindle rotation and bearing stiffness.

(3) Cooling function

Water supplied for the motor and hydrostatic bearing can be used for cooling water as well, which can effectively maintain temperature of the spindle. As a result, a serious deterioration in the machining accuracy due to thermal deformation of the spindle can keep minimum. In addition, the cooling function can effectively avoid the mechanical contacts between spindle body and housing.

In this paper, an experimental result of diamond turning, which has been conducted with the spindle, is presented. In addition, measurement results of the bearing stiffness, which have been conducted in order to consider a cause of unsatisfactory machining result, are also presented.

3. Diamond Turning Test

Developed water driven spindle has been tested for diamond turning. Figure 2 shows the spindle placed on a commercial precision machine tool. Face cutting tests using a single point diamond cutting tool have been conducted in order to investigate performances of the spindle. Aluminum and cupper alloys, A5086 and C1020, have been used as workpiece materials. A surface roughness and a machined workpiece are shown in Fig. 3. In this case, optical quality surface can be successfully obtained. However, the surface roughness, Ra =23 nm, is considerably larger than
the target level in our study.

From the viewpoint of the spindle performance, important factors that affect the surface roughness would be the followings:

(1) Stiffness of the water hydrostatic bearings
(2) Rotational accuracy

In this paper, the issue of bearing stiffness is investigated. The influence of rotational accuracy of the spindle on the machining results will be considered in the future.

4. Measurement of Stiffness of Hydrostatic Bearing

Figure 4 shows a relationship between radial direction forces to the spindle and resultant displacement. In a series of the experiments, the stiffness of the journal bearing has been measured using bearing chokes with two different lengths, i.e. 0.5 and 1.0 mm, respectively. A choke with 1mm in length is originally designed, however, the experiments with the choke, 0.5 mm in length, were conducted in order to examine the influence of the length.

Journal bearing stiffness, when no load torque is applied to the spindle, was designed to be 29 N/µm. However, it is found that actual bearing stiffness is only 29 % of the required stiffness. Because of the insufficient bearing stiffness, slight changes in cutting forces could affect positions of the spindle during diamond turning. It is considered that the insufficient stiffness is a possible reason of the relatively large surface roughness.

Next, a reason of the insufficient bearing stiffness is discussed. Pressure ratios of the hydrostatic journal and thrust bearings were designed to be 0.5, which is the theoretical optimum condition for obtaining maximum bearing stiffness. In this case, theoretically, the recess pressure, \( p_r \), should be a half of the supply pressure, \( p_s \). Pressure-flow characteristics, i.e. flow resistances, of both bearing chokes and hydrostatic bearing surfaces are crucial factors to determine the pressure ratio, \( p_r / p_s \).

Figure 5 shows the pressure-flow characteristics of the choke designed for the hydrostatic journal bearing. The characteristics obtained by the experiments significantly differ from the theoretical relationship. In this case, the actual flow resistance of the choke was approximately 24 times of that of theoretical relationship. If the actual flow coefficient of the hydrostatic journal bearings is the same to the theoretical relationship, actual recess pressure, \( p_r \), becomes approximately only 8 % of the theoretical value.

5. Spindle Speed

Water, supplied from a pump to the spindle, flows primarily into the motor and hydrostatic bearing besides leakage. Flow distributions for the motor and hydrostatic bearings are determined by flow resistances of the two parts. Therefore, the characteristics of the bearing choke presented in Sec. 4 affect not only the characteristics of the hydrostatic bearing but also that of the spindle motor. More specifically, the motor flow should be larger than the expected since the actual flow resistance of the bearing choke became significantly large.

Figure 6 shows the spindle speed characteristics. In fact, it is found that the spindle speed obtained theoretically, which is given by a dashed line, is lower than that of experimental result. In contrast, the solid line, which is calculated with the measured flow coefficient of the bearing choke, shows the relatively similar trends to the experimental result. From these results, it is verified that the
characteristics of the bearing choke play an important part of the spindle motor performances as well as the bearing stiffness.

6. Summary

A water-driven spindle developed for ultra-precision machine tools was tested for diamond turning. An optical quality surface was generated in the test. However, the surface roughness did not reach required level.

In order to investigate the unsatisfactory result of the diamond cutting test, a stiffness of the water hydrostatic bearing has been measured. As a result, low stiffness of the bearing was appeared. An experiment to measure the pressure-flow characteristic of the choke of the hydrostatic bearing has been conducted. The result shows that the flow resistance of the choke is too high to obtain an optimum stiffness of the bearing. This issue is now being investigated in our study.

It is considered that the rotational accuracy of the spindle must be another factor to determine the diamond cutting performance. Therefore, the rotational accuracy of the spindle will be measured and investigated. Especially, an influence of supply water pressure pulsation on the machining performance could play important factor.

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