WATER ENERGY DRIVE SPINDLE SUPPORTED BY WATER HYDROSTATIC BEARING FOR ULTRA-PRECISION MACHINE TOOL

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Key words: Advanced Spindle, Hydraulic Built-in Motor, Water Hydrostatic Bearing, Ultra-precision Machine Tool

1. Introduction

Ultra-precision machine tools are essential for machining precision parts such as molds for various plastic lenses, polygon mirrors for laser printers and so on. Precise motions of the machine tools; i.e., rectilinear and rotational motion; are very important requirements to attain precision machining, in addition to an advanced control algorithm for machine tool control. For the advanced control issue, Nakao and Dornfeld have presented an effective control algorithm[1]; which is termed the position and AE dual feedback control; for diamond turning machine. It has been shown that the control technique is effective to improve an accuracy of the geometric generating motion of precision machine tool.

This paper presents a new spindle to attain precise rotational motion. The present spindle effectively uses water flow. That is, the water flow can be used for rotating the spindle; i.e., built-in motor; supporting the spindle; i.e., hydrostatic bearing; and cooling the spindle. This paper first describes principles and structure of the spindle. Then performances of the designed spindle are discussed through theoretical and experimental studies.

2. Principle and structure of proposed spindle

Figure 1 illustrates the spindle structure proposed in this study. This spindle has three features, which all use water flow effectively. The features are described in this section.

2.1 Motor function (Hydraulic built-in motor)

First feature of the spindle is that rotational motion of the spindle is generated by water flow energy[2], [3]. In order to rotate the spindle, simple flow channels are designed in the spindle body so that water flow in the channel can generate torque for rotational motion. Pressurized water is supplied from the outside of the spindle into a flow channel; named the main channel; which passes through the center of the spindle in axial direction. After water flows the main channel, the water is discharged from the main channel to outside of the spindle, again, in order to generate torque for spindle rotation. For generating the torque, bend-formed channels, termed the flow-out channel, are designed at two cross sections of the spindle. As illustrated in Fig. 1, the flow-out channels are located between the main channel and the outer surface of the spindle. Flowing water through the flow-out channels, angular momentum of the water flow alters significantly. Therefore, torque to rotate the spindle can be generated, which is based on the angular momentum theory. It is noted that the simple flow

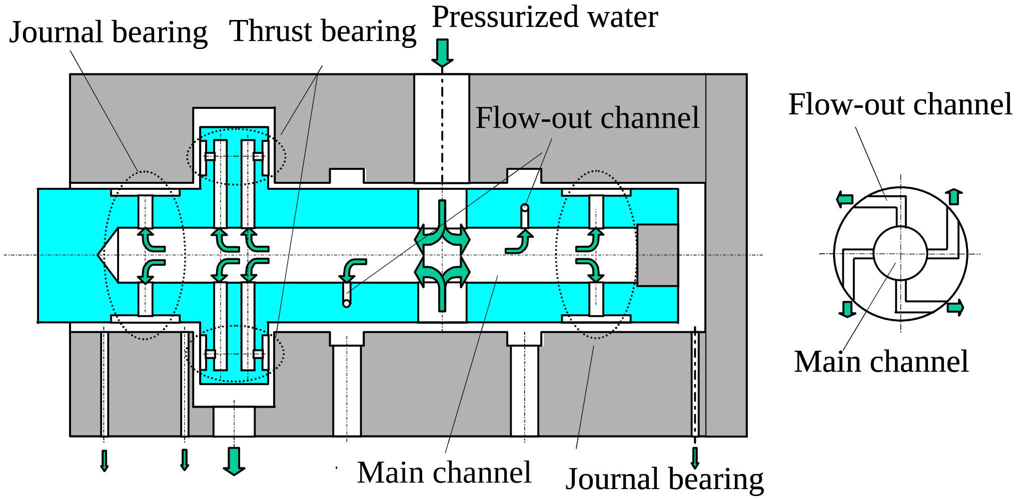

Fig. 1 Structure of proposed spindle

channels; the main channel and the flow-out channels; operate as a built-in motor driven by water flow.

2.2 Supporting function (Water hydrostatic pressure bearing)

Second feature of the spindle is that water hydrostatic bearings support the spindle. The water flow supplied to the spindle is used as lubricant fluid for the water hydrostatic bearings as well as the working fluid for the built-in motor, described in Section 2.1. Advantages of the water hydrostatic bearing of the spindle are the followings:

(i) Since water is the incompressible fluid, the water hydrostatic bearing is more suitable for the design of an advanced spindle with higher bearing stiffness. In contrast, conventional spindle used for most of the ultra-precision machine tools uses air for hydrostatic bearing as the lubricant fluid. In this case, due to higher compressibility of air, it is not easy to design a hydrostatic bearing with higher stiffness. In spite of the difficulty, an air hydrostatic bearing with higher stiffness is still needed, designer have to design larger bearing surface area and small gap size of bearings. However, larger bearing surface needs large and/or longer spindle. It is apparent that both requirements; i.e., larger bearing surface area and small gap size of the bearing; are very difficult to be attained in machining and fabricating process of the spindle.

(ii) The viscosity of water is smaller than that of oil, which enables us to operate the spindle with higher rotational speeds.

2.3 Cooling function

Third feature of the spindle is a cooling function for the spindle. Water is effectively cool the spindle, because water flows both inside and outside of the rotating spindle body. Therefore, controlling water temperature minimizes the spindle deformation due to thermal effects. In addition, in comparison with oil, water has an advantage in terms of cooling performance, since the thermal conductivity of water is higher than that of oil.

3. Calculated spindle performance

In order to develop the present spindle in a design process, it is the most important issue to determine sizes of main parts of the spindle that affect spindle performances. For example, design parameters to be determined are gap size between casing and spindle, diameter of the flow-out channel, gap sizes at each hydrostatic bearing and so on. In this study, mathematical model to represent spindle performance have been derived. Based on the mathematical model, design algorithm and software have also been developed to determine principal design parameters in order to satisfy given specifications; i.e., rated power, rated rotational speed and stiffness of hydrostatic bearings. The developed software for spindle design can calculate 10 design parameters. Using the software, a set of optimum parameters can be calculated so as to obtain highest efficiency at given operational condition. Spindle performances obtained by theoretical studies are given by Figs. 2 to 4, respectively.

4. Experimental results

Figure 5 shows the developed spindle. A performance of rotational speed is given by Fig. 6. This figure shows experimental result as well as theoretical result. It is shown that a rotational speed of the spindle reaches 10,000 rpm by supplying 20 *l*/min water flow.

Figure 7 shows water temperature during spindle operation. A water temperature control unit is equipped to a water supply unit, and water temperature was set to 20 degree in this experiment. As a consequence, water temperature was controlled from 19.8 to 20.8 degree. Therefore, it is considered that the water flow inside and outside of the spindle body can minimize spindle deformation due to the thermal effects by not only spindle operations but also cutting operations.

5. Summary

A spindle driven by water flow energy for ultra-precision machine tool was presented. Principles of the spindle operation and spindle structure were also presented. Theoretical and experimental studies showed performances of the spindle. Rotational motion accuracy of the spindle and stiffness of the water hydrostatic bearings will be measured in future work. Then the developed spindle will equipped with an ultra-precision machine tool for precision machining experiments.

Motor, hydrostatic bearings and cooling function, which are all operated by water flow energy, are fully integrated into the developed spindle, effectively. In addition, since water is the incompressible fluid, water hydrostatic bearings has an advantage for designing higher stiffness bearing with small bearing size. In fact, the developed spindle size is small. This advantage means that the spindle is suitable for the meso scale precision machining.

The developed spindle can be operated by water flow, including pure water. It is, therefore, considered that the spindle can be used in semi-conductor plants. New applications in such attractive field will be explored.

This research work is financially supported by the Grant-in-Aid for Scientific Research (C) of Japan Society for the Promotion of Science.

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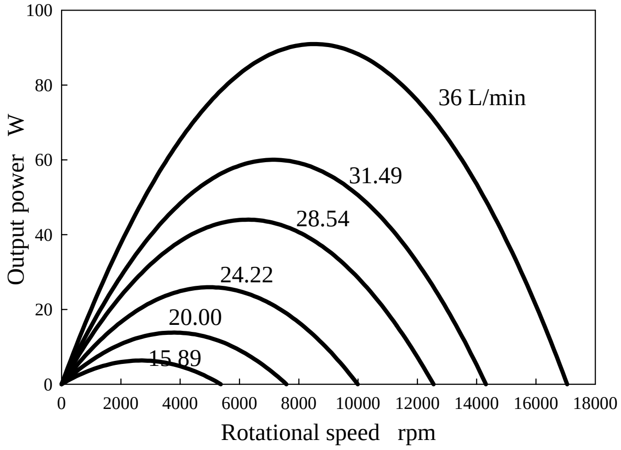

Fig. 2 Relation between rotational speed and power

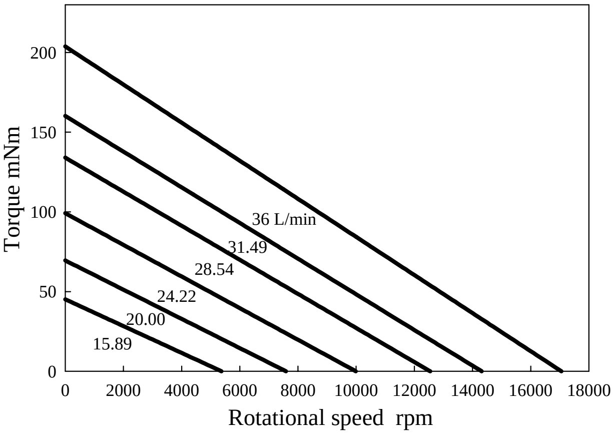

Fig.3 Relation between rotational speed and torque

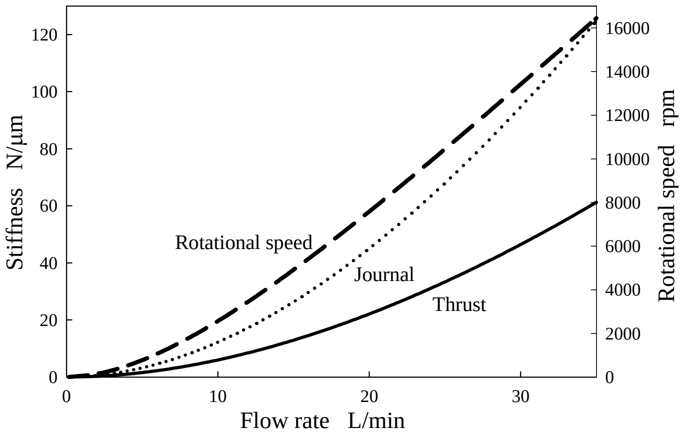

Fig. 4 Relation between flow rate and stiffness and rotational speed

Fig. 5 Developed spindle

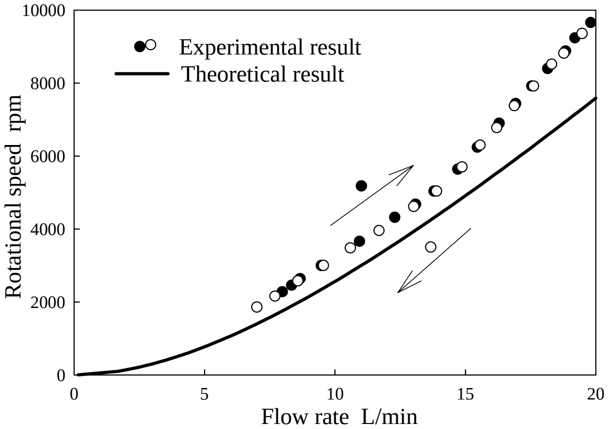

Fig. 6 Relation between flow rate and rotational speed

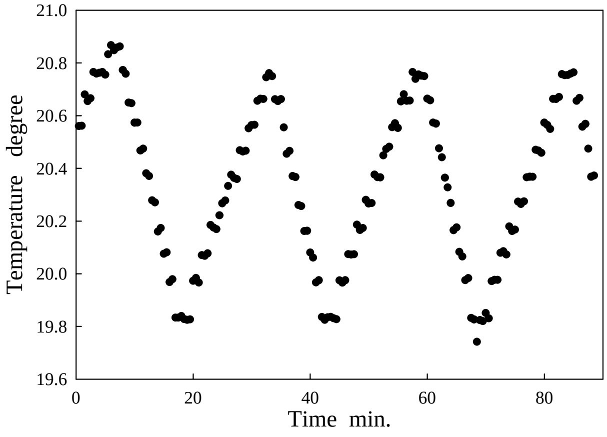

Fig. 7 Cooling water temperature