Feasibility study on a spindle supported by high stiffness water hydrostatic bearings for ultra-precision machine tool

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Abstract

A prototype of a spindle supported by water hydrostatic thrust bearings is considered in the present paper. Stiffness of the bearing of the spindle is designed to be 1 kN/μm. Due to lack of the lubricative property of water, several materials for the bearing parts are considered.

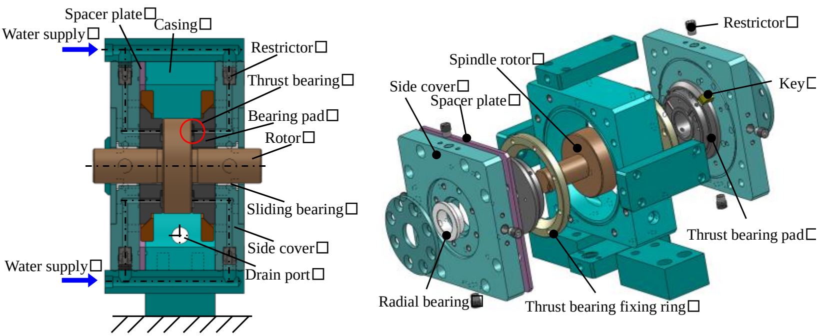
1 Introduction

A design of the spindle supported by water hydrostatic bearings for ultra-precision machine tools is considered in this paper. Bearing stiffness for the ultra-precision machine tools is a crucial characteristic to be taken into account in the spindle design. Besides the bearing stiffness, precise rotational motion accuracy and thermal stability of the spindle are important as well. In order to meet the requirements, the hydrostatic bearings are in many cases used to support the spindle. Among them, the water hydrostatic bearings[1]-[4] can be a suitable candidate for the bearing, because of the low viscosity and high thermal conductivity of water.

In general, the stiffness of the hydrostatic bearings increases with the increase in the supply pressure of the lubricant fluid. Thus, the stiffness of oil or water hydrostatic bearings is relatively easy to increase. However, the higher viscosity of oil must be a disadvantage in the higher spindle speed operation. On the other hand, in the case of air bearings, allowable maximum pressure is restricted due to the compressibility of air. These considerations indicate the water hydrostatic bearing is suitable for the spindle application if the higher bearing stiffness is required.

Accordingly, this paper studies a spindle design supported by the water hydrostatic bearings. An objective of the new spindle design is to aim the thrust bearing stiffness of 1 kN/μm. The paper thus considers a design of the water hydrostatic thrust bearings. Specifically, we consider the influences of the supply pressure and bearing gap on the achievable bearing stiffness.

In the design of the water hydrostatic bearings, the materials of the mating surfaces should be appropriately chosen. We thus consider materials for the bearing pads to made of gun metal, engineering ceramics, carbon impregnated resin and polyetheretherketone (PEEK) as the candidates of the materials. Before designing actual spindle for the ultra-precision machine tool, a spindle with simplified structure is designed as a prototype. The structure and materials of the spindle is presented with the characteristics of the water hydrostatic bearings of the spindle.



(a) Cross section of spindle (b) Exploded view

Figure 1: Structure of designed spindle with water hydrostatic thrust bearings

2 Designed prototype spindle with water hydrostatic thrust bearings

A structure of designed prototype spindle is given in Fig. 1. The spindle is equipped with water hydrostatic thrust bearings. Meanwhile sliding journal bearings, instead of water hydrostatic radial bearings, are used to support the spindle rotor in the radial directions. Thus we consider the design of the water hydrostatic thrust bearings for the spindle in this paper.

All the parts of the spindle except for the bearing pads and sliding journal bearings are made of the stainless steel. As shown in Fig. 1, the rotor is placed between two bearing pads that are fixed on side covers. The bearing pads shown in Fig. 2 are exchangeable so that various pads made of different materials can be tested in experiments. In the present study, several bearing pads are made of gun metal, engineering ceramics, engineering plastics and carbon impregnated resin. Among the materials, it is considered that the gun metal and the carbon impregnated resin have better wear characteristics in the water lubrication. In particular, the carbon impregnated resin has many industrial applications in water lubrication, because of its self-lubricating property. Operating tests are currently being prepared using different pads to find suitable material for the water hydrostatic bearings. The results will be compared in the future work. The sliding journal bearings are made of the engineering plastics.


Figure 2: Bearing pad

As well known, the bearing gap is a critical parameter determining the bearing stiffness. Thus, the spindle is designed so that the gap of the thrust bearing can be changed using a spacer plate that is placed between spindle casing and a side cover. Bearing restrictors that are carefully designed[4] are inserted in the both side plates.

3 Design of water hydrostatic thrust bearing

For precision machine tool applications, the bearing has to be designed with careful considerations on the bearing stiffness. Assuming cutting force is 1 N during single point diamond turning. The resultant displacement of the bearing due to the cutting force must be minimized. If the displacement is needed to be less than 1 nm, the required bearing stiffness reaches 1 kN/μm. For next generation of the precision machining, a spindle with the stiffness of 1 kN/ μm is highly desired.

The thrust bearing of the designed spindle is a multi-recess opposed pad bearing. The outer and inter diameters of the bearing pad are 82 mm and 32 mm, respectively. The stiffness of the bearing is calculated as given in Fig. 3. It is given for various bearing gaps h_0, showing the stiffness of 1 kN/ μm is achieved if the gap and the supply pressure are 17 μm and 3 MPa, respectively. In order to prepare a water pump for the designed hydrostatic bearings the required flow rate for the bearings is needed for estimating the power and size of the pump. Therefore, the water flow rate is calculated for various gaps and the supply pressures as shown in Fig. 4. This indicates that the required water flow rate is about 7.5 L/min, thus the power of pump becomes 375 W.

In this spindle design, the spindle speed in the normal operation is considered to be 2,000 - 3,000 min^{-1}. The loss of the power due to the viscosity of water during spindle rotation must be taken into account. For instance, the supply of water flow increases the temperature of water. This must be minimized by an appropriate water temperature control system that will be designed in our future work.

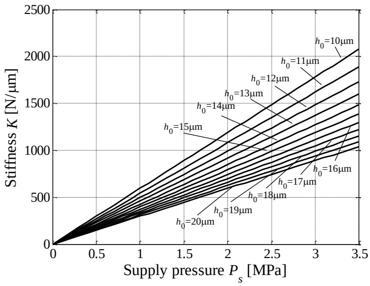


Figure 3: Bearing stiffness

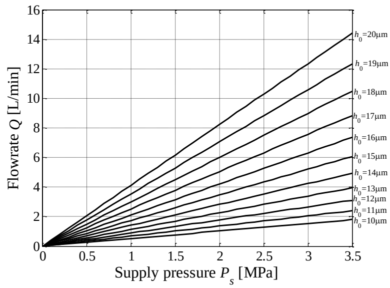


Figure 4: Flow rate for designed bearing

4 Summary

A spindle design supported by water hydrostatic thrust bearings was considered in the paper. An objective bearing stiffness was 1 kN/μm in order to improve machining accuracy of the single point diamond turning. It is then verified that the bearing stiffness of 1kN/μm is obtained by the supply pressure 3 MPa and the gap of 17 μm for given bearing sizes; inner and outer diameters are 32 mm and 82 mm, respectively. The bearing part of the spindle is exchangeable. Thus various materials will be tested in the experimental works for finding suitable material combination for the water hydrostatic bearings.

Acknowledgement

This research work is financially supported by the Mitutoyo Association for Science and Technology.

References:

[1] Y. Nakao, M. Mimura, and F. Kobayashi, Water Energy Drive Spindle Supported by Water Hydrostatic Bearing for Ultra-Precision Machine Tool, Proc. of ASPE 2003 Annual Meeting, pp. 199-202, 2003,.

[2] A. Slocum, et al., Design of Self-Compensated, Water-Hydrostatic Bearings, Precision Engineering, Vol. 17, No. 3, pp. 173-185, 1995.

[3] Y. Nakao, M. Kawakami, Design of Water Driven Stage, Proceedings of 9th International Conference of the European Society for Precision Engineering and Nanotechnology, Vol. 1, pp. 200-203, 2009.

[4] Y. Nakao, S. Nakatsugawa, M. Komori and K. Suzuki, Design of Short-Pipe Restrictor of Hydrostatic Thrust Bearings, Proc. of ASME 2012 International Mechanical Congress and Exposition, CD-ROM, 2012.