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Displacement control of water hydrostatic thrust bearing by hybrid use of constant resistance restrictors and flow control valve

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Abstract
Displacement control of a water hydrostatic thrust bearing is considered. Hybrid use of conventional constant resistance restrictors and a commercialized flow control valve controlled by applied electrical voltage is applied to the bearing control. A feedback control system is then designed for the water hydrostatic bearing system. The performance of the control system is tested experimentally. The result shows that positioning accuracy of 0.2 micrometers can be achieved. Infinite stiffness of the bearing is also successfully achieved. Furthermore, the designed control system reveals the excellent control performance against external load changes.

Keywords: Water hydrostatic bearings, Ultra-precision machine tools, Feedback control system, Displacement control, Water hydraulics

1. Introduction

Precise motions of the spindle and table of ultra-precision machine tools are significantly important. Accordingly, most of the ultra-precision machine tools are equipped with hydrostatic bearing systems [1]. Among them constant pressure types of the hydrostatic bearing systems are generally used. For the ultra-precision machine tools, the higher bearing stiffness is the important index rather than the load capacity. However, due to its working principle of the bearings, external forces acting on the bearing cause resultant displacement of the bearings, degrades the machining accuracy.

Spindles supported by water hydrostatic bearings for ultra-precision machine tools have been designed and studied [2-4]. The water hydrostatic bearings are advantageous for achieving higher bearing stiffness because of the incompressibility of water. In addition, the water hydrostatic bearings give excellent thermal stability due to both higher heat conductivity and low viscosity.

This paper considers displacement control of a water hydrostatic thrust bearing by designing feedback control system. If desired displacement is set to be a constant value for the control system, the bearing displacement can be constant regardless of the change of external forces acting on the bearing, achieving the infinite stiffness of the bearing.

In this study, a commercialized flow control valve is used with conventional constant resistance restrictors to control the flow rate for the water hydrostatic bearing. Based on a consideration on the suitable layout of the conventional constant resistance restrictors and the flow control valve, a hybrid use of the constant resistance restrictors and electrically controllable flow control valve is proposed and designed.

The designed feedback control system is applied for the control of a water hydrostatic thrust bearing that sustains a rotary table with water hydrostatic radial bearings. The performance of the control system is tested via experiments. The results show that infinite stiffness of the bearing is successfully achieved. In addition, step commands are applied to the control system. The results show that positioning accuracy less than submicron is also verified. Furthermore, the designed control system reveals the excellent control performance against external load changes.

2. Water hydrostatic thrust bearing

2.1. Rotary table supported with water hydrostatic thrust and radial bearings

A water hydrostatic thrust bearing studied is a single pad and multi-recess type bearing as depicted in Fig. 1. Four recesses are made on the bearing surface. A rotary table is supported by the water hydrostatic thrust and radial bearings. All the component of the water hydrostatic bearings and the rotary table are made of stainless steel in order to prevent the parts from corrosion.

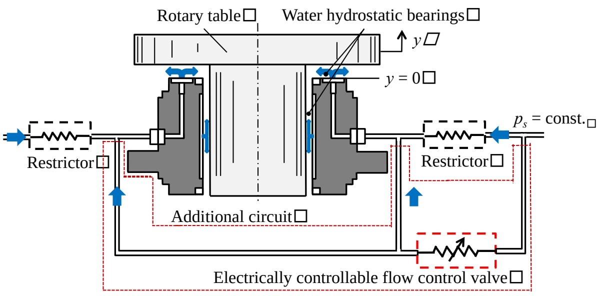

Figure 1. Structure of water hydrostatic thrust bearings with constant resistance restrictors and flow control valve

2.2. Water hydrostatic bearings with hybrid use of constant resistance restrictors and flow control valve

In order to control recess pressure of the bearing, an electrically controllable flow control valve is added to the water hydrostatic bearings with constant restrictors as shown in Fig. 1. Layout of the restrictors and the flow control valve is illustrated in Fig. 2. The regular recess pressure to sustain the table is controlled by the restrictors. By contrast the flow control valve placed in parallel with the constant restrictors supplies and controls additional water flow to increase the recess pressure in accordance with the increase of external loads. The control of the flow control valve can be made independently of the original bearing functions with the restrictors. In addition, it should be noted that the control system can be added to the existing conventional hydrostatic bearing systems afterwards, in order to improve its performances.

An advantage of the hybrid use of the constant resistance restrictors and the flow control valve is that the function of the restrictors and the valve can be separated as presented. If the restrictors are replaced with a flow control valve, the flow control valve has to control flow rate precisely and widely. This makes it difficult to design and fabricate the valve. In addition, the achievable improvement in the control performance is thus limited.

Displacement of the table is measured with a capacitance sensor set under the rotary table. Flow control valve is controlled using a PC based controller. A PI control system was designed and used for the control.

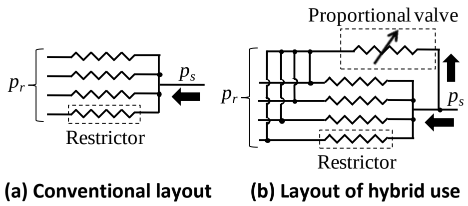

Figure 2. Layout of hybrid use of restrictors and flow control valve

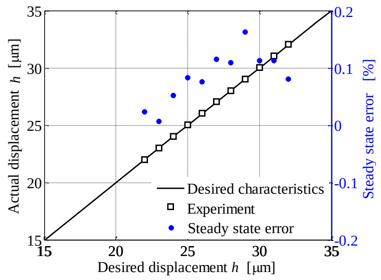

Figure 3. Static characteristics of designed displacement control system

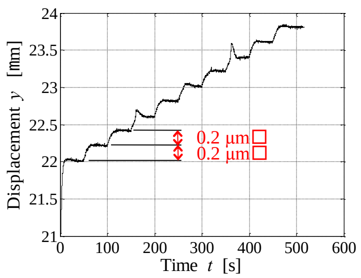

Figure 4. Step response and resolution of control performances

3. Experiments and considerations

The designed PI control system for the hybrid use of the constant resistance restrictors and the flow control valve was tested experimentally. Static characteristics and positioning accuracy of the control system were first tested. As given in Fig. 3, the measured static characteristics indicate that the designed control system is capable of controlling the displacement with the steady state error less than 0.2 %. In addition, the dynamic response of the control system was investigated by the step response method. In the experiment, a series of step signals of 0.2 micrometers step were input and the response was measured as depicted in Fig. 4. The result also shows that the designed water hydrostatic bearing system successfully controlled the table displacement with 0.2 micrometers step. The setting time of about 6 seconds was observed. It will be reduced by modifying the controller.

Response of the designed water hydrostatic bearing system against the external load of 9.8 N was investigated. In the experiment, a constant mass of 1 kg was placed on the table so that response of the system against stepwise external load can be observed as presented in Fig. 5. It is shown that the table position was lowered due to the applied external load. The maximum displacement of the table due to the loads became 0.8 micrometers instantaneously. It is however verified that the designed controller compensated the influence of the load successfully. The dynamic response will be improved by adding a disturbance observer to the feedback controller.

The control system was tested with different additional loads. In the experiments, the desired signal of the constant displacement of 22 micrometers was input so that stiffness infinity performance can be investigated. As given in Fig. 6, the stiffness of the water hydrostatic bearing system with designed controller is infinite if the external load is less than 350 N.

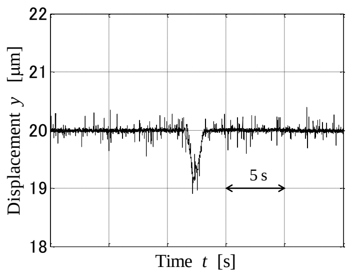

Figure 5. Step response against applied external load

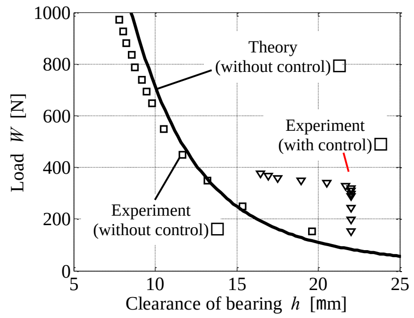

Figure 6. Bearing stiffness of designed control system

4. Summary

A hybrid use of conventional constant resistance restrictors and electrically controllable flow control valve was proposed and applied to the control of displacement of water hydrostatic thrust bearings. The characteristic of the designed control system was investigated experimentally. In the experiments, static as well as dynamic characteristics including the response against external load changes were studied. The results show that the control system revealed excellent performances.

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