euspen's 17th International Conference & Exhibition, Hannover, DE, May 2017
www.euspen.eu

Feasibility study on nano tracking control of axial displacement of spindle using hydrostatic thrust bearings

Yohichi Nakao [1], Yasumasa Yamada [1] and Akio Hayashi [1]

[1] *Kanagawa University*

nakao@kanagawa-u.ac.jp

Abstract

Nano-order displacement control of water hydrostatic thrust bearings in the axial direction is considered. In particular, the displacement control according to time varying control signal is experimentally investigated with step inputs and sinusoidal inputs. The displacement control of the hydrostatic thrust bearings is carried out by the flow control of the lubricating fluid of hydrostatic bearings that is made using electrically controllable flow control valves. It is then verified that the displacement of the hydrostatic bearings was successively controlled with the nano-order accuracy. The tool wear and/or the thermal deformation of the ultra-precision machine tools will be compensated by the nano tracking control system developed in this study.

Keywords: Hydrostatic bearings, Displacement control, Flow control, Machine tool spindle, Ultra-precision Machine Tools

1. Introduction

In order to improve the performance of the spindle of the ultra-precision machine tools, displacement control of the constant pressure type of the hydrostatic thrust bearings has been considered in our previous study[1,2]. In principle, the resultant displacement of the hydrostatic bearings due to the change in the external forces is inevitably taken place. To cope with the problem, a bearing displacement control system has been designed. In order to control the bearing displacement, the lubricating flow into the bearing surfaces was controlled using electrically controllable flow control valves. The control performances of the designed control system were tested. Static and dynamic characteristics of the feedback control system were investigated experimentally. Then the following results were drawn.

(1) The steady state error was less than 0.2 nm. In addition, the control resolution was less than 50 nm.
(2) The settling time of the system was about 0.1 seconds when the external stepwise load of about 1 N was applied.

The results indicate that the designed control system can compensate the undesirable bearing displacement due to the change in the external loads acting on the bearings.

Now, if the displacement in the axial direction of the hydrostatic thrust bearings can be controlled for the time varying command signal, such as sinusoidal signals, special function such as micro actuating operations of the spindle can be added to the spindle system. For instance, the control system can be used for adjusting small depth of cut. Furthermore, the control system can be applied as the compensation device for tool wear and/or thermal deformation of the machine tool, as well.

In this study, the control performance of the designed control system is investigated for the control application with the time varying desired signals. First, the step responses of the control system are presented. Furthermore, the sinusoidal signals with various frequencies are input to the system. Then the tracking performances are investigated.

2. Structure of displacement control system

Axial displacement of the spindle supported by hydrostatic bearings is controlled by controlling supplied flow rate into the bearings. As depicted in Fig. 1, an opposed pat type of the water hydrostatic thrust bearing is considered. Flow control valves control the bearing displacement in the axial direction.

Recess pressure of the hydrostatic bearings can be controlled by changing the flowrate of lubricating fluid. By adding appropriate feedback loop, the axial bearing displacement can be controlled according to the control command signal. In the control system, commercialized electrically controllable flow control valves were used. The flow control valves are used with the bearing restrictors as presented in Fig. 2.

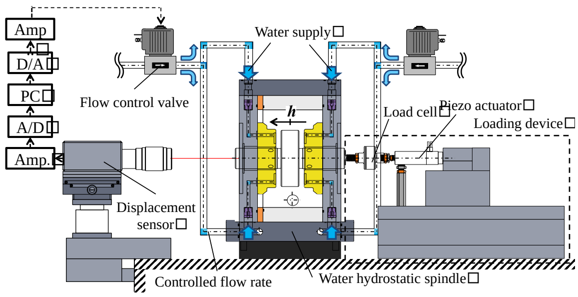


Figure 1. Hydrostatic thrust bearings with displacement control system

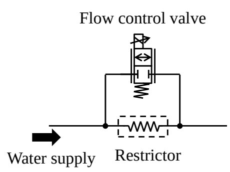


Figure 2. Flow control valve and restrictor

3. Designed control system

In advance of the design of the feedback control system, mathematical model of the hydrostatic bearing system with flow control valves was introduced and it was then linearized. In this study, one of the flow control valves is used for controlling the bearing displacement. The structure of the controlled system is presented as Fig. 3.

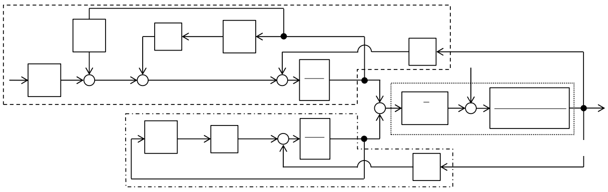


Figure 3. Structure of controlled system

In this study, the direction of the bearing displacement where the rotor moves to left as depicted in Fig. 1 is defined to be positive. If the external load is zero, the transfer function between the applied voltage and the bearing displacement is introduced as Eq. (1).

$$G_{parallel}(s) = \frac{-m\bar{A}AR_{p11}}{Ms^2 + cs + k - m\bar{A}A(R_{p12} + R_{p2})} \quad (1)$$

A conventional PI feedback control system is designed for the bearing displacement control system. In the experiments, the bearing displacement was measured using the laser displacement sensor, as presented in Fig. 1.

4. Experimental results

Performances of the designed control system were investigated experimentally. Step response of the control system is shown in Fig. 4 with the input voltage. In the experiment, the spindle moved to the right. The step size was 10 nm. It is then verified that the bearing displacement of the 10 nm resolutions was effectively controlled. Furthermore, the time constant of the control system is approximately 0.3 seconds.

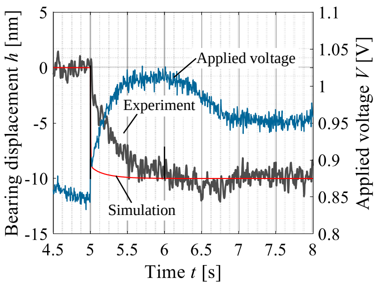


Figure 4. Step response of designed control system

In addition to the step response of the control system, the tracking performance of the designed control system was investigated with sinusoidal input signals with different frequencies as depicted in Figs. 5 (a)-(c). The spindle displacement is precisely changed according to the desired signal if the input frequency is 0.1 Hz. If the frequency is increased as presented in Figs. 5 (b) and (c), the tracking error is obviously observed, however the smooth sinusoidal response is still made. From the experiments, the frequency characteristics of the designed control system are given as shown in Fig. 6. In the results, delay in the response is obvious as well.

The delay in the response is due to the characteristic of the designed control system. In the study, a conventional PI feedback control system was designed for the control system. The dynamic characteristics of the system will be improved by designing a sophisticated controller. The improvement of the control performance will be considered as a next step of the work.

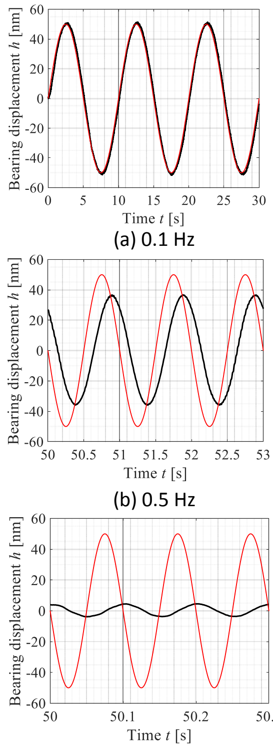
5. Summary

Displacement control of the water hydrostatic thrust bearings was considered. In particular, the tracking control with nano order displacement was studied. In the step response of the system, the better response was observed. The time constant of the system was about 0.3 seconds. The tracking performance of the system was also investigated via sinusoidal inputs with different frequencies. Smooth responses according to the sinusoidal commands with low frequencies were obtained. Further improvement to reduce tracking error will be needed, it will be considered in the future work.

References

[1] Nakao Y, Yamada K and Suzuki K, Design of Spindle Supported by High Stiffness Water Hydrostatic Thrust Bearing, Proceedings of the ASME 2013 International Mechanical Engineering Congress and Exposition IMECE 2013, (2013).

[2] Yamada Y, Hayashi A and Nakao Y, Design of positioning control system of opposed pad water hydrostatic thrust bearings, *Proc. of ASPE Annual Meeting*, (2016).



(c) 10 Hz

Figure 5. Response of control system against sinusoidal inputs

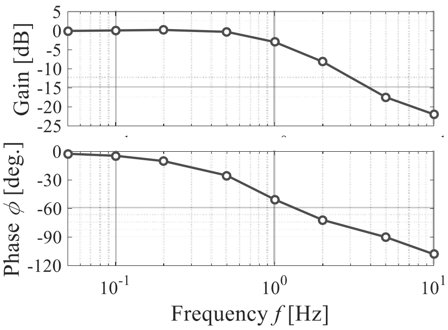


Figure 6. Frequency response of designed control system