CONTROLS OF PITCHING AND STRAIGHTNESS ERROR MOTION OF WATER DRIVEN STAGE DURING FEED MOTION

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Abstract. Simultaneous control of the pitching and straightness error motion of the water driven stage is considered. The table of the developed water driven stage is supported by the water hydrostatic bearings. Furthermore, the table is driven by a water-driven mechanism fabricated inside the table. Accordingly, the table moves without any mechanical contacts. In addition, recess pressures of the water hydrostatic bearings can be controlled separately, achieving the controls of the pitching and straightness error motion of the table. However, the pithing control interferes the control of the straightness error motion of the table. To cope with the problem, this paper designs a cross-coupled control system. Control performance of the designed control system is experimentally investigated. Then, the designed control system achieves the pitching of 0.5×10^{-3} degrees and the straightness error motion of 93 nm during feed motion, simultaneously.

Keywords: Water hydraulics, Pitching control, Cross-coupling control, Hydrostatic bearings, Ultra-precision machine tools

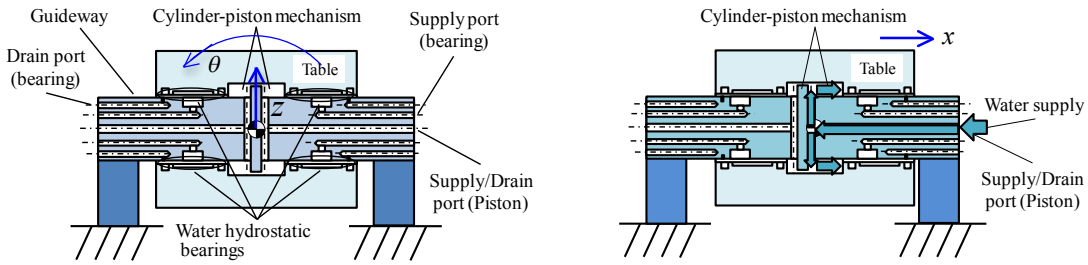
INTRODUCTION

The water driven stage that can be used for a feed table of the ultra-precision machine tools was developed in our previous study[1]. The table of the stage is supported by water hydrostatic bearings. Generally, lubricating fluid of hydrostatic bearings is oil or air. However, by using water as the lubricating fluid, the generation of frictional heat can be effectively reduced, because the viscosity of water is less than that of oil. Because of the incompressibility of water, the water hydrostatic bearings achieve higher bearing stiffness and load capacity than air pressure bearings. In addition, the higher thermal stability of the stage is expected because of the large heat capacity and the thermal conductivity of water. The table of the stage can be driven by supplied water into the internal cylinder-piston mechanism of the stage. Since the driving force due to the mechanism acts on the center of gravity of the table. Consequently, the drive mechanism suppresses undesirable pitching and yawing of the table effectively. Although the driving force of the water driven stage acts on the center of gravity of the moving table, the attitude error including the pitching cannot be perfectly removed. For instance, the attitude error is occurred due to the form error of the guide-way and the off-center external loads such as the cutting force acting on the workpiece set on the table. In our previous study[2], in order to achieve further improvement of the machining accuracy, the pitching control system of the water driven stage has been designed. The performance of the pitching control system has been investigated via experiments. However, if the pitching of the table is only controlled, unintended resultant straightness error motion of the table was generated. The purpose of this study is to design a control system that can control both of the table pitching and straightness error motion according to the command signals, regardless of the form error of the guide-way and the off-center external loads.

WATER DRIVEN STAGE

Figure 1 shows the structure of water driven stage[3]. The table of the water driven stage can be driven by the internally fabricated water hydraulic piston-cylinder mechanism with square cross-section. A structural feature of the water driven stage is the laterally and vertically symmetrical structures. Accordingly, the driving force due to the water hydraulic system acts on the center of gravity of the table. As a result, the pitching and yawing error motions of the table, causing the machining error of the ultra-precision machine tools, due to the driving

forces can be minimized. Another feature of the stage is that the table is supported in non-contact by water hydrostatic bearings.
In addition, the water supplied to the water hydraulic drive system and the water hydrostatic bearings can be also used as the cooling media to avoid the temperature change of the stage, achieving better thermal stability of the stage. In general, the lubricating fluid of hydrostatic bearings for ultra-precision machine tools is air or oil. In contrast, water as the lubricating fluid of the hydrostatic bearings is advantageous because it generates less friction forces than oil hydrostatic bearings. Furthermore, water hydrostatic bearings are appropriate for achieving higher bearing stiffness than air pressure bearings.
In order to maintain constant feed motion of the developed water driven stage, the speed control system was designed. The performance of the speed control system of the water driven stage was then investigated via experiments and simulations[1]. An important demand for achieving further improvement of the machining accuracy of the ultra-precision machine tool is to control the pitching and straightness error motions, though effective approaches to achieve them are not established yet.
It should be now mentioned that each recess of the water hydrostatic bearings of the stage has independent water-supply ports. Thus, each recess pressure can be controlled independently using an appropriate control system. Attitude of the table such as the pitching can then be controlled by controlling a combination of the bearing pressures of the separated bearing recesses. Similarly, the straightness error motion such as the displacement of the table in the lateral and vertical directions except for the feed direction of the table can be controlled as described in the paper.
The control of the attitude and the straightness error motion can be made within the short range of the bearing gaps, meaning the controllable displacement of the control system is quite limited. In return for the limitation of the controllable displacement, the precise control can be made. This will be attractive advantage for the ultra-precision machine tool applications.



(a) Water hydrostatic bearings (b) Water hydraulic driving structure

FIGURE 1. Water driven stage

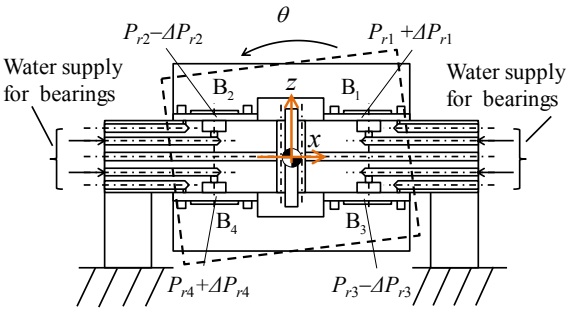


FIGURE 2. Pitching and straightness error motion

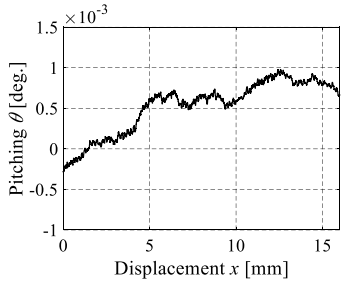
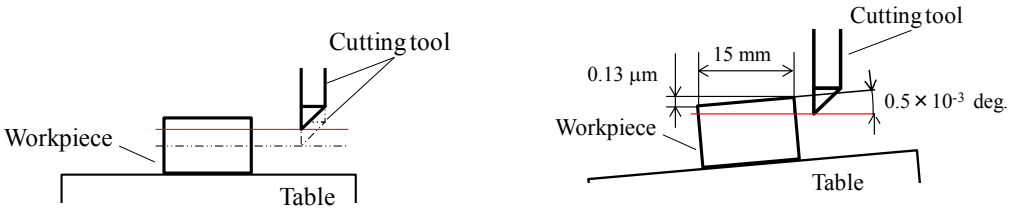


FIGURE 3. Pitching motion without designed controller



(a) Cutting without error motion (b) Cutting with pitching error motion

FIGURE 4. Influence of pitching motion on machining accuracy

CONTROL PRINCIPLE OF PITCHING AND STRAIGHTNESS EROR MOTION

The water driven stage is a linear table in which the table moves in the direction of x in Fig. 2. The paper considers the control of the pitching denoted by θ and the straightness error motion of the center of gravity of the table, namely the undesired displacement z in the vertical direction. The paper only considers the table motion in the plane shown in Fig. 2. The error motions are generated due to the structural errors of the guide-way and/or the external forces including the cutting forces acting on an off-center position of the table.
The ideal motion of the water driven stage is to move only along the x-direction in Fig. 2. However, an actual motion of the table has pitching error component as presented in Fig. 3. The straightness error motion of 0.21 μm was also observed. In this case, if the water driven stage is used for the grooving operation as shown in Fig. 4. The resultant error motions including the pitching and the straightness error motion changes the depth of cut.
For the next generation's precision parts used in the leading-edge industries, desired machining accuracy for the ultra-precision machining attains several tens of nanometers. Accordingly, further improvement of the motion accuracy of the ultra-precision machine tool is absolutely needed. Control objectives considered in the paper are thus to control both the pitching θ and the straightness error motion defined by the displacement of the center of gravity of the table in the z direction during feed motion.

Measurement of pitching and straightness error motion

Measurement and control system of the water driven stage is presented in Fig. 5. The pitching of the table of the water driven stage is measured by a laser tilt sensor. The output signal of the sensor is the electric voltage that is fed into the PC based controller via a 14 bits A/D converter. Theoretically, the resolution of the measurement of the pitching is 6.94×10^{-5} degrees. The displacement of the table in the feed direction of x is measured by a laser interferometer. The output of the sensor is fed into the controller as well.
Measurement of the undesired vertical displacement of the table is carried out using a capacitance sensor as follows. As shown in Fig. 5, the capacitance sensor measures the distance between the sensor and the straight edge that is set on the top surface of the table. In this case, the vertical displacement can be measured correctly only if zero pitching motion can be assumed. However, the influence of the pitching motion on the measurement has to be considered. Furthermore, the capacitance sensor measures the profile error of the top surface of the straight edge during feed motion as well. Accordingly, effective measurement technique is needed to measure the straightness error motion precisely.

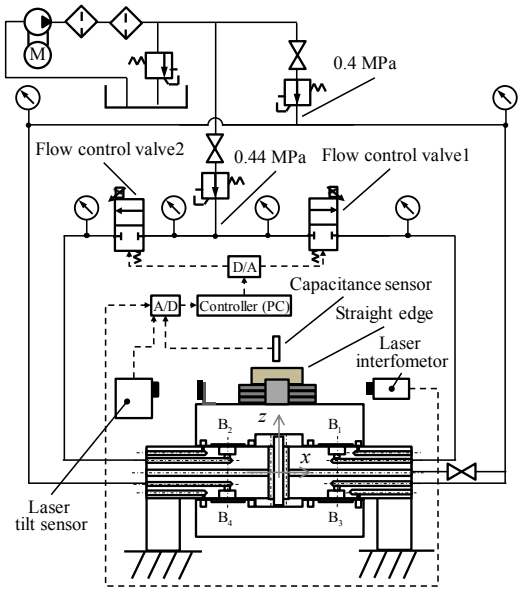


FIGURE 5. Measurement and control system

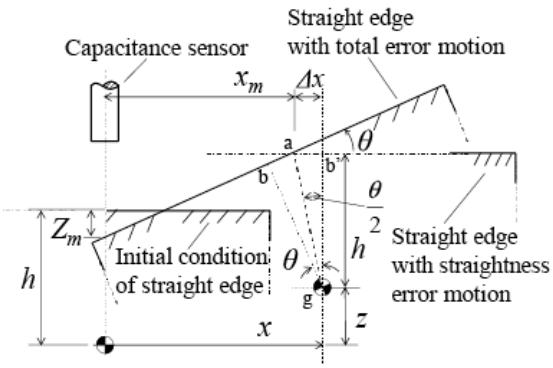


FIGURE 6. Measurement of straightness error motion

The pitching θ can be measured by the laser tilt sensor as described above. In addition, the laser interferometer measures the table displacement x in the feed motion. The relationship between the pitching θ, the displacement x and the straightness error motion z, namely the vertical displacement, are represented in Fig. 6. The capacitance sensor measures z_m that is not actual straightness error motion. However, the actual straightness error motion z defined as the vertical displacement of the center of gravity of the table can be given by Eq. (1).

$$z = \left(x - h\tan\frac{\theta}{2} \right)\tan\theta - y_e(x) - z_m \tag{1}$$

In Eq. (1), x is the displacement of the table along the feed direction measured by the laser interferometer, h is determined by the height of the table. The profile error of the top surface of the straight edge is given by $y_e(x)$. The function $y_e(x)$ can be measured by an appropriate profilometer prior to the control. Accordingly, the straightness error motion of the table can be calculated in real time using Eq. (1). Thus, the straightness error motion of the table can be measured and then fed into the controller.

Control principle of pitching and straightness error motion

The control of the pitching and straightness error motion of the table is carried out by the control of the hydrostatic bearings fabricated in the water driven stage. Feedback controls of the hydrostatic bearings have been studied for air hydrostatic bearings[4] and oil hydrostatic bearings[5]. Furthermore, the feedback control of the water hydrostatic bearing has been studied as well[6].

The pitching and straightness error motion of the table considered in this study are controlled by changing the recess pressures of the water hydrostatic bearings on the top and bottom surfaces of the table. As depicted in Fig. 2, two recesses B_1 and B_2 are fabricated on the top surfaces. Pressures of the recesses of B_1 and B_2 can be controlled independently since the separated supply ports are connected to each recess of B_1 and B_2. Identical recess structures B_3 and B_4 and separated supply ports are designed for the bearings on the bottom surfaces of the water hydrostatic bearings, as well. Furthermore, electrically controllable flow control valves are connected to each supply ports so that the recess pressures can be controlled by changing the flow rate into the recesses. Accordingly, the pitching and the straightness error motion of the table supported by the water hydrostatic bearings can be controlled by changing the recess pressures.

For instance, if both recess pressures P_{r1} and P_{r2} are increased identically, the table moves upward. In contrast, if both recess pressures P_{r1} and P_{r2} are decreased, the table moves downward. Thus, the vertical displacement control can be made. In addition, if the recess pressure P_{r1} are only increased or both the recess pressures P_{r1} and P_{r4} are increased by the flow control valves, the table moves counter clockwise as depicted in Fig. 2. Accordingly, combinations of the control of the recess pressures achieve the pitching and straightness error motion, simultaneously with an appropriate feedback controller. Four recesses B_1, B_2, B_3 and B_4 that can be controlled are fabricated for the water driven stage. Thus, all the independent recesses can be used for the control objectives. However, the present paper investigates the control system that controls the pressures of the two recesses B_1 and B_2. In the following section, a design of the feedback control system will be discussed.

DESIGNED FEEDBACK CONTROL SYSTEM

The developed control system of the water driven stage is depicted in Fig. 7. In our previous study[2], the interference between the pitching and the straightness error motion was observed. Namely, the pitching control affects the straightness error motion of the table. Accordingly, both feedback loops of the pitching and the straightness error motion must be designed. For the simultaneous controls of interfered controlled objects, a cross-coupled structure of the control systems[7]-[10] can be used. As presented in Fig. 7, a cross-coupled structure of the control system is thus designed so that both of the pitching and the straightness error motion of the table can be simultaneously controlled. In Fig. 7, $u_{\theta 1}$ is the input signal for pitching control, whereas u_{z1} is the input for the straightness error motion control. Furthermore, u_1 is the input for the flow control valve connected to the recess B_1 depicted in Fig. 2. In contrast, the bearing pressure of the recess B_2 is controlled by the input signal u_2.

If the steady state conditions of the pitching and the straightness error motion of the table are considered, the pitching θ and the straightness error motion z of the table are given by Eq. (2) and Eq. (3), respectively.

$$\theta = K_{\theta 1}u_1 - K_{\theta 2}u_2 \tag{2}$$

$$z = K_{z1}u_1 + K_{z2}u_2 \tag{3}$$

Now, u_1 and u_2 are defined as Eq. (4) and Eq. (5).

$$u_1 = u_{\theta 1} + u_{z1} \tag{4}$$

$$u_2 = u_{\theta 2} + u_{z2} \tag{5}$$

Furthermore, $u_{\theta 2}$ and u_{z2} are defined as Eq. (6) and Eq. (7).

$$u_{\theta 2} = -\frac{K_{z1}}{K_{z2}}u_{\theta 1} \tag{6}$$

$$u_{z2} = \frac{K_{\theta 1}}{K_{\theta 2}} u_{z1} \tag{7}$$

From Eq. (2) to Eq. (7), the controlled pitching and straightness error motion of the table are introduced as Eq. (8) and Eq. (9), respectively.

$$\theta = \left(K_{\theta 1} + K_{\theta 2} \frac{K_{z1}}{K_{z2}} \right) u_{\theta 1} \tag{8}$$

$$z = \left(K_{z1} + K_{z2} \frac{K_{\theta 1}}{K_{\theta 2}} \right) u_{z1} \tag{9}$$

It is verified that the pitching is only controlled by $u_{\theta 1}$, the straightness error motion is only determined by u_{z1}, respectively. Accordingly, the controls of the pitching and the straightness error motion can be successfully decoupled. Finally, conventional PI controllers are designed for the pitching and the straightness error motion control so that zero steady state error of the pitching and the straightness error motion can be achieved. In the paper, the control system with the cross coupled-structure presented in Fig. 7 is tested experimentally.

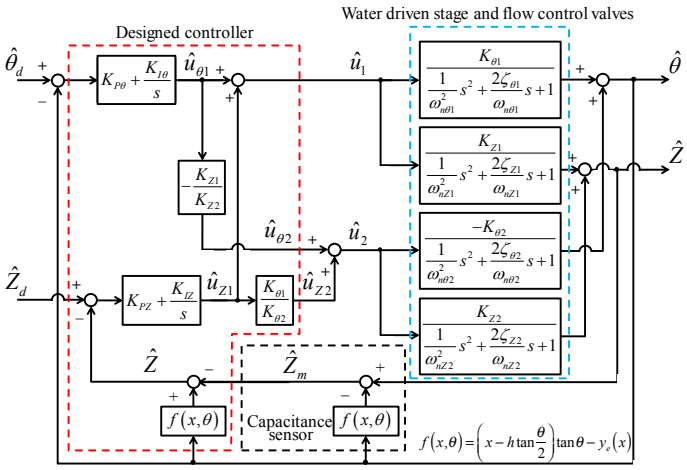


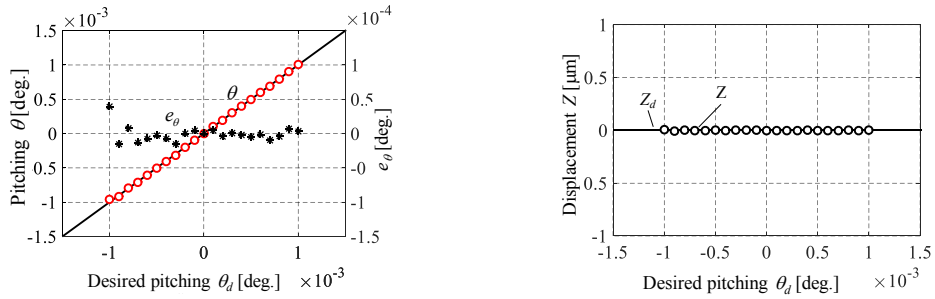
FIGURE 7. Designed cross-coupled control system

EXPERIMENTS

Performance of designed feedback control system without feed motion

Control performance of the designed cross-coupled feedback control systems was investigated. The control performance was examined for without feed motion and with feed motion, respectively. The tests of the control performance without feed motion were conducted so that the table of the water driven stage was positioned at an end of the stroke. The results are presented below.

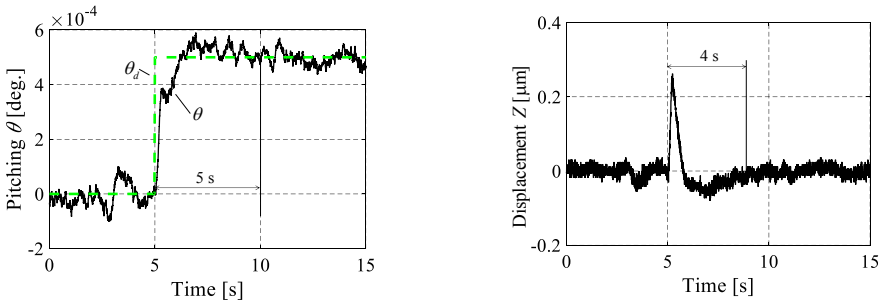
In the experiments, the various magnitudes of desired pitching signals were input to the control system. During the experiment, the desired signal to the straightness error motion controller was set to be zero. As presented in Figs. 8(a) and (b), the pitching changes according to the desired pitching signals, whereas the vertical displacement of the table was kept constant. In Fig. 8(a), the pitching error is also presented, indicating the pitching error is less than 1.0×10^{-4} degrees.



(a) Pitching (b) Straightness error motion

FIGURE 8. Controls of pitching and straightness error motion without feed motion

In addition to the static characteristics of the designed cross-coupled control system, step response of the system was investigated as presented in Fig. 9(a) and (b). In the experiment, a step input was input to the pitching control system while the zero-displacement signals were input to the straightness error motion control system.



(a) Pitching (b) Straightness error motion

FIGURE 9. Step response of pitching control system without feed motion

The experimental result indicates that a good step response of the pitching is observed. During the control, the straightness error motion was kept to be zero successfully except for the transient response of the control. As a step response of the pitching control, the step response of the table in the z-direction was successfully carried out using the control system of the straightness error motion as well. A good control performance was then observed. By virtue of the control performance, attractive new functions including the micro depth of cut control, for instance, can be added to the ultra-precision machine tools.

Influences of the external loads acting on the table on the control performance were also investigated experimentally. In the experiments, the external loads were applied by putting various masses on the off-center position of the top surface of the table as presented in Fig. 10. For the reference of the experiments, the responses of the control system without feedback control loops are presented in Fig. 10 as well. It is obviously verified that the external loads change the pitching and the straightness error motion considerably, if the designed feedback control system was not used.

The responses of the designed feedback control system are also presented in Fig. 10. In the experiments, the constant control commands were input to the pitching and the straightness error motion control system. As depicted in Fig. 10, the response of the pitching and the straightness error motion control systems are successfully kept constant regardless of the external loads.

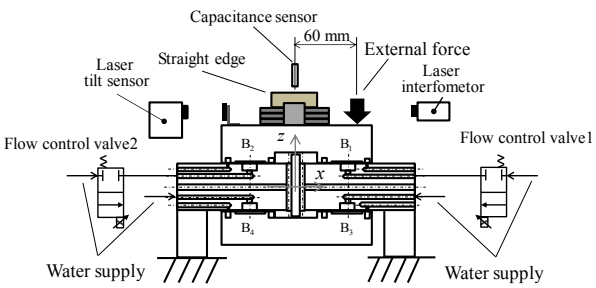


FIGURE 10. Experiment with off-center external forces

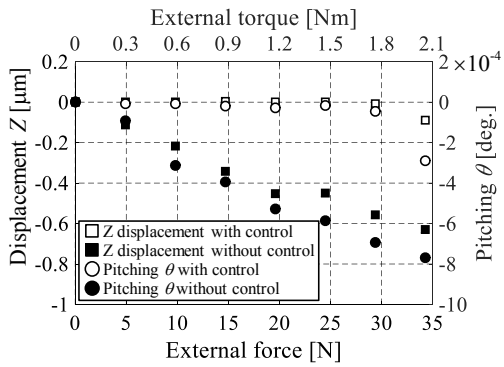


FIGURE 11. Influence of off-center external forces

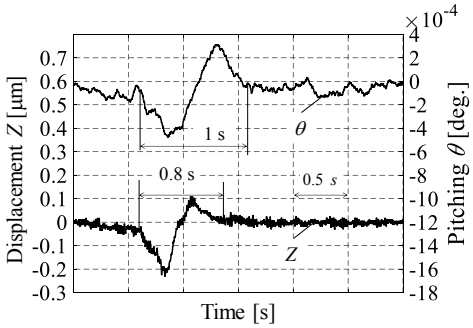


FIGURE12. Transient response against off-center external force

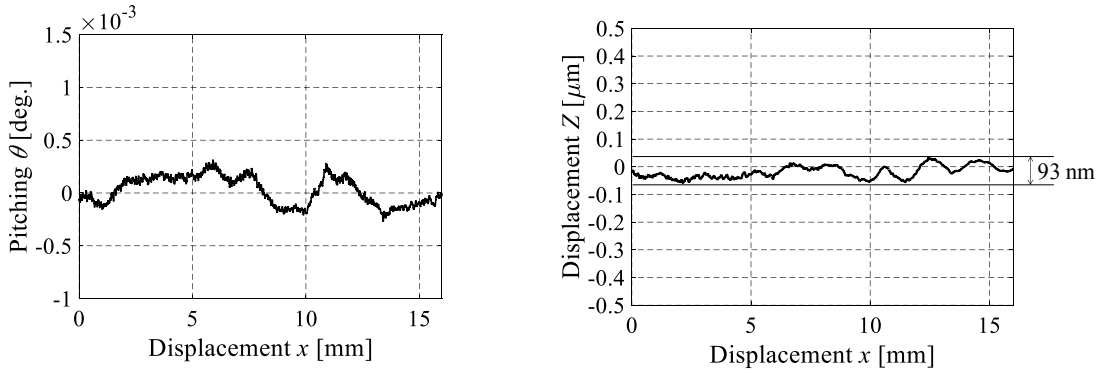
Furthermore, transient responses of the control system are measured as presented in Fig. 12. In the experiment, a mass was put at an off-center position on the top of the table. The control results show that the influence of the external load was successfully compensated by the designed control system. The settling time in the transient response are rather long. However, the settling time will be reduced by designing sophisticated controller.

Performance of designed feedback control system during feed motion

Finally, the pitching and straightness error motion controls of the table during the feed motion were investigated. In the experiments, the desired commands for the pitching and the straightness error motion controllers were input so that the table can be the zero pitching and zero straightness error motion from the initial attitude and vertical position of the table. In Figs. 13(a) and (b), the pitching and the straightness error motion of the table are represented. If the designed feedback controller was not used, the pitching of 1.2×10^{-3} degrees was observed as presented in Fig. 3 with the straightness error motion of 0.21 μm. In contrast, the designed controller successfully reduces both errors.

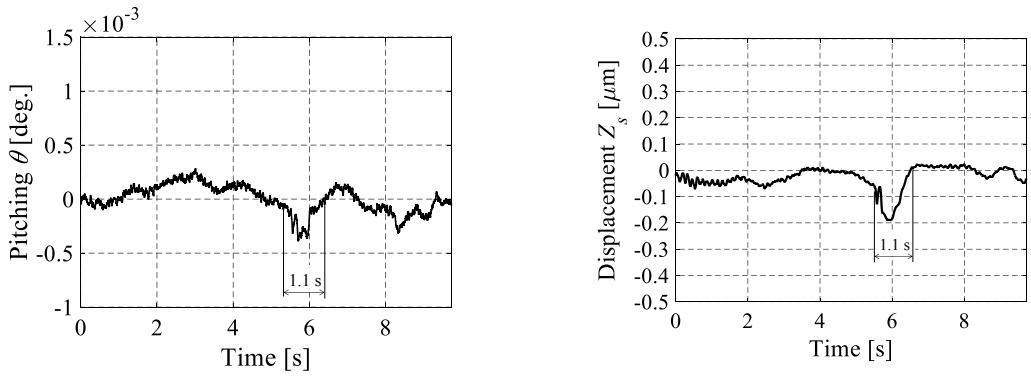
Effectiveness of the designed control system on the compensation performance against external load was tested during feed motion of the table as well. In the experiment, a constant mass of 1 kg was placed on the top surface of the table during feed motion so that the stepwise external load acts on the table. Since the mass was placed at an off-center position, the external moment effect was applied to the control system. The mass must affect the pitching and straightness error motion, accordingly.

Experimental results are depicted in Figs. 14(a) and (b). In the experiment, the mass was placed at about 5.5 seconds. Slightly change in the pitching due to the external load is observed, however it reduces within 1.1 seconds. The good pitching control performance can be maintained afterward. In contrast, the change in the straightness error motion is rather significant. However, the influence of the external load on the straightness error motion is compensated as well.



(a) Pitching (b) Straightness error motion

FIGURE 13. Pitching and straightness error motion controlled during feed motion



(a) Pitching (b) Straightness error motion

FIGURE 14. Influence of off-center external force on control performance

CONCLUSIONS

In this study, the control of the pitching and straightness error motion of the table of the water driven stage was investigated. It was indicated that the pitching error of the table was 0.5×10^{-3} degrees during feed motion without the developed control system.
Simultaneous control of the pitching and straightness error motion of the water driven stage was proposed. The principle of the control of the pitching and straightness error motion of the table of the water driven stage is to use control pressures of two bearing surfaces by the flow control valves.
A feedback control system of the water driven stage was designed. The control system has a cross-coupled structure. Then designed control system was tested experimentally. The experimental results showed that the control system effectively control both the pitching and the straightness error motion. The designed control system with the cross-coupled structure successfully decoupled the pitching and the straightness error motion.
In addition, the designed control system compensated the influence of the external moment effect acting on the moving table on the pitching and the straightness error motion. In particular, the control system effectively compensated the influence of the dynamic change in the external loads. It was also confirmed that the control system controlled pitching error due to the straightness error of the guide-way during feed motion of the table, as well.
The designed control system successfully controlled the pitching and the straightness error motion according to the step inputs. Accordingly, it was verified that the designed control system of the water driven stage can be used for not only achieving precise linear motion but also changing the pitching and vertical motions according to time series commands. Thus, the control system improves the machining accuracy. Furthermore, the control possibility of the pitching and the straightness error motion controls against the time series commands will give attractive functions to generate various precise parts needed to the leading-edge industries such as automobile, medical, aviation industries and so on. In addition, the developed control system can be applied to not only machine tools but also other various motion control systems. For instance, the motion accuracies of the linear table systems that are used in the semiconductor industry and the display industry producing large flat panel displays can be also improved by the proposed technique.

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