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Development of an Ultra Precision Hydrostatic Guideway Driven by a Coreless Linear Motor

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ABSTRACT

In order to develop the hydrostatic guideways driven by a coreless linear motor for ultra precision machine tools, a prototype of guideway is designed and tested. A coreless linear DC motor with a continuous force of 156 N and a laser scale with a resolution of 0.01 μm are used in the system. Experimental analysis on the static stiffness, motion errors, positioning error and its repeatability, micro step response and velocity variation of the guideway are performed. The guideway shows infinite stiffness within 50 N applied load in the feed direction, and by the motion error compensation method using the Active Controlled Capillary, 0.08 μm linear motion error and 0.1 arcsec angular motion error are acquired. The guideway also reveals 0.21 μm positioning error and 0.09 μm repeatability, and it shows stable responses following a 0.01 μm resolution step command. The velocity variation of feeding system is less than 0.6 %. From these results, it is estimated that the hydrostatic guideway driven by a coreless linear motor is very useful for the ultra precision machine tools.

Key Words : Hydrostatic guideway, Ultra precision, Coreless linear motor, Static stiffness, Motion errors, Positioning error, Repeatability, Mico step response, Velocity variation

1. Introduction

As the industrial applications of ultra precision aspheric lens or reflector are abruptly increased in the field of optics and home electronics, the need for the development of ultra precision machine tools is also being increased.

Machining accuracy of ultra precision machine tools mainly depends on the accuracy of the motional elements. Especially, the accuracy of guideway is the most important among them. Generally, the required motion accuracy of the guideway for ultra precision machine tools to machine an aspheric lens is about 0.1~0.2 μm with a resolution of 0.01 μm order, and hydrostatic guideway is the most frequently used due to its inherent characteristics such as low friction, high damping and high stiffness[1, 2].

On the other hand, an ultra precision feeding system driven by a coreless linear motor with a repeatability of 0.01 μm is widely used as the production equipment for semiconductor in lithography process[3,4]. This trend has a strong influence on the design concept of machine tools. In the view point of design and assembling, the coreless linear motor is very attractive. However, it is not easy to find reports on the technical experiences or design examples regarding this subject.

In order to develop a hydrostatic guideway driven by a coreless linear motor for ultra precision machine tools, a guideway is designed and its basic performances are experimentally analyzed in this paper. In the design stage, it is assumed that the hydrostatic guideway is applied to an ultra precision lathe. Static stiffnesses in the feed,

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vertical and horizontal directions are tested for estimating the load characteristics against the applied cutting force. Motion errors, positioning error and its repeatability are tested and compensated to estimate the accuracy characteristics. The motion error compensation method using the ACCs(Active controlled capillary)[5] is applied to remove the motion errors and NC compensation is applied to improve the positioning accuracy. Micro step responses and velocity variations are also tested for estimating the machinability in the ultra precision machining condition.

2. Design of a guideway and its feeding system

2.1 Layout and feeding system

It is generally known that the cutting force in ultra precision turning process is less than 10 N. If we suppose that the required form error of ultra precision parts is about 0.1 μm, the required static stiffness of the cutting system should be at least 100 N/μm. Considering the conventional structure of the ultra precision lathe as shown in Fig. 1, static stiffness of the cutting system is comprised of the horizontal stiffness of X-axis guideway, the stiffness of Z-axis guideway in the feed direction, the axial stiffness of spindle and the stiffness of tool post. In general, the stiffness of the tool post is high enough, but the axial stiffness of the spindle is weaker than the stiffnesses of the guideway. Therefore, to assure high stiffness of the cutting system, the stiffnesses of the guideway must be high enough. Considering this fact, the stiffnesses of the guideway were designed to be 200 N/μm or more, which is twice the required stiffness for the cutting system.

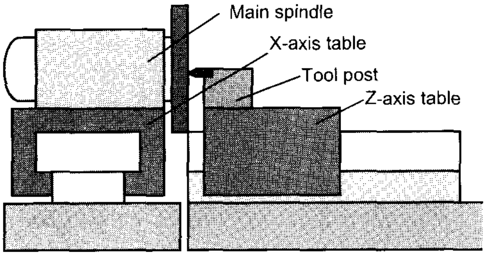


Fig. 1 Example of an ultra precision lathe

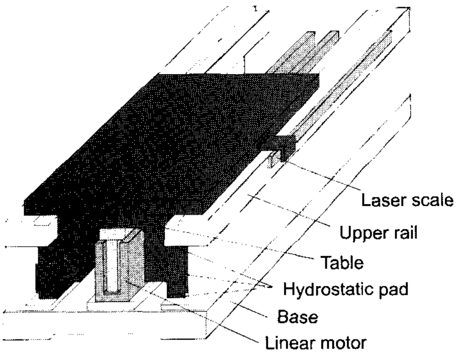


Fig. 2 Structure of designed hydrostatic guideway

The structure of the hydrostatic guideway was designed to be the reverse restraint shape, that is, the hydrostatic table is covered with the two rails as shown in Fig. 2, and the stroke of the table is 250 mm.

The axial stiffness of the guideway depends on the thrust force of the linear motor controlled by a closed-loop feedback system, which is called dynamic stiffness. As the practical thrust force of the linear motor varies according to the controller gains, the controller should be designed so that the dynamic stiffness exceeds the expected maximum cutting force. A coreless linear DC motor (LEA, Anorad) with a continuous force of 156 N was used in this research. Also, a laser scale(BS75A, Sony, accuracy 0.28 μm / 250 mm) with a resolution of 0.01 μm was used as a feedback sensor. Since the laser scale is mounted on the side of the table, NC compensation is applied to remove the Abbe's offset error. The driving point of the linear motor set to be the center of the table. A schematic diagram is shown in Fig. 2.

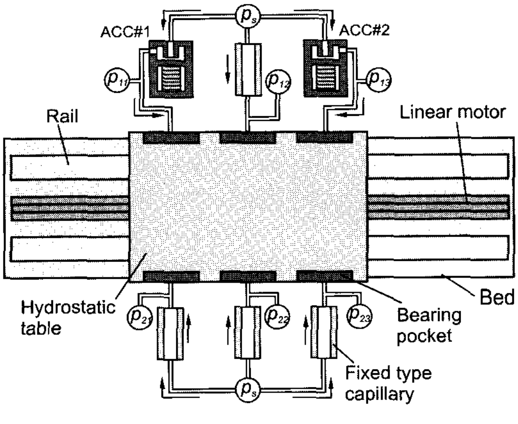


Fig. 3 Compensating method of horizontal motion errors using two ACCs

On the other hand, for ultra precision machining within 0.1 μm form error, the horizontal motion of the hydrostatic guideway also has to be in the same level of accuracy. A motion error compensation method utilizing the ACCs(Active controlled capillary)[5], which had been proposed by the authors, was applied for the compensation of the horizontal linear and angular motion errors. The ACCs were connected to both ends of the pocket on one side of the table as shown in Fig. 3. The linear and angular motion errors were compensated simultaneously. To reduce the influence of oil temperature variations on the repeatability of hydrostatic guideway, an oil conditioner (AKS206, Daikin) with a control resolution of ±0.1°C, was used.

2.2 Performance design of hydrostatic guideway

The pad dimension of the hydrostatic guideway was designed to satisfy the stiffness conditions discussed in section 2.1. Calculated static stiffnesses and flow rates according to the bearing clearance are shown in Fig. 4.

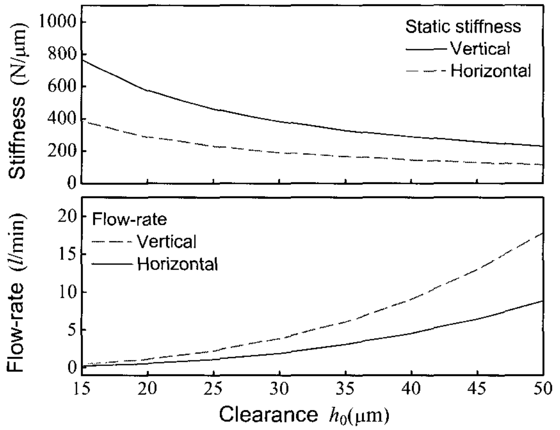


Fig. 4 Static stiffness and flow-rate of hydrostatic guideway according to the bearing clearance

Table 1 Designed performances of hydrostatic guideway

Specifications	Horizontal	Vertical
Number of pad	3	6
Pad size	80×20 mm	80×20 mm
Clearance	25 μm	25 μm
Load capacity (ε=0.1)	2,110 N	4,220 N
Static stiffness (ε=0)	224 N/μm	448 N/μm
Flow rate	1.15 *l*/min	2.30 *l*/min
Supply pressure 100N/cm^2, Oil viscosity 10cSt(40°C)		

When the bearing clearance is increased, assembling process becomes easy and heat generation is also reduced, but the static stiffness is decreased and the consuming flow rate is increased exponentially. Therefore, bearing clearance is set to be 25 μm to minimize the flow rate within the acceptable range of static stiffness. Design specifications and performances of the hydrostatic guideway are represented in Table 1.

3. Performance tests and discussions

3.1 Experimental method

The static stiffnesses in the horizontal and vertical directions were measured using a screw which applies the load, a load cell and four electric micrometers (resolution 0.01 μm, Mahr) placed at the each end point of the rectangular table. The average values from four electric micrometers were used to represent the static stiffness.

Motion errors, positioning accuracy and repeatability at the table center were measured using a laser interferometer(5529A, HP). Micro step responses from the continuous step feed command of 0.01 and 0.02 μm were measured using a capacitive type sensor (Microsense 3401, ADE, resolution 1 nm) at the end of the table.

Velocity variations were acquired by measuring the profile of the table according to the command velocity profile in the form of square wave, using a laser interferometer.

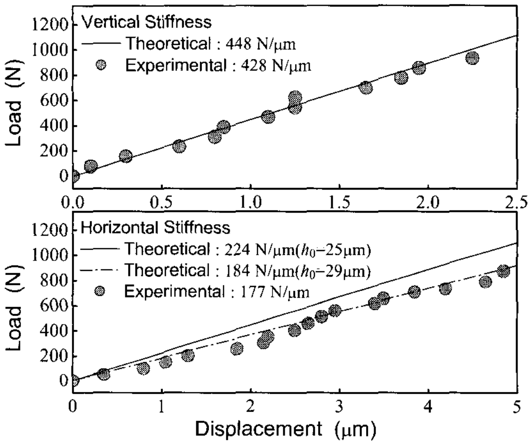
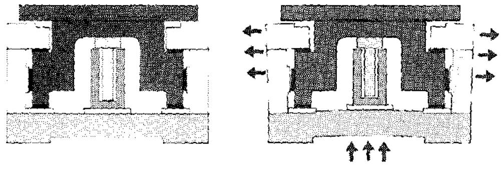


Fig. 5 Static stiffness of guideway in the vertical and horizontal directions

3.2 Static stiffness

The measured static stiffnesses in the horizontal and verical directions are shown in Fig. 5. Theoretically calculated values are shown in the same figure. The measured vertical stiffness was 428 N/μm, and it agreed well with the theoretically expected value. From this result, it was confirmed that the flow characteristics of capillary, which plays a major role in the practical use, was well adjusted in the assembling process of the hydrostatic guideway. However, the measured horizontal stiffness was 177 N/μm which was less than the design value. The reason was that due to the pocket pressure (design value of 50 N/cm^2) of the hydrostatic pad, elastic deformation took place in both sides of the rail and the base plate as shown in Fig. 6, where the arrows depict the deformation directions. The deformation increases the bearing clearance and consequently decreases the static stiffness. The measured deformations were 4 μm at both sides of the rail and 2 μm at the base plate. Re-calculated stiffness, considering the deformations with increased bearing clearance (h_0=29 μm), agreed well with the measured value as shown in Fig. 5(b). As most of the guideways are placed on the bed, the deformation of base plate may not occur in real machines. However, the structural stiffness of both sides of the rail must be designed to be strong enough to minimize elastic deformations.



(a) before deformation (b) after deformation

Fig. 6 Aspect of elastic deformation by pocket pressure

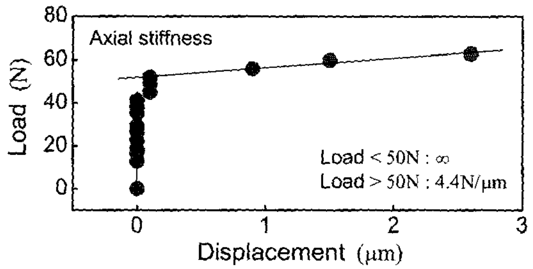


Fig. 7 Static stiffness of guideway in the feed direction

The measured static stiffness in the feed direction is shown in Fig. 7. Theoretically, infinite stiffness was expected within the range of continuous force, 156 N. However, in reality, infinite stiffness was maintained only within the range of 50 N, and the stiffness was abruptly decreased to about 4.4 N/μm due to the saturation of integral gain when the applied force exceeded 50 N.

The range of the infinite stiffness can be extended by decreasing the mass or decreasing the resolution of feed back sensor or improving the control algorithm. In this research, as the maximum cutting force was estimated to be as much as 10 N in the design stage, it is confirmed that the tested hydrostatic guideway can be utilized for ultra precision machine tools.

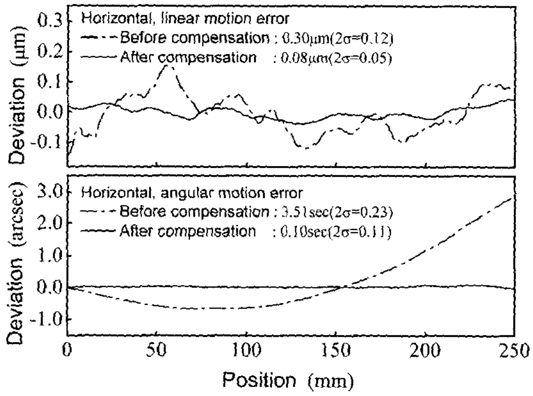


Fig. 8 Improvement of motion errors by the compensation method using the ACCs

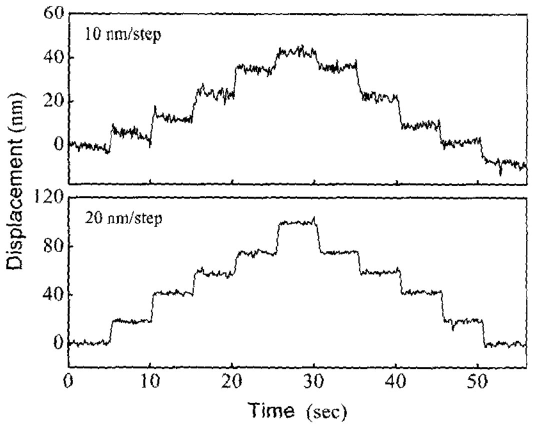


Fig. 9 Micro step responses of guideway

3.3 Motion errors

The horizontal motion errors before and after the compensation was measured are shown in Fig. 8. The linear and angular motion errors before the compensation were 0.30 μm and 3.51 arcsec for a stroke of 250 mm, respectively. As it was difficult to expect the machined form accuracy of 0.1 μm with these level of motion errors, the motion error compensation method shown in Fig. 3 was applied. In the first step, displacement corresponding to the position of table is calculated using the measured motion errors multiplied by the gains(input voltage/unit displacement) acquired from the preliminary test. The input voltages were calculated and applied for each ACC. Because of the nonlinearity of the piezo actuator used in the ACC, the motion errors were not substantially improved in the first time compensation. The iterative control algorithm was applied until the required accuracy was acquired.

The compensated motion errors are shown in Fig. 7. After three iterations, 0.08 μm linear motion error and 0.10 arcsec angular motion error were acquired. It is estimated that the accuracy is good enough to be applicable to ultra precision machining.

3.4 Micro step response and positioning error

The responses of five continuous micro step feed commands of 0.01 μm and 0.02 μm were tested as shown in Fig. 9. Displacement of the guideway is distinct even in the case of 0.01 μm/step, which is the resolution of the laser scale. Also it is seen that there is no lost motion or nonlinear displacement induced by the structural asymmetry in the reciprocal motion. On the other hand, error near the start point and the end point, which was about 6~7 nm, was due to the nonlinearity of electric divisions in the laser scale

The positioning error and the repeatability of the guideway estimated following the ISO 230-2 code are shown in Fig. 10. Measurement was performed five times in each test, and the values shown in the figure were calculated statistically from the measured values.

The positioning error and its repeatability before the compensation were 3.08 μm and 0.15 μm(2σ), respectively as shown in Fig. 10(a). By the Abbe's offset error originating from the mounted position of the laser scale, the positioning error largely exceeds the accuracy of the laser scale(0.28 μm/250 mm). The positioning error and its repeatability after the NC compensation with respect to the center position of the table are shown in Fig. 10(b). They were reduced to 0.21 μm and 0.09 μm(2σ), respectively. Comparing the positioning error with the repeatability, it is confirmed that the improvement of positioning error is limited by the repeatability which is mainly affected by the thermal characteristics of the lubricant and the measuring error of the laser interferometer due to the variation in room temperature.

3.5 Velocity variation

The velocity variation of the guideway in response to square profile input commands were tested at the feed rates of 30 mm/min and 720 mm/min which correspond to the cutting speed and high feed rate, respectively, in

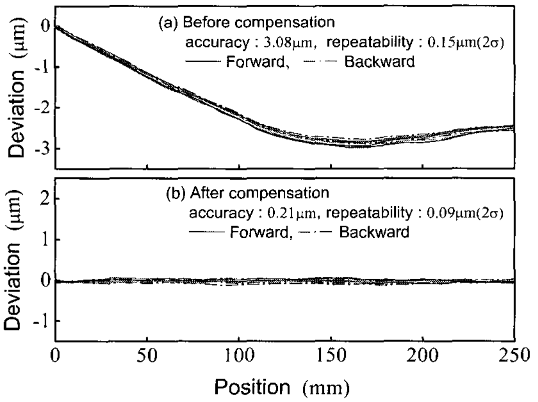


Fig. 10 Positioning error and its repeatability of guideway before and after the NC compensation

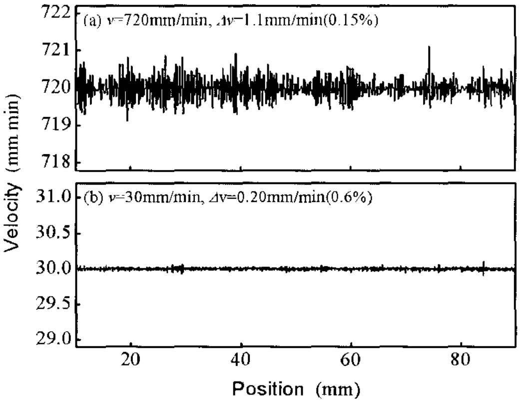


Fig. 11 Velocity variations of guideway

ultra precision machining. The extracted profile within a constant velocity range is shown in Fig. 11. The measured velocity coincided exactly with the command velocity. The velocity variation was 0.2 mm/min when the feed rate was 30 mm/min, and it was 1.1 mm/min when the feed rate was 720 mm/min. Since the deviations from the desired velocity are only 0.60 % and 0.15 %, respectively, it is estimated that the guideway is stable enough to be applied in ultra precision machining.

4. Conclusions

In order to develop hydrostatic guideways driven by a coreless linear motor for ultra precision machine tools, a prototype guideway was built and tested in this research. Experimentally analyzed results are summarized as follows:

1) The static stiffness of the hydrostatic guideway in the feed direction is infinite within the range of 50 N.
2) Linear and angular motion errors are reduced to 0.08 μm and 0.1 arcsec within a stroke of 250 mm by the compensation using the ACCs.
3) Micro step responses of the guideway are distinct with a step size of 0.01 μm, which is the resolution of the laser scale, and there is no lost motion or non-linear displacement induced by the structural asymmetry in the reciprocal motion.
4) The positioning error and its repeatability are reduced to 0.21 μm and 0.09 μm(2σ), respectively by the NC compensation.
5) As the maximum ratio of velocity variation is about 0.60 % within the range of frequently used cutting speed, it is estimated that the guideway is stable enough to be applied in ultra precision machining.
6) From the above results, it is estimated that the hydrostatic guideway driven by a coreless linear motor is very useful for ultra precision machine tools.

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