Magnetically preloaded aerostatic guideway for high speed nanometer positioning

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Abstract
Demands for nanometer positioning with a high resolution and a long stroke have increased in a variety of industries. Performance of guide elements is one of the most important issues for realizing such positioning systems. In general, an ultra-precision positioning system has aerostatic guideway which can restrain a moving table without non-linear behavior, i.e., friction and backlash. Characteristics of aerostatic guideway affect the performance of the positioning system. This study is aiming at developing an aerostatic guideway which can achieve a high speed nanometer positioning. The aerostatic guideway preloaded by magnetic attraction force can lead to provide a compact structure, and the characteristics can be easily controlled without increased driving force. However, the relative velocity between permanent magnets and the attracted surface causes the induced eddy current, which deteriorates the performance during high speed positioning. In this study, in order to minimize the eddy current loss, the magnetic attraction force is successfully added to a mechanism following the positioning table. In order to evaluate the proposed structure, a positioning system is developed by using the magnetic attraction force preloaded aerostatic guideway. The positioning system is constructed by a positioning table and a following table. Basic characteristics of the aerostatic guideway are experimentally evaluated. From the results, the magnetic attraction force-preloaded guideway can be designed so as to obtain high stiffness. By optimizing the magnetic force, the performance of the positioning system was evaluated. The experimental results of frequency response confirm that the response of the positioning system can be improved by applying magnetic attraction force. In addition, the results of stepwise positioning confirm that the proposed positioning system has high positioning resolution. These results confirm that the proposed guideway achieves high speed nanometer positioning capability.

Key words: Ultra-precision positioning, Aerostatic guideway, Magnetic preload, Eddy current loss, Bearing clearance

1. Introduction

Nanometer positioning systems with a long stroke have been recently required in a variety of industries. Performance of a guideway is one of the most important issues for realizing such positioning systems. Aerostatic guideways are widely used in ultra-precision positioning systems. These aerostatic guideways can support a table in a noncontact condition and can prevent various non-linear behaviors such as friction and backlash (Shinno, et al., 2011).

Characteristics of aerostatic guideway depend on the bearing clearance. Therefore, the characteristics of the aerostatic guideway are determined by the preload which adjusts the bearing clearance. In addition, the characteristics curve depends on the type of restrictor. There are some restrictor types; i.e., inherent orifice, groove admission, porous restriction, slot restriction (Togou, 2002, Yoshimoto, et al., 2001). Among these types, the porous restriction method is widely known so as to provide higher stiffness to the aerostatic guideway (The Japan Society for Precision Engineering ed., 2000). In this study, the porous restriction is applied to the restrictor, and then evaluates the characteristics of the
preloaded aerostatic guideway. An aerostatic guideway preloaded by magnetic attraction force provides contactless and compact structure. However, the relative velocity between a permanent magnet and an attracted surface causes the eddy current loss which deteriorates performance during high speed positioning. Therefore, the magnetic attraction force-preloaded aerostatic guideway without eddy current loss is required to realize the high speed nanometer positioning system.

This study proposes a novel magnetically preloaded aerostatic guideway, which can realize high speed nanometer positioning. In general, the driving speed of the typical precision positioning table is about 100 mm/s (Abdullah, et al., 2013, Altintas, et al., 2011). Therefore, this study set the target velocity of the positioning system to 100 mm/s. In order to evaluate the performance of the positioning system equipped with the proposed guideway, characteristics of the aerostatic guideway, i.e., frequency response, step response, and CP (continuous path) motion response, are demonstrated.

2. Proposed magnetically preloaded aerostatic guideway

2.1 Concept of a proposed magnetically preloaded aerostatic guideway

Characteristics of aerostatic guideway, i.e. stiffness, damping, and flow rate of air, depend on the bearing clearance determined by bearing preload. Low stiffness and low damping capacity cause motion errors, and high flow rate vibrates a levitating table. Therefore, it is necessary to apply a suitable preloading method for avoiding these problems. There are some preloading methods; a weight load, a vacuum load, an electrostatic load, and a magnetic load in contactless preloading methods (Ro, et al., 2010). Although a preloading method using weight load can apply large force, it makes a response of the system low. The preloading method using vacuum and electrostatic attraction force cannot apply large force. The magnetic preloading method with permanent magnets can easily apply large force without heat generation, however the relative velocity between the permanent magnets and the attracted surface causes the eddy current which acts as viscous resistance.

Because the eddy current increases in proportion to the relative velocity, it is necessary to minimize the eddy current loss during high speed positioning. In order to decrease effect of the eddy current, this study performs appropriate design of the aerostatic guideway. Eddy current is caused by changing magnetic flux in conductive material. Therefore, the eddy current can be prevented by placing conductive material into constant magnetic field. However, it is difficult to realize an uniform magnetic field. In this study, the eddy current is prevented by reducing the relative velocity between a magnet and a conductive material. The relative velocity can easily reduce by adding a mechanism following to the moving magnet. Figure 1 shows a structural concept of the proposed positioning system. In a conventional structure, magnetic attraction force acts to stationary structure, so that the eddy current is excited in the attracted surface. Accordingly, the eddy current are induces in the system and deteriorates the positioning performance during a high speed driving. Thus, magnetic attraction force is preloaded to an additional table which is controlled so as to follow the positioning table. Consequently, the eddy current is prevented by removing the relative velocity between the permanent magnet and the attracted surface.

2.2 Positioning system with the proposed aerostatic guideway

Figures 2 and 3 show the structural configuration of the positioning system with the proposed guideway, and an appearance of the positioning system developed. Table 1 shows fundamental specifications of the positioning system. The positioning system was constructed by both a positioning table and a following table. A voice coil motor for driving the positioning table was symmetrically installed into the positioning table, as shown in Fig. 3. This structure achieves driving at the center of gravity of the positioning table. A laser interferometer with a sub-nanometer resolution was used for a position feedback sensor. In addition, the measurement at the center of gravity was realized by adjusting a laser axis to the center of gravity of the table. Both the positioning table and the guideway were made of alumina ceramics, and formed a symmetrical structure so as to reduce thermal deformation. In this way, the positioning system realizes contactless support, contactless drive, minimization of motion error, and minimization of abbe error. The permanent magnets were fixed on the bottom of the positioning table, and the bearing clearance of the aerostatic guideway was determined by the magnetic attraction force. The following table with VCM was installed under the positioning table, and was driven by a ball screw mechanism. A laser displacement sensor fixed on the following table was used for measuring the relative displacement between the positioning table and the following table. This structure makes possible to enlarge the VCM stroke and consequently achieves long range ultra-precision positioning.

Fig. 1 Concept of a proposed magnetic attraction force preloaded aerostatic guideway

(a) Conventional structure
(b) Proposed structure

Fig. 2 Positioning system with the proposed aerostatic guideway

(a) Side view
(b) Front view

Fig. 3 Appearance of the positioning system with the proposed aerostatic guideway

(a) Over view
(b) Top view

Table 1 Specifications of the positioning system

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<table>
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<tr>
<td>Full stroke</td>
<td>300 mm</td>
</tr>
<tr>
<td>Stroke of VCM</td>
<td>2.5 mm</td>
</tr>
<tr>
<td>Mass of table</td>
<td>7.8 kg</td>
</tr>
<tr>
<td>Max. velocity</td>
<td>220 mm/s</td>
</tr>
<tr>
<td>Max. acceleration</td>
<td>5.35 m/s²</td>
</tr>
<tr>
<td>Control frequency</td>
<td>10 kHz</td>
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A full-closed loop controller with a PID compensator was used for precision positioning (Wakui, 1999). The positioning table and the following table were controlled independently. Figure 4 shows the block diagram of the overall positioning system. Gain parameters of the PID controller were determined by Ziegler-Nichols ultimate sensitivity method (Ziegler and Nichols, 1942). In this study, the gains were determined by applying 10 nm step reference to the positioning table and 0.1 mm step reference to the following table.

3. Development of the proposed aerostatic guideway of the positioning system

3.1 Investigation of the relationship between bearing clearance and stiffness

Bearing clearance is one of the most important factors to determine characteristics of aerostatic guideway. Therefore, optimization of the bearing clearance is required to improve performance of aerostatic guideway. In general, the stiffness of aerostatic bearing has the maximum value in relative to the bearing clearance (Aoyama, et al., 2006, Nishio, et al., 2011, Yoshimoto, et al., 1999). In order to design the suitable bearing clearance of aerostatic guideway developed, the relationship between the bearing clearance and the stiffness was investigated. Figure 5 shows a setup for measuring characteristics of the aerostatic guideway. An air cylinder was installed on the center of the table in the vertical direction, and a load cell fixed on the table measured the applied load to the bearing. In order to minimize the measurement error due to tilting motion, the vertical displacement of the levitated table was measured by two capacitive displacement sensors. In this experiment, magnetic preload was not added to the aerostatic guideway.

\[ \begin{align*}
\frac{K_{\text{amp}}}{s} \quad & P_1 + \frac{I_1}{s} + D_1 \quad \text{Positioning table controller} \\
\frac{1}{L_s s + R_s} \quad & 1 \quad \text{Current amplifier} \\
\frac{K_{\text{VCM}}}{s^2} \quad & 1 \quad \text{VCM} \\
\frac{1}{M_{\text{follow}} s^2} \quad & 1 \quad \text{Following table} \\
\frac{1}{M_{\text{move}} s + C_{\text{move}}} \quad & 1 \quad \text{Motor driver} \\
\frac{1}{J_s s^2 + C_m s} \quad & \frac{1}{s} \quad \text{Ball screw} \\
\frac{1}{x_{\text{ref}}} \quad & x_{\text{relative}} \quad \text{Positioning table} \\
\frac{1}{x_{\text{relative}}} \quad & x_{\text{follow}} \quad \text{Following table} \\
\end{align*} \]

Fig. 4 Block diagram for controlling the positioning system
Figure 6 shows the relation between the bearing clearance and the load to bearing including the mass of the positioning table. In addition, Fig. 7 shows the relationship between the bearing clearance and the stiffness which was calculated from the difference value of the load curve. From the results, because of the bearing clearance was decreased with the increase the load, and the deviation of the stiffness was increased at the small bearing clearance. As shown in Fig. 7, the stiffness increases with the decrease of the bearing clearance. In addition, the maximum stiffness exists around the bearing clearance of 3 µm, because the load curve had no inflection point. When the bearing clearance is around 3 µm, the positioning table may contact with the guide surface. Therefore, the bearing clearance was set to be 5 µm.

Fig. 5 Experimental setup for evaluating characteristics of the aerostatic guideway

![Experimental setup for evaluating characteristics](image1)

Fig. 6 Relationship between bearing clearance and load

![Relationship between bearing clearance and load](image2)

Fig. 7 Stiffness of the aerostatic guideway

![Stiffness of the aerostatic guideway](image3)
3.2 Design of magnetic attraction force

An optimum air gap exists between a permanent magnet and an attracted surface to keep a noncontact condition. Ideally, magnetic attraction force was inversely proportional to the square of the air gap (The Institute of Electrical Engineers of Japan ed., 1993). However, this relationship is changed due to the variety of factors, i.e., volume of magnet and leakage of magnetic flux. In order to apply the suitable magnetic attraction force, it is important to measure the relationship between the magnetic attraction force and the air gap.

In this study, the magnetic attraction force was estimated by measuring the force needed to take away the magnet, which was adsorbed to the same material of the attraction surface for the positioning system with some air gap by inserting shim. The relationship between the magnetic attraction force and the air gap is shown in Fig. 8. The attraction force of 3 magnets was measured in order to measure the average of the attraction force per magnet. The magnetic attraction force decreases with increasing of the air gap. The air gap between the magnet surface and the attracted surface was determined to be 0.5 mm, because the distance between the positioning table and the following table is 0.5 mm. In this time, the attraction force becomes a half compared to the case of no air gap. From the result of Fig. 6, in order to set the bearing clearance to be 5 µm, the magnet force of 1000 N is required in the case of no air gap. At that time, in order to minimize the tilting motion of the positioning table, the permanent magnets were required to symmetrically arrange with respect to the moving axis. Therefore, 20 magnets each of which has the attraction force of 89.2 N at no air gap were applied to the aerostatic guideway. The permanent magnets shown in Fig. 9 were installed on the magnet plate, and used to load the magnetic force.

![Fig. 8 Relationship between magnetic attraction force and air gap of magnet](image1.png)

![Fig. 9 Appearance of the magnet plate](image2.png)
4. Performance evaluation of the positioning table system with the proposed aerostatic guideway

4.1 Characteristics of the positioning system with the proposed aerostatic guideway

In order to evaluate the effect of magnetic attraction force preloaded, the characteristics of the aerostatic guideway were measured. Basic characteristics of the aerostatic guideway are shown in Table 2. By applying the designed magnetic preload to the guideway, the stiffness of the aerostatic guideway increased from 20.4 N/µm to 298.8 N/µm and the flow rate decreased from 2.96 L/min to 2.66 L/min. The damping ratio decreased from 1.98 to 0.35. These results were qualitatively consistent with the theoretical relationship between the bearing clearance and the characteristics of aerostatic guideway (Slocum, et al., 2003). In addition, these results were almost correspondent with the results, as shown in Fig. 7. The stiffness improved by the preload increases the stability of the positioning system, because tilting of the positioning table during acceleration is suppressed. Therefore, the control gain which was determined by the ultimate sensitivity method can be increased.

Next, in order to evaluate the frequency response, the positioning system was controlled by adjusting the control gain under each conditions, and was driven with a swept sine of 0.1 mm amplitude reference. The Bode plot was obtained by calculating the gain of each frequency. Figure 10 shows the measured result. With increasing the stiffness of the aerostatic guideway, a controller gain can be increased. From these results, a bandwidth of the positioning system increased from 374 Hz to 588 Hz. Inversely, with decreasing the damping of the aerostatic guideway, a peak gain of the positioning system was increased. Consequently, by applying the magnetic attraction force preload, the positioning stability was improved.

4.2 Performance of the positioning system

In order to evaluate the positioning resolution of the developed system, a constant reference and a nanometer stepwise reference were applied to the system. Figure 11 shows the response to the constant reference. By applying magnetic attraction preload, the residual vibration amplitude decreased from 2 nm to 1 nm. In addition, the standard deviation of the response decreased from 0.74 nm to 0.49 nm. From these results, the residual vibration of the positioning system was decreased and the stability of the positioning system was improved by increasing the bandwidth. Therefore, the stiffness of the aerostatic guideway provides a large effect on the performance of the positioning system.

Figure 12 shows the stepwise response of the system. Clear 1 nm step without overshoot could be observed in the result with the magnetic attraction preload. From the results, the positioning resolution of the system was improved from 2 nm to 1 nm. Therefore, the resolution of the positioning system could be improved by magnetic preload.

Table 2 Basic characteristics of the aerostatic guideway

<table>
<thead>
<tr>
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<th>Without preload</th>
<th>With preload</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearing clearance</td>
<td>17.23</td>
<td>5.51</td>
</tr>
<tr>
<td>Stiffness[N/µm]</td>
<td>20.4</td>
<td>298.8</td>
</tr>
<tr>
<td>Damping ratio</td>
<td>1.98</td>
<td>0.35</td>
</tr>
<tr>
<td>Air flow[L/min]</td>
<td>2.96</td>
<td>2.66</td>
</tr>
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</table>

Fig. 10 Amplitude of frequency response
In order to evaluate the performance of following reference, the continuous path (CP) positioning of 100nm was performed. In this drive, the following table could not move because driving distance was shorter than the stroke of VCM. Driving conditions were a velocity of 50 nm/s and an acceleration of 100 nm/s². Figure 13 shows response of the CP positioning and tracking error. By applying the magnetic preload, tracking error of the positioning table decreased at a constant velocity, while the tracking error during acceleration and deceleration were slightly improved by the preload. This result was considered to be caused by decreased damping. These results confirmed that the performance of the position system can be improved by the preload, while more improvement of the performance at acceleration and deceleration requires the increase in damping.

Tracking error during high speed CP driving was investigated within a travel length of 100mm. Driving conditions were a feed rate of 50 mm/s and an acceleration of 100 mm/s². Figure 14 shows the response of the high speed CP motion of 100 mm without magnetic preload. Figure 15 shows the response of the high speed CP motion of 100 mm with magnetic preload. Tracking error in micrometer order could be observed in both results. These errors were considered as effects of the large vibration of the relative displacement. The following table follows to the positioning table in the range of 0.2 mm. By increasing relative velocity, the effect of eddy current could not be ignored. Therefore, the error was considered as the effects of performance of the following table. However, by magnetic attraction force preload, the average of the tracking error decreased 10 % as compared with the case of without magnetic attraction force preload.

From these results, by using the proposed magnetic preloaded aerostatic guideway, the improvement performance of the positioning system could be confirmed within a small travel range.

![Fig. 11 Constant control response](image1)

![Fig. 12 1 nm stepwise response](image2)
5. Conclusions

This paper presented a magnetic attraction force-preloaded aerostatic guideway for achieving high speed nanometer positioning system. In addition, performance of the positioning system equipped with the proposed aerostatic guideway was evaluated. As a result, the following conclusions could be drawn.

(1) In order to achieve high speed nanometer positioning, a magnetic preload mechanism was proposed so as to prevent eddy current.
(2) Improvement of the positioning stability was confirmed by a constant reference response, because stiffness of aerostatic guideway was increased by applying the preloaded aerostatic guideway.
(3) By the magnetic attraction force preloaded, a 1 nm positioning resolution and a 10% improvement of following performance could be realized.
(4) In order to improve higher speed positioning performance, it is important to enhance the performance of the following table, because micro meter order tracking error was considered as effect of the large vibration of the relative displacement.

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References


Fig. 14 Response of 100 mm CP driving without preload

Fig. 15 Response of 100 mm CP driving with preload