A Dual-mode Pico-positioning System using Active Aerostatic Coupling

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This paper proposes a dual-mode ultraprecision positioning system for machine tools and measuring machines. The objective was to position a machine table with a picometer order of resolution, i.e., pico-positioning. A twist-roller friction drive (TFD) was used in coarse-mode positioning. The TFD, which was driven by an AC servomotor, is a kind of lead screw in mechanical terms, and several centimeters of machine table movement was controlled with a nanometer order of positioning resolution. To eliminate lateral vibration caused by the TFD, an active aerostatic coupling driven by piezoelectric actuators was inserted between the TFD and the machine table. This active aerostatic coupling was also applied as a feed drive device for fine-mode positioning; in the fine mode, the positioning resolution was 50 pm. Factors influencing pico-positioning, such as how noise from displacement sensors and vibrations in the aerostatic guideway affect positioning resolution, are discussed.

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NOMENCLATURE

AIR = active inherent restrictor
PZT = piezoelectric actuator
TFD = twist-roller friction drive
C = restrictor constant
D_1 = diameter of the drive roller
D_2 = diameter of the driven roller
d = inner diameter of the restrictor
h = air-film thickness on the bearing surface
h_d = restrictor gap
L = lead of the twist-roller friction drive
P_a = atmospheric pressure
P_s = supply pressure
P_0 = pressure at the restrictor
W_{in} = inflow air volume
W_{out} = outflow air volume
Δh = small change in h
Δh_d = small change in h_d
θ = crossing angle between the drive and driven rollers

1. Introduction

Positioning is a fundamental function of ultraprecision machine tools, aligners for integrated circuits, and measuring machines used in cutting-edge industry. For example, the optical element die of the most recent laser disk (Blu-ray or HD-DVD) is machined using an aspheric generator, which is a kind of ultraprecision NC machine tool.[1] The die should have a form accuracy of less than 40 nm, so the positioning resolution of an aspheric generator can be as small as 1 nm. Conventional positioning systems used in ultraprecision machines are composed of a servomotor and a lead screw. Researchers have also recently developed and applied a direct positioning system using a linear motor. At best, the positioning resolution of these conventional feed drive devices is limited in the order of several nanometers.[2] Development of positioning technology for the next generation of ultraprecision machines will be based on the ability to create sub-nanometer positioning: positioning of a machine table with a sub-nanometer order of resolution. The ever-increasing demand for improved performance among ultraprecision machines has produced an urgent need for the creation of novel feed drive devices to improve positioning technology.[3]

I have developed a novel kind of friction feed drive device called a twist-roller friction drive (TFD), the application of which in a positioning system has produced a sub-nanometer order resolution.[4,5] The TFD is a lead screw with a minute lead, in mechanical terms. The servomotor's rotational motion greatly reduces the machine table's linear motion, and motion reduction is a key technology in sub-nanometer positioning. Another key technology for improving positioning resolution is the application of a dual-mode positioning system, in which a high-resolution short-stroke positioning device for fine-mode positioning is mounted on a long-stroke positioning device for the coarse mode.[6,7] I propose a dual-mode positioning system using the TFD for the coarse mode and a fine adjustment of the motor shaft using a piezoelectric actuator for the fine mode. This dual-mode positioning system can have a positioning resolution of less than 0.1 nm.[8]

This paper presents a novel dual-mode ultraprecision positioning system to allow positioning with a picometer order of resolution, i.e., pico-positioning. Pico-positioning technology will be essential to future ultraprecision machines. In this system, the basic coarse mode for nanometer positioning with long strokes is executed with a combination of the TFD and the AC servomotor. However, because the TFD has the disadvantage of producing lateral vibration, an aerostatic coupling is inserted between the TFD and the machine table to eliminate it.[9] The coupling applies an aerostatic thrust bearing with an active inherent restrictor (AIR), previously developed by the author.[10] This active aerostatic coupling can also be used as the fine-mode positioning device. The AIR consists of a piezoelectric actuator with a through hole, one end of which is located on the bearing surface and acts as an inherent restrictor. The piezoelectric actuator can control the restriction gap and consequently air-film thickness on the bearing surface. Because of the aerostatic mechanism of the AIR, piezoelectric actuator deformation in the AIR unit allows greatly reduced table displacement. Such reduction in frictionless motion is effective for ultraprecision positioning, and an active aerostatic guideway using the AIR can produce a positioning resolution of 10 pm.[11]

The goal of this study was to produce a fine-mode positioning resolution in the order of picometers. This paper will discuss issues related to attaining this goal, such as how noise from displacement sensors and vibrations in the aerostatic guideway influence positioning resolution. These discussions will clarify the feasibility of pico-positioning using an active aerostatic guideway.

2. Dual-Mode Pico-positioning System

2.1 System composition and dual-mode control

Figure 1 presents the proposed dual-mode positioning system. A box-type machine table is guided on a square aerostatic guideway. Table movement is detected by a laser scale or a capacitance sensor. In the coarse mode, a twist-roller friction drive (TFD) driven by a servomotor positions the machine table. Table strokes in the coarse mode are 40 mm. Figure 2 presents the TFD mechanism; a drive roller driven by the motor is pressed against a driven roller with a crossing angle θ. To increase contact stability, these rollers are preloaded pneumatically (pressurized air is supplied under the driven roller). Mechanically, the TFD is considered to be a lead screw, and the following equation calculates the lead L of the TFD:

$$L = \pi \cdot D_1 \tan \theta \tag{1}$$

Equation (1) indicates that by setting a small crossing angle, the lead can be less than 1 mm, and a small lead is beneficial to improving positioning resolution. Because the TFD has the disadvantage of producing lateral vibration in the driven roller, an active aerostatic coupling is inserted between the driven roller of the TFD and the machine table to suppress this vibration, as shown in Fig. 1. The aerostatic thrust bearing in the coupling supports a thrust ring attached to the end of the driven roller of the TFD. Aerostatic lubrication of the thrust bearing allows the thrust ring to move freely in the lateral direction. Consequently, while the driving force from the TFD is transmitted to the machine table, lateral vibration from the driven roller can be isolated. As will be discussed in detail below, the active aerostatic coupling is also used as a feed drive device during fine-mode positioning. Table strokes in the fine mode are only several hundred nanometers, and this mode is expected to result in pico-positioning.

Figure 3 presents the control system for the dual-mode pico-positioning system. Displacement of the machine table is detected by a laser scale or a capacitance sensor, and then the detected table displacement is input to a motion controller via a digital counter or an AD converter. The motion controller is a kind of digital signal processor (DSP) with various input/output interfaces (counter, AD converter, and DA converter, as shown in Fig. 3).[12] The motion controller is supervised by a microcomputer (PC). Motion programs

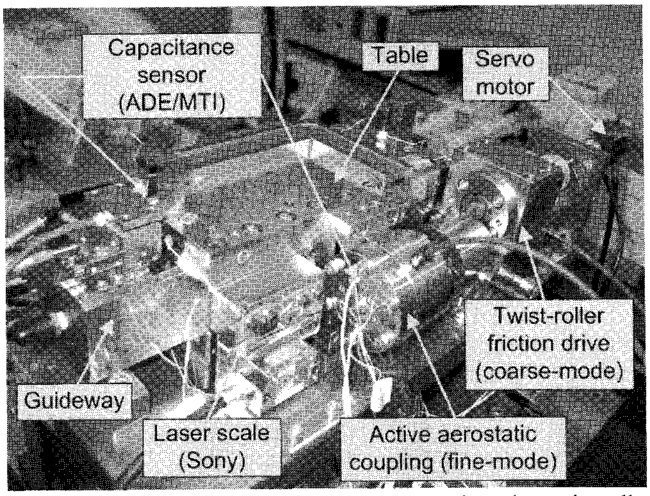

Fig. 1 Dual-mode pico-positioning system using the twist-roller friction drive and active aerostatic coupling

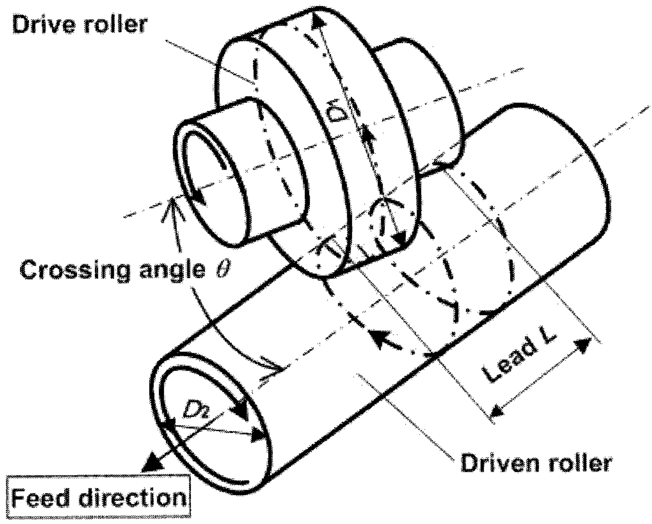

Fig. 2 Mechanism and arrangement of elements in the twist-roller friction drive

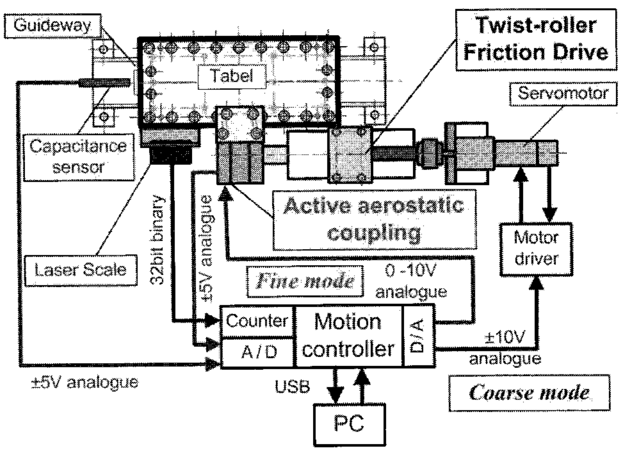

Fig.3 Control system for the dual-mode pico-positioning system using a twist-roller friction drive and active aerostatic coupling

for managing the motion controller and for positioning the machine table are coded on the PC, and then downloaded to the motion controller. Information about the positioning system, such as table position and table velocity, are gathered by the motion controller, sent back to the PC, and then displayed on the PC monitor. Based on the motion program for a specified positioning, the motion controller calculates output voltage to the servomotor (in coarse-mode positioning) or to the active aerostatic coupling (in fine- mode positioning). The motion program can select a combination of the sensor and actuator.

2.2 Active aerostatic coupling for fine-mode positioning

In fine-mode positioning, the active aerostatic coupling is used as a short-stroke feed drive device. Figure 4 shows the surface of the aerostatic thrust bearing pad in the coupling; the surface has eight air outlet holes. When the bearing pad is assembled, each hole functions as an inherent restrictor. Four of the eight holes (the black circular areas in Fig. 4) are active inherent restrictors (AIRs). An AIR consists of a piezoelectric actuator (PZT) with a through hole. The PZT can move one end of the hole up or down on the bearing surface.

A capacitance sensor is embedded adjacent to each AIR to detect changes in air-film thickness.

Figure 5 presents a schematic diagram of the active aerostatic coupling's positioning mechanism, illustrating AIR cross sections before and after positioning. When the PZT is retracted by decreasing the supply voltage, restriction gap h_d increases by Δh_d, after which air flow volume increases and air-film thickness h increases by Δh. The relationship between h and h_d can be expressed with the following equation, illustrated in Fig. 6 [13]:

$$h = \sqrt[3]{\frac{C \cdot P_s \cdot P_a}{(P_0^2 - P_a^2)} h_d} \qquad (2)$$

Thus, the thrust ring and consequently the machine table can be moved by changing the length of PZT in the AIR. As shown in Fig. 6, the curve gradient can be less than unity, meaning that the actual table displacement can be much less than the deformation of the piezoelectric actuator. The reduction ratio (the ratio of Δh to Δh_d) for a reasonable air-film thickness can range from about 1 to 30. This frictionless motion reduction mechanism effectively improves positioning resolution.

Figure 7 illustrates the control system for the active coupling. The aerostatic coupling effectively suppresses lateral vibration in the driving mechanism, but inevitably deteriorates the stiffness in the feed direction. Active control of the aerostatic coupling can increase the coupling's thrust stiffness. The embedded capacitance sensor detects any change in the thrust bearing's air-film thickness, which is communicated to the PC via an AD converter. The PC calculates the voltage required to compensate for the air-film thickness, and then outputs the voltage to the AIR via a DA converter. Thus, the air-film thickness can recover and thrust stiffness can be infinite.

For fine-mode positioning of the machine table, an external capacitance sensor pointed at the machine table is used as a feedback sensor to detect table displacement. In this case, the PC calculates the appropriate voltage to change the air-film thickness based on the positioning program, and then outputs the voltage to the AIR. Thus, the air-film thickness changes and the machine table moves according to the positioning program. As discussed above, positioning finer than PZT resolution can be realized without mechanical contact. The laser scale can also be used for long-stroke positioning. When analyzing positioning resolution during fine-mode positioning, an ultrasensitive fiber-optic displacement sensor[13] is used instead of the external capacitance sensor.

3. Positioning in the Coarse Mode

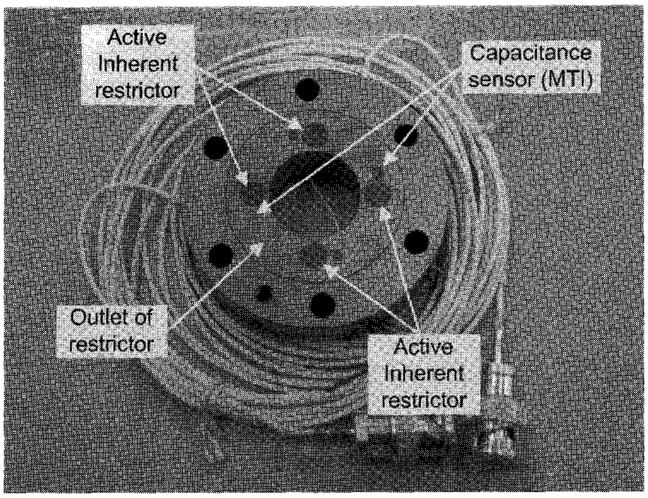

Fig.4 Thrust-bearing surface of the active aerostatic coupling system

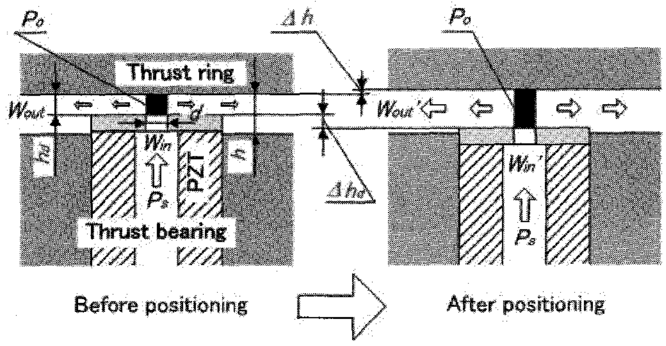

Fig.5 Positioning mechanism using active aerostatic coupling

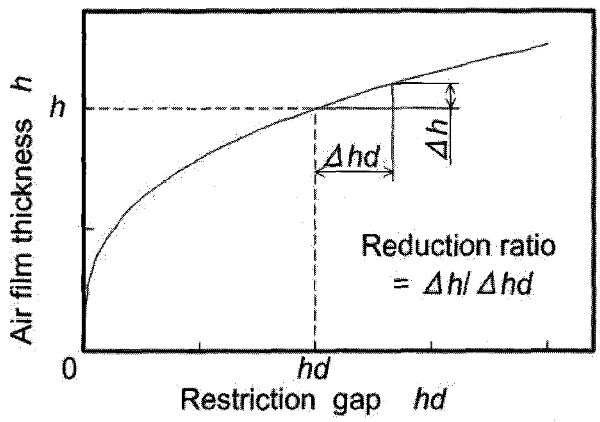

Fig.6 Control of air-film thickness by active aerostatic coupling

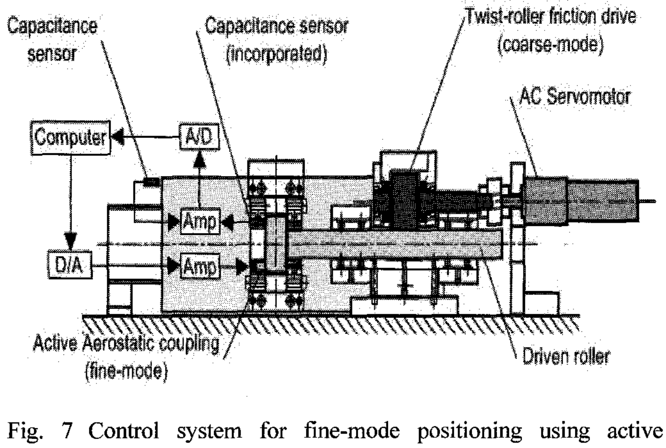

Fig. 7 Control system for fine-mode positioning using active aerostatic coupling

A full 40-mm stroke can be controlled in the coarse mode, but this paper is mainly focused on the system's positioning resolution. Therefore, coarse mode performance was analyzed for short-range step positioning. For position control using the motion controller, the laser scale acts as a feedback sensor for table displacement. The motion program for step positioning repeats a specified step width five times in one direction, then repeats the same step width five times in the reverse direction.

Figure 8 illustrates the results of step positioning in the coarse mode. The table displacements shown in Fig. 8 were detected by the external capacitance sensor pointed at the machine table. This capacitance sensor was not aligned with the laser scale used as a feedback sensor for positioning. Thus, some Abbe's error could be expected, but table movement actually followed the stepping command of the motion program accurately, as shown in Fig. 8.

Positioning resolution was determined to be 5 nm, a sufficient value for the coarse mode. A finer positioning resolution can be obtained by selecting the capacitance sensor as the feedback sensor instead of the laser scale.

4. Ultraprecision Positioning in the Fine Mode

4.1 Characteristics of active aerostatic coupling

The aerostatic coupling's basic function is to isolate lateral vibration induced by the driving mechanism, the TFD. Figure 9 presents the effect of isolating the vibration of the coupling; the lateral vibration amplitude of the TFD driven roller was in the range of several micrometers. In contrast, the machine table's lateral movement was in the order of 10 nm. Table motion straightness can be further improved with the active aerostatic guideway using the AIR.[15]

Aerostatic coupling has the disadvantage of decreasing the feed drive device's thrust stiffness, which can be increased with active control. Figure 10 shows the effect of active aerostatic coupling control on thrust stiffness, when the capacitance sensor incorporated in the coupling was used as a feedback sensor. Change in air-film thickness on the coupling's thrust bearing was measured when the machine table had a step load of 0.5 N. As shown in Fig. 10(a), the air-film thickness changed by 80 nm without control. Thus, the coupling stiffness was finite and the feed drive device's thrust stiffness decreased. In contrast, Fig. 10(b) shows that with active control, the bearing pad moved once to the loading direction, but finally returned to the original position. This recovery involved a settling time of about 30 ms, so the coupling's static stiffness in the feed direction was effectively infinite. Figure 11 presents the coupling's frequency response, when table vibration against the sinusoidal excitation was measured. Based on the sensor setting, the sensor output had a phase delay of π, i.e., measurement results are displayed in the reversed phase. As shown in Fig. 11(a), without control the coupling compliance was almost constant and the phase delay was slightly under the frequency of 100 Hz. Both compliance and phase delay increased in higher frequency ranges. As shown in Fig. 11(b), compliance in the lower frequency ranges was greatly reduced with active control and the phase advanced by about $\pi/2$. This result indicates that lateral vibration was isolated and that the active aerostatic coupling acted as a rigid coupling. Comparison of Figs. 11(a) and (b) reveals that the active control was effective for vibrations lower than 30 Hz.

4.2 Fine-mode positioning

The active aerostatic coupling can also be used as a fine positioning device. A fiber-optic sensor is used as a feedback sensor. Before fine-mode positioning is executed, it is important to analyze how air-film vibrations caused by the coupling's aerostatic bearing and the machine table's aerostatic guideway and sensor noise affect the system's feedback control to determine limitations of the system's positioning resolution. Figure 12 shows the frequency characteristics of the signal detected using a fiber-optic sensor with a 100-Hz low-pass filter. As shown in Fig. 12(a), without an air supply to the coupling and guideway, the sensor detected the machine base's background vibration and noise from the sensor itself. Overall amplitude was in the range of 10 pm, but amplitude in the lowest frequency range increased. This might have been caused by the influence of vibration from the floor. As shown in Fig. 12(b), when pressurized air was supplied to the positioning system, the amplitude of noise increased to the order of 0.1 nm. This was due to the air-film vibration in the aerostatic elements. Therefore, this air-film vibration makes it difficult for the positioning system to achieve pico-positioning using a conventional aerostatic guideway.

As shown in Fig 12(c), when the active control applied active aerostatic coupling, the amplitude of noise decreased in the range lower than 10 Hz. This result indicates that active aerostatic coupling controlled by the positioning loop was able to suppress not only the air-film vibration, but also vibration from the floor and sensor noise. This result agrees with the frequency response shown in Fig. 11(b).

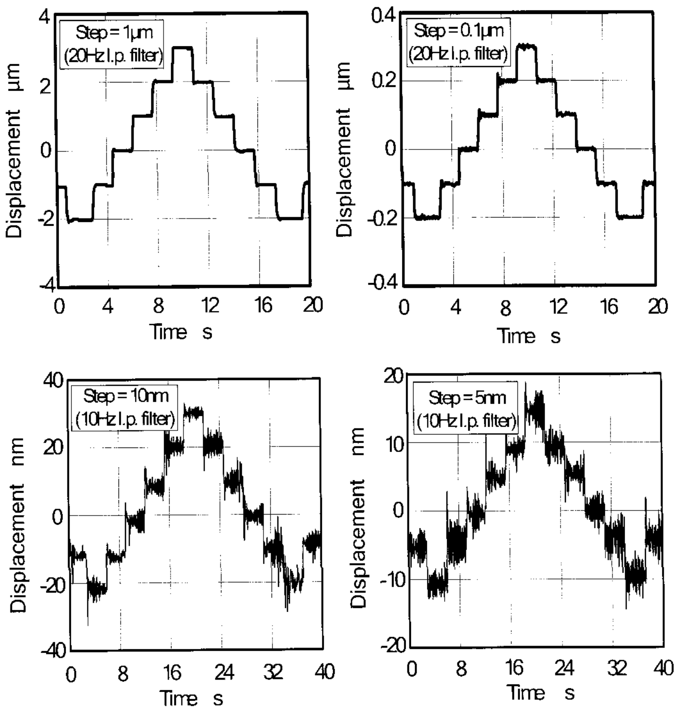

Fig. 8 Step positioning in coarse mode (laser scale feedback)

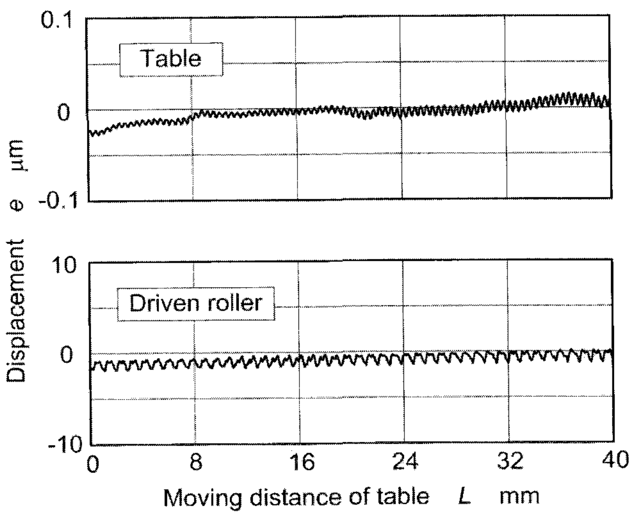

Fig. 9 Effect of aerostatic coupling on vibration isolation

Therefore, the use of active aerostatic coupling should enable a positioning resolution in the order of 10 pm.

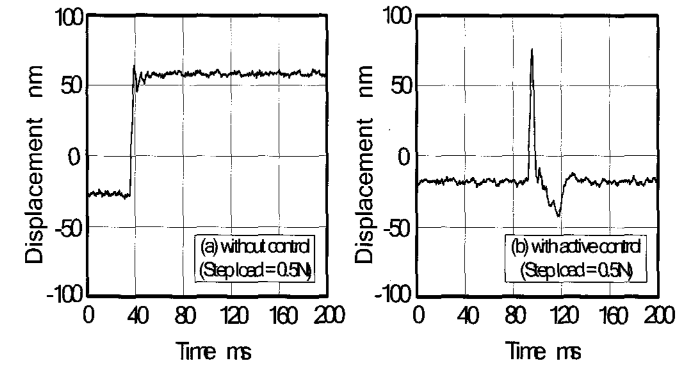

Fig. 10 Step response of active aerostatic coupling

Figure 12(c) also indicates that the active control did not cause decreased amplitude in the higher frequency range. The amplitude of the higher frequency range can be decreased by a low-pass filter with lower cutoff frequency, but the inevitable phase delay of the control signal causes instability in the feedback control system. Therefore, the low-pass filter for the position control loop should have a cutoff frequency higher than 100 Hz. Noise levels ranging from 40 to 200 Hz should be reduced to further improve positioning resolution. A novel method to minimize noise levels by employing an active inherent restrictor in the coupling is currently being developed.[16]

Figure 13 presents the results of step positioning in the fine mode using the active aerostatic coupling. Steps of 1 nm, 0.5 nm, and 100 pm are clearly resolved. The 50-pm steps were blurred by noise, but the figure reveals that the table movement for the five-step instruction was 250 pm. Consequently, positioning resolution in the fine mode can be assumed to be 50 pm. Noise levels from the control system should be minimized to further improve positioning resolution.

5. Conclusions

This study showed that the proposed dual-mode positioning system using an active aerostatic coupling as a fine-mode positioning device effectively improved positioning technology. The results from experimental analysis of the positioning system can be summarized as

(1) The positioning resolution in the coarse mode using the twist-roller friction drive was 5 nm. Improvements to the feedback sensor should yield finer resolution.
(2) The active aerostatic coupling had infinite stiffness in the feed direction, while the radial stiffness for isolating vibration from the driving mechanism was zero. Such ideal coupling improved positioning performance.
(3) The positioning resolution in the fine mode using the active aerostatic coupling with the current control system was evaluated to be 50 pm.

The novel positioning techniques proposed in this study should improve positioning technology for the next generation of ultraprecise machines. Further improvement of control tactics will enable pico-positioning, the goal of this research.

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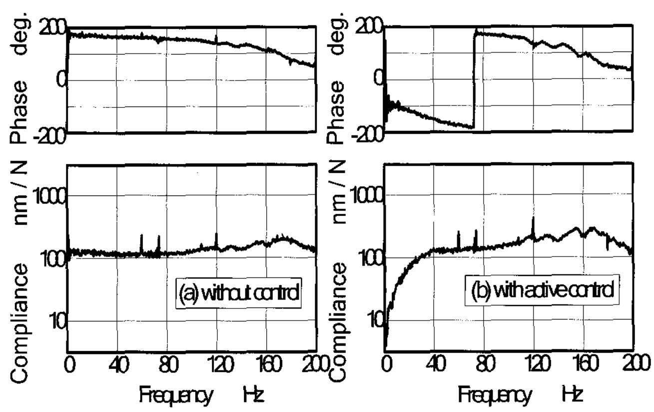

Fig.11 Frequency response of active aerostatic coupling

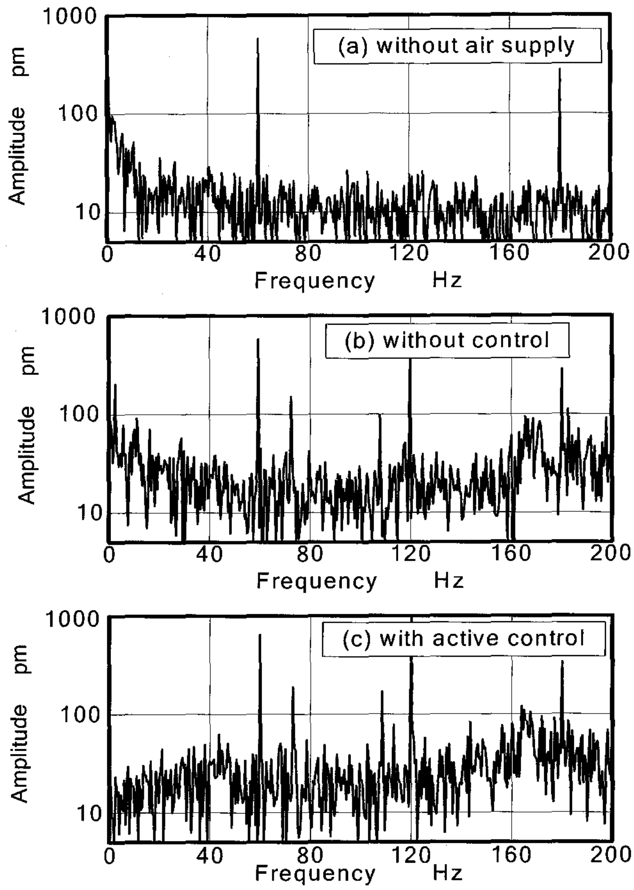

Fig 12 Noise level of the control system detected using a fiber-optic sensor with a 100-Hz low-pass filter

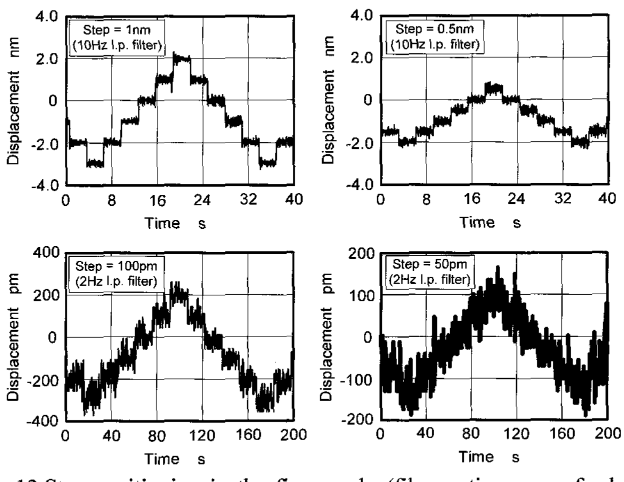

Fig.13 Step positioning in the fine mode (fiber-optic sensor feedback)

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