A Novel Picometer Positioning System for Machine Tools and Measuring Machines

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Abstract: A novel tri-mode ultraprecision positioning system for machine tools and measuring machine is proposed. The basic coarse mode uses a Twist-roller Friction Drive (abbr. TFD), and controls several tens of millimeters of the machine-table travel with nanometer order of positioning resolution. The fine mode also utilizes the TFD with a fine adjusting mechanism. The resolution of the fine mode is in the range of sub-nanometer. For realizing picometer positioning, the ultra-fine mode is executed by using an active aerostatic guideway. On the bearing surface of this active guideway, several Active Inherent Restrictors (abbr. AIRs) are embedded for controlling the table position. An AIR unit consists of a piezoelectric actuator having a through hole, one end of the hole on the bearing surface acts as an inherent restrictor. Owing to the aerostatic mechanism of the AIR, the deformation of the piezoelectric actuator in the AIR unit causes much reduced table displacement. Such motion reduction is effective for ultraprecision positioning. Current positioning resolution of the ultra-fine mode is 50pm, however the final goal of the positioning resolution is expected to be in the order of picometer.

Keywords: active control, aerostatic bearing, machine tool, nanotechnology, picometer, piezoelectric actuator, positioning

1. INTRODUCTION

Ultraprecision machine tools and measuring machines are essential industrial equipments in the field of nanotechnology. For example, the mold of two-focused pick-up lenses for CD and DVD are machined by using a kind of ultraprecision machine tool called an aspheric generator, where both the aspheric lens profile and the grooves for Fresnel lens are machined under numerical control [1,2]. The grooves of the mold of optical waveguide for LCD are cut by using a CNC grooving machine [1]. Fundamental and essential function of these ultraprecision machine tools is “positioning.” For ultraprecision measuring machines, the positioning is also an important property. The positioning resolution of these ultraprecision machines should be in the range of nanometer. Several positioning systems are employed; the combination of a servomotor, a ball screw and a hydrostatic guideway is the typical feed drive system for ultraprecision machines. Recently, a linear motor is used instead of the conventional combination of the servomotor and the ball screw [1,2].

The demand for the performance of the ultraprecision machine is ever increasing. For optical memory disk of the next generation, Blu-ray Disc or HD-DVD, optical elements of sophisticated profile with higher precision should be mass-produced within reasonable cost. For the mass-production of these optical elements, the positioning system of the machine tool should be improved and/or a novel positioning system should be invented. Sub-nanometer order (0.1nm) of positioning resolution can be obtained by a commercially available machine tool where a hydrostatic lead screw is used [1]. Dual mode positioning systems are proposed for improving the positioning resolution; a high-resolution short-stroke positioning device for fine mode positioning is mounted on a long-stroke coarse mode positioning device. We’ve reported that the positioning resolution of a dual mode positioning system using a friction drive mechanism for the coarse mode and a piezoelectric actuator for the fine mode can be less than 0.1nm [3].

In the present paper, we propose a novel tri-mode ultraprecision positioning system for machine tools and measuring machines. The proposed system has three positioning mode, i.e. coarse, fine and ultra-fine mode. Several innovative positioning devices are utilized in these modes. The coarse mode for nanometer positioning with long stroke is executed by using a Twist-roller Friction Drive (abbr. TFD) invented by the authors [4] and an ordinary AC servomotor for driving the TFD. The fine mode for sub-nanometer positioning also employs the TFD, however the TFD is driven by a fine adjusting mechanism using piezoelectric actuators. In these coarse and fine modes, a laser scale with the resolution of 70pm is used for detecting the table displacement. A capacitance sensor is also used in the fine mode positioning.

For realizing picometer positioning, the ultra-fine mode is incorporated into the proposed system. The ultra-fine mode utilizes an aerostatic guideway activated by an Active Inherent Restrictor (abbr. AIR) for controlling the table position. The AIR consists of a piezoelectric actuator having a through hole, one end of the hole on the bearing surface acts as an inherent restrictor [5]. Owing to the aerostatic mechanism of the AIR, the deformation of the piezoelectric actuator in the AIR unit causes much reduced table displacement. Such motion reduction is effective for ultraprecision positioning. The table displacement is detected by a high-resolution fiber-optic sensor [6]. It is reported that the positioning resolution of the active aerostatic guideway using the AIR is 10pm [5]. These coarse, fine and ultra-fine modes can be controlled by a motion control system using a personal computer and a special driver. In the present paper, the mechanism of the tri-mode positioning unit, the control system and the result of ultra-precision positioning are shown.

2. TRI-MODE POSITIONING SYSTEM

2.1 Configuration of tri-mode positioning unit

The unit of the proposed tri-mode positioning system is shown in Fig. 1 and the cross sectional view of the positioning unit is shown in Fig.2. A rectangular machine table is guided by an aerostatic guideway and positioned under three positioning modes, namely, coarse, fine and ultra-fine mode. The basic coarse mode positioning employs the TFD mechanism driven by an AC servomotor. The TFD and the table are connected by an aerostatic coupling that reduces the vibration generated in the TFD. In the coarse mode, full stroke of the machine-table travel (40mm) can be controlled with nanometer order of resolution. For the fine mode positioning, a fine adjustment using piezoelectric actuators incorporated into a motor holder drives the TFD. For realizing picometer positioning resolution, the ultra-fine mode employs an aerostatic guideway with the AIR. Guiding the machine table, this active aerostatic guideway controls the air-film thickness on the bearing surface for the ultra-fine positioning of the table in the lateral direction (perpendicular to the paper, in Fig.2). In the followings, the mechanisms of the novel feed drive devices invented by the authors are explained.

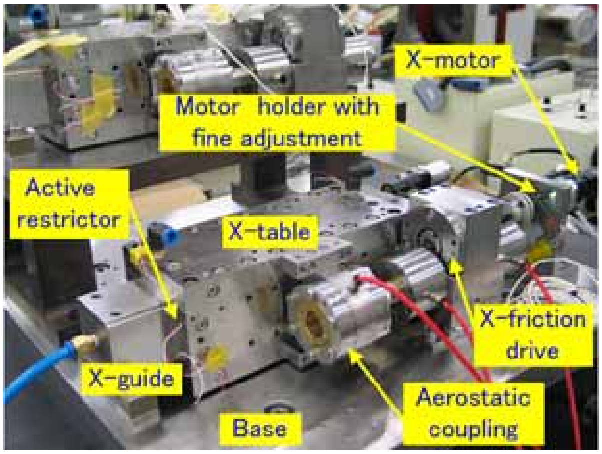

Fig. 1 Unit of Tri-mode ultraprecision positioning system

2.2 Twist-roller friction drive for coarse and fine mode

As shown in Fig.2, the drive shaft of the TFD (red element) is connected to the servomotor (pink element), and pressed against the driven roller (yellow element) supported by aerostatic radial bearings. Figure 3 shows the arrangement of the elements of the TFD and their movement in an exaggerated form. The drive shaft driven by an AC servomotor causes a helical motion in the driven roller because there is a minute crossing angle between the axes of the drive shaft and the driven roller. Consequently, the driven roller is fed in its axial direction, namely the TFD is mechanically regarded as a kind of lead screw. By reducing the crossing angle, the lead of the TFD can be less than 0.1mm, which is about one-hundredth of that of an ordinary lead screw of the same dimensions. Small lead of the feed mechanism is advantageous for improving positioning resolution. We have reported that the resolution of a positioning system using the TFD is in the order of sub-nanometer where a special precision AC servomotor was used as a driving motor [7]. In the present system, this TFD driven by the ordinary servomotor is used for the full stroke coarse mode positioning with nanometer order of resolution.

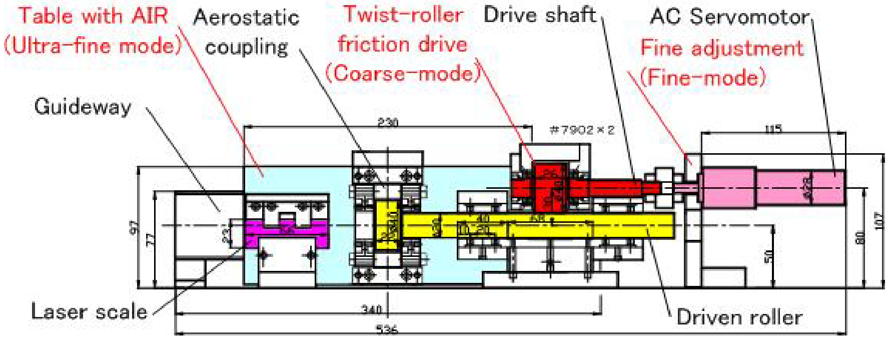

Fig. 2 Cross-sectional view of Tri-mode ultraprecision positioning system

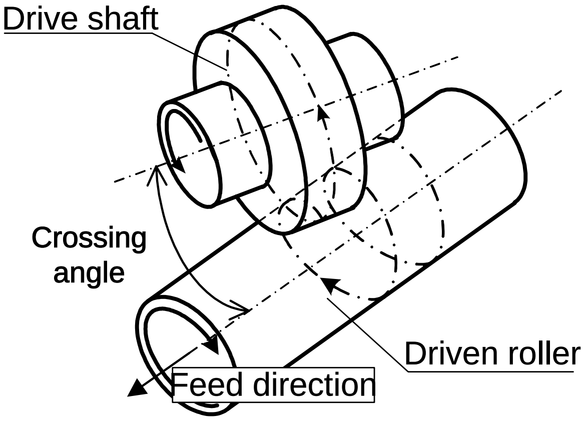

Fig. 3 Schematic view of twist-roller friction drive

In the fine mode, the TFD is also used, but driven by a fine adjusting mechanism show in Fig. 4. This fine adjustment is incorporated into the motor holder; the servomotor housing is fixed to a motor-holding element that is suspended radially by four hinges. One end of each hinge is fixed to an outer frame and another end is moved by piezoelectric actuators. Thus whole the motor can be rotated slightly around the motor shaft by deforming the piezoelectric actuators. Combination of the TFD and the fine adjustment allows about several-hundredth of reduction ratio, namely one micrometer of deformation of the piezoelectric actuator causes nanometer order of the displacement of the table. In effect, the resolution of the ordinary servomotor is improved.

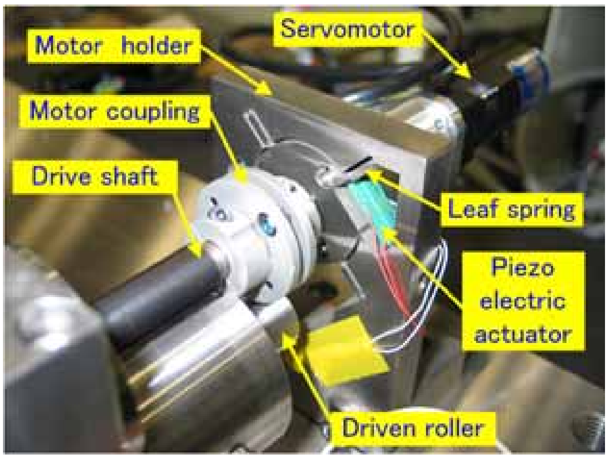

Fig. 4 Fine adjustment incorporated into motor holder

2.3 Active inherent restrictor for ultra-fine mode

For the ultra-fine mode positioning, the active aerostatic guideway with the AIR is used. The positioning mechanism

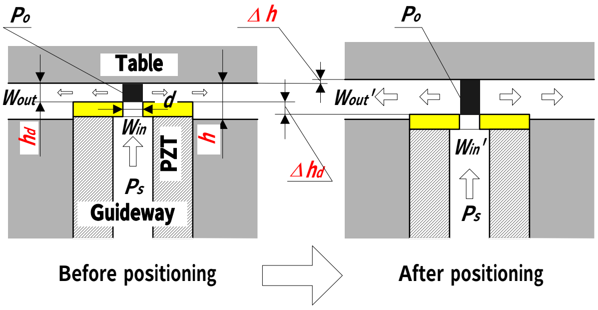

Fig. 5 Positioning mechanism of active aerostatic guideway

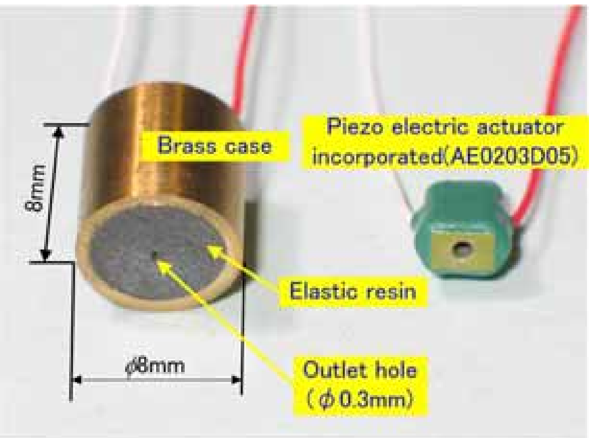

Fig. 7 Assembled AIR unit (left) and piezoelectric actuator (right)

of the active aerostatic guideway is illustrated in Fig. 5. The AIR unit consists of a piezoelectric actuator (PZT) having a through hole. The air outlet of the AIR on the bearing surface acts as an inherent restrictor. The restriction gap h_d can be controlled by the piezoelectric actuator. As h_d increses by Δh_d, the air-film thickness h increases by Δh because the air-volume through the restrictor increases. Thus, the table position can be controlled by the AIR, and the ultra-fine positioning of the table can be executed. Owing to the aerostatic mechanism, the table displacement is much less than the deformation of the piezoelectric actuator. Such friction-less motion reduction mechanism is effective for sub-nanometer and picometer positioning.

The procedure for assembling the AIR unit is shown in Fig.6, from left to right. A piezoelectric actuator having a through hole is inserted into a brass case, then the space between the actuator and the case is filled with silicone rubber. Finally, the top of the actuator is covered with elastic resin and a small air outlet hole is drilled through the resin layer to the through hole of the actuator. An assembled AIR unit and the piezoelectric actuator incorporated are shown in Fig.7. Overall size of the AIR unit is 8mm in diameter and 8mm in length. The AIR unit is incorporated into the machine table. The machine table consists of four plates surrounding the rectangular guide rail as shown in Fig.1. Figure 8 shows the inside of two plates constructing the machine table, where another two plates are removed. In Fig.8, vertical and horizontal bearing surfaces can be seen. On each bearing surface, two AIR units are embedded. As explained for Fig.5, these AIR units are used for ultraprecision positioning. At the central part of each plate in Fig.8, there are grooves of the surface restrictor for the aerostatic table guide.

Fig. 6 Assembling of AIR unit (from left to right)

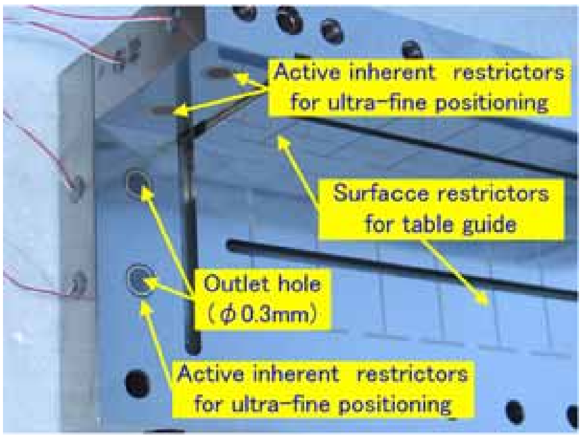

Fig. 8 Bearing surface of active aerostatic guideway

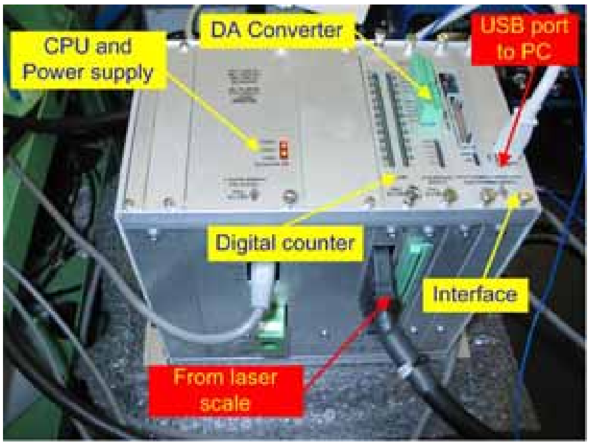

Fig. 9 Motion controller UMAC (Delta-Tau)

3. CONTROL SYSTEM

3.1 Motion controller and control system

The proposed tri-mode positioning system can be controlled by a Delta-Tau motion controller, UMAC shown in Fig.9. The UMAC consists of a CPU and power supply unit, a digital

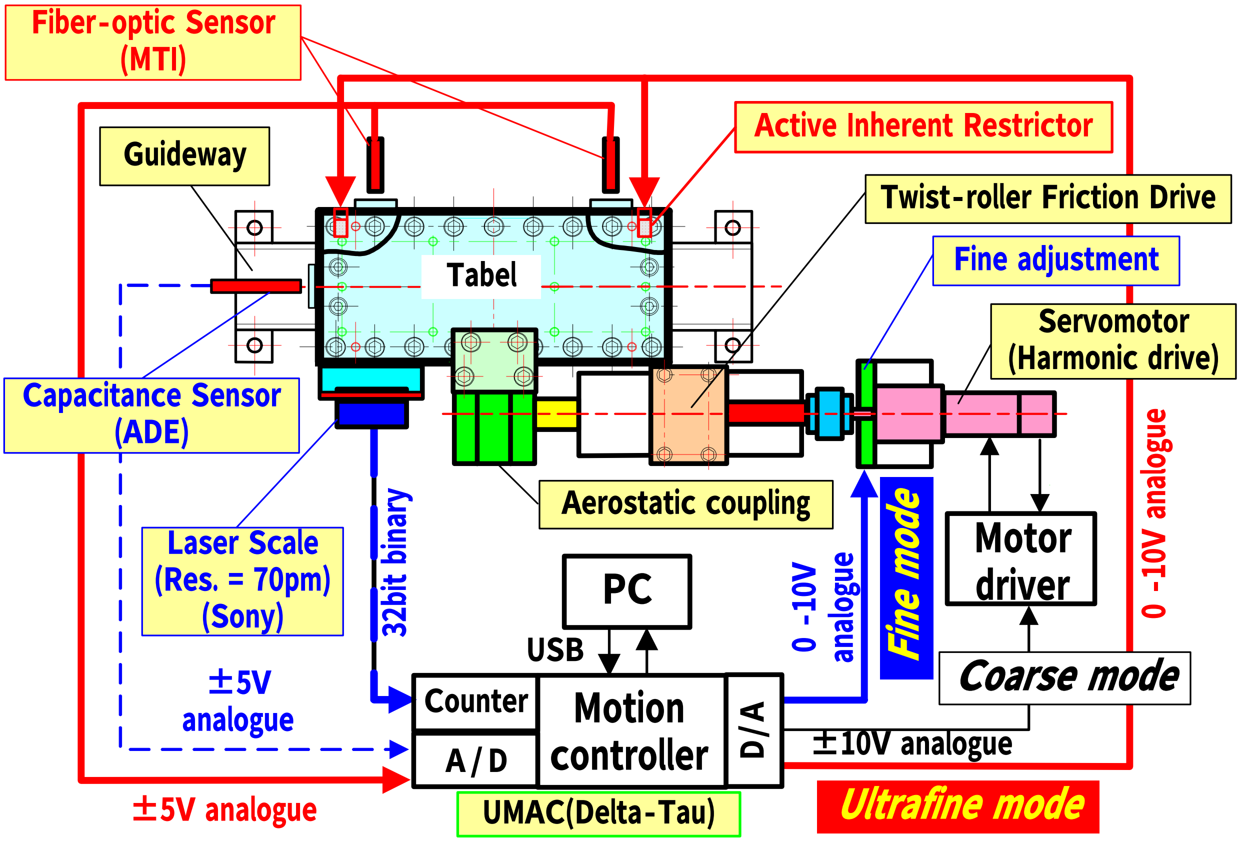

Fig. 10 Motion control system for tri-mode positioning system

counter unit, an AD/DA converter unit and an interface unit having a USB port. The performance of the UMAC is monitored by a personal computer via USB. Including the UMAC controller, whole control system is shown in Fig.10. In the coarse and fine mode, the displacement of the table is detected by a laser scale. A 48-bit binary counter unit attached to the controller is used for reading the digital data from the laser scale. Then the UMAC controller uses the detected table position for PID feedback control of the machine table. The UMAC also has the facility of feed-forward control. The digital output from the UMAC is converted into analogue voltage by using a 16-bit DA converter unit. Then the analogue output is fed to the AC servomotor (in the coarse mode), or the piezoelectric actuator in the fine adjustment (in the fine mode). In the fine mode, a capacitance sensor is also used as the feedback sensor when the resolution and the stability of the laser scale are insufficient. For the analogue capacitance sensor, a 16-bit AD converter unit is used. In the ultra-fine mode, the table displacement in the lateral direction is detected by a fiber-optic sensor. The analogue displacement of the table is converted into digital data by the AD converter. Then the voltage for the AIR unit in the active aerostatic guideway is calculated, and output via the DA converter.

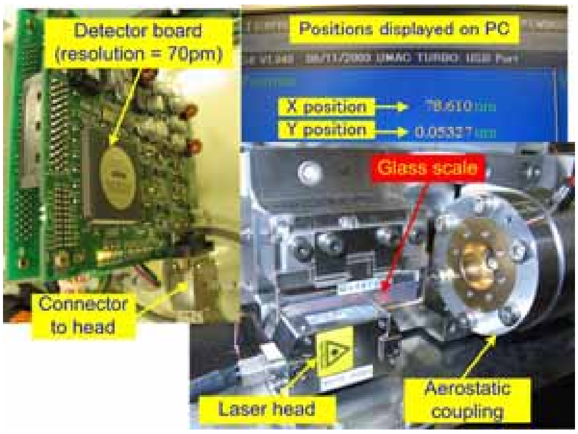

Fig. 11 Laser scale and detector board

3.2 Sub-nanometer sensing of table position

The laser scale system used for the coarse and fine mode positioning is shown in Fig.11. The movement of a diffraction grating glass scale attached to the machine table is detected by a laser head (right). The grating constant of the glass scale is 0.14μm, however by using the interpolating technique installed on the detector board (left), the resolution of the laser scale is 70pm. The table position is displayed on the screen of the monitor PC shown in the upper part of Fig. 11, where the resolution of the position display is 0.001nm.

The displacement of the machine table in the ultra-fine mode is detected by a fiber-optic sensor. Characteristic of the fiber-optic sensor we used is shown in Fig.12. It can be seen in Fig. 12 that the sensitivity of the front slope is 0.48nm/mV. Nominal resolution of this sensor is 0.25nm over the frequency range to 130kHz, however finer resolution can be obtained by using a low-noise DC amplifier and an external low-pass filter.

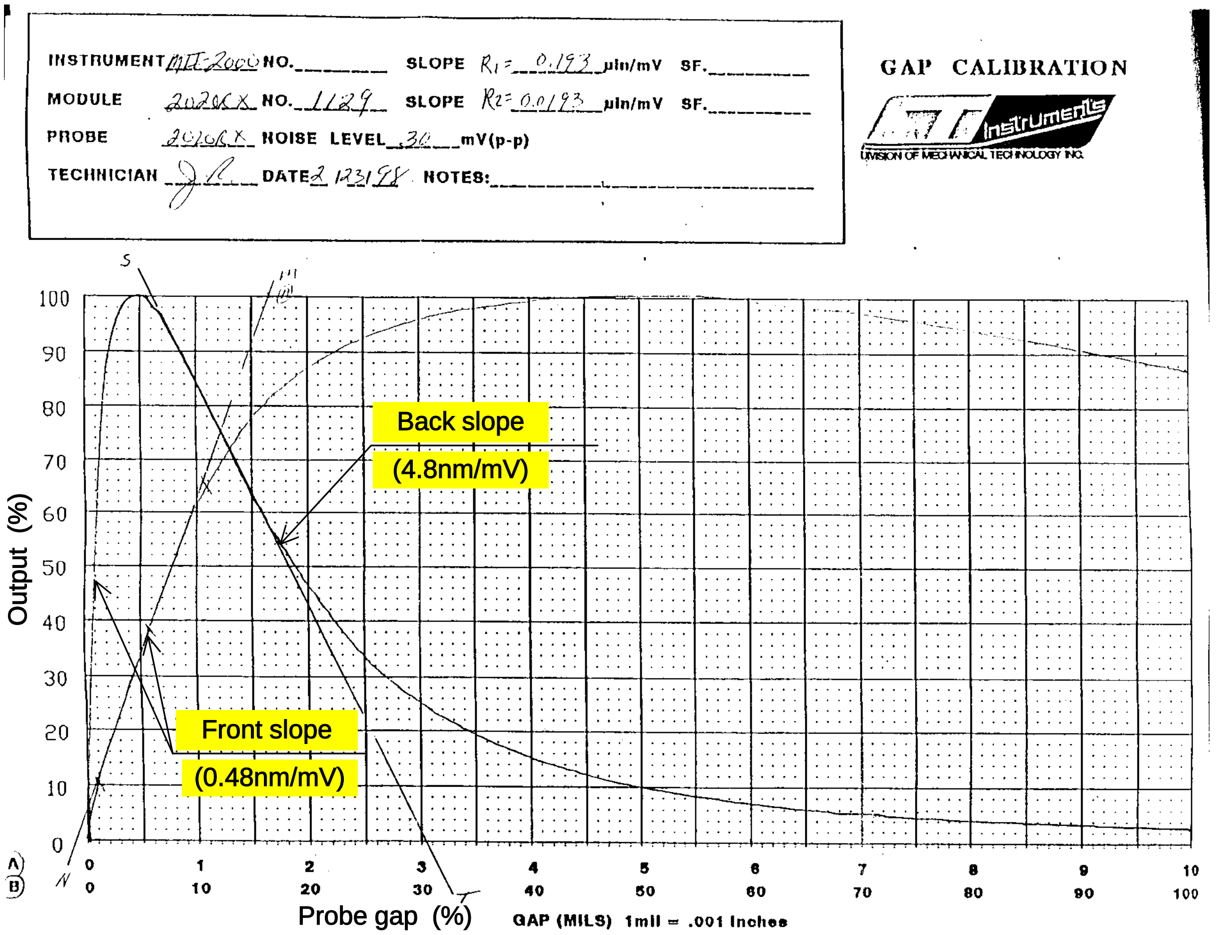

Fig. 12 Characteristic of fiber-optic displacement sensor (sensitivity curve of MTI-2000 measured by MTI)

4. POSITIONING PERFORMANCE

4.1 Nanometer positioning in coarse and fine mode

By using the coarse mode of the motion control system shown in Fig.10, the positioning performance of the proposed positioning system is analyzed. An instruction of step positioning with various step widths is applied to the machine table, and the response of the table is detected by a separate capacitance sensor that is not arranged in the feedback loop of the motion control system. For the feedback control of the table, the laser scale is used. Therefore, some Abbe's error may be expected, however, it is shown that the controllable minimum step width is 5nm. Thus, nanometer order of positioning resolution can be obtained for full stroke travel (40mm) of the machine table.

In the next, the positioning performance of the system in the fine mode is analyzed; the fine adjustment in the motor holder is utilized, while the servomotor is disabled. The response of the table for the step positioning is detected by the capacitance sensor that is also used as the feedback sensor. The result of step positioning is shown in Fig. 13, where a 0.2nm width of step is repeated five times in one direction, the in the reverse direction. Noise level is fairly high, however, every step can be recognized. Thus, it is show that sub-nanometer positioning resolution can be realized by using the fine mode.

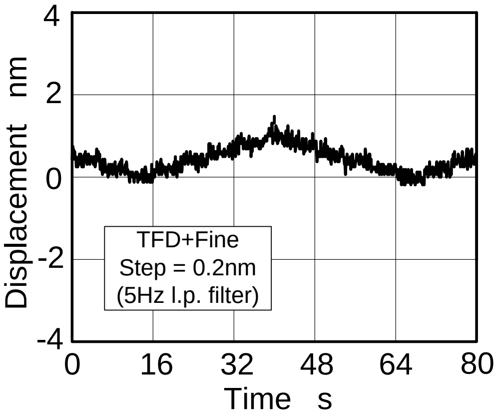

Fig. 13 Sub-nanometer step positioning in fine mode

4.2 Ultra-fine mode toward picometer positioning

The positioning performance of the proposed system in the ultra-fine mode is analyzed. The active aerostatic guideway positions the machine table in the direction perpendicular to the feed axis. The fiber-optic displacement sensor is used as the feedback sensor. The step responses of the table for various step widths are also detected by this fiber-optic sensor, and shown in Fig. 14. It is shown that the responses with the width

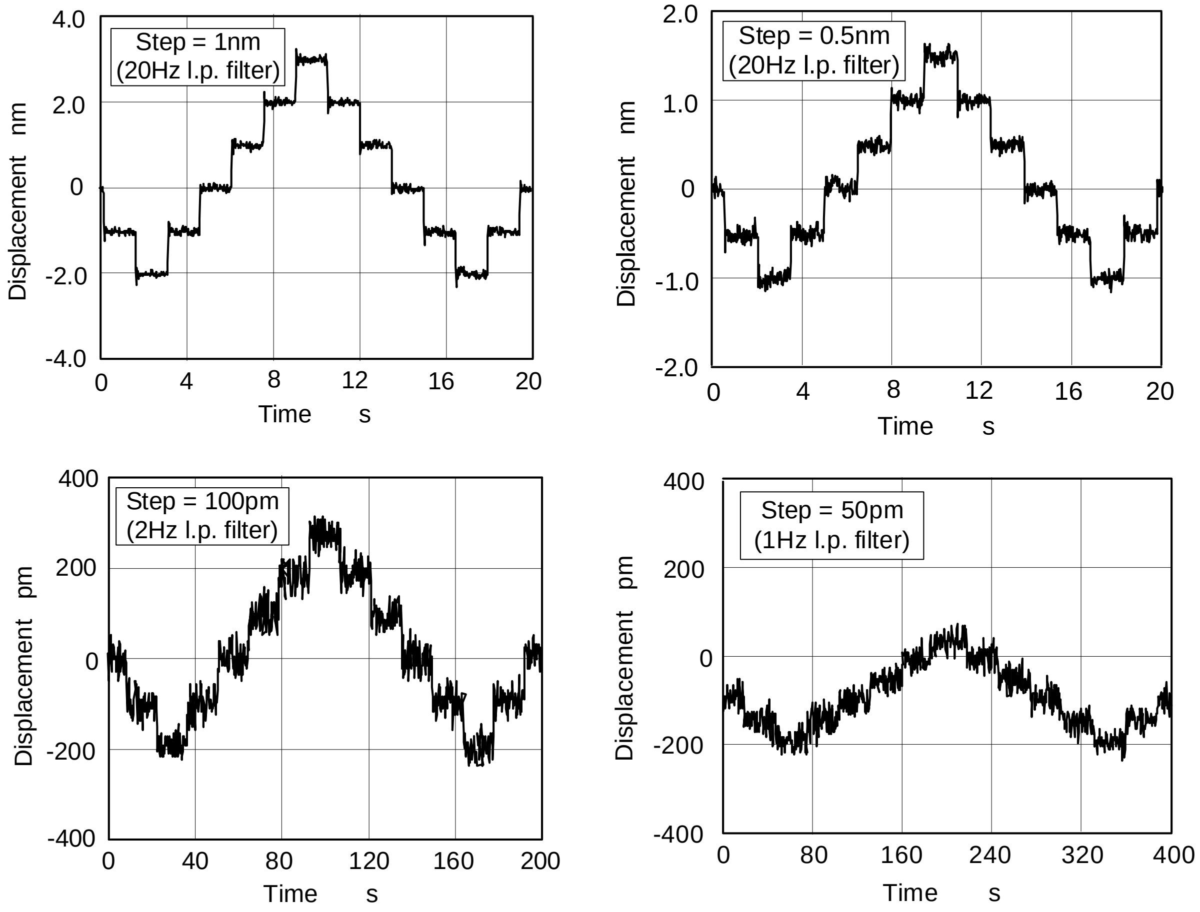

Fig. 14 Sub-nanometer and picometer step positioning in ultra-fine mode

of 1nm and 0.5nm are clearly resolved. Noise level is much less than the response in Fig.11. This is because the difference in the noise and sensitivity of the sensor used for the ultra-fine mode. The responses of finer step width are also shown in Fig.14. In the current experiment, the step of 100pm can be recognized apparently, and the minimum recognizable step width is 50pm. However, it was reported that the positioning resolution of another ultraprecision positioning system with active aerostatic guideway is 10pm [5]. Therefore, the positioning resolution in the ultra-fine mode of this system can be at least 10pm, and the final goal of our research is picometer positioning. For attaining our goal, the noise lever of the controlling and measuring system should be improved.

5. CONCLUSIONS

A tri-mode ultraprecision positioning system is proposed where several novel positioning devices we've developed are employed. The positioning performance in the coarse mode is sufficient for the long stroke nanometer positioning. The positioning resolution in the fine mode is 0.2nm, and sub-nanometer positioning is realized. In the ultra-fine mode, current positioning resolution is 50pm, which is insufficient for picometer positioning. For picometer positioning, noise level of the sensor and the control system for the ultra-fine mode should be decreased.

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REFERENCES

[1] Homepage of Nachi-Fujikoshi Corp. http://www.nachi-fujikoshi.co.jp
[2] Homepage of Precitech Inc. http://www.precitech.com
[3] H. Mizumoto, et. al., *Proceedings of 4th International Conference of the euspen*, Vol.1, pp.378-379, 2004.
[4] H. Mizumoto, et. al., *Precision Engineering*, Vol.19, No.2/3, pp.141-146, 1996.
[5] H. Mizumoto, et. al., *Proceedings of 16th ASPE annual meeting*, Vol.1, pp.119-122, 2001.
[6] Homepage of MTI Instruments Inc. http://www.mtiinstruments.com
[7] H. Mizumoto, et. al., *Ann. of CIRP*, Vol. 45/1, pp.501 -504 ,1996.