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Three-dimensional Nano-motion System for SPM-based CMM*

Hiroshi SAWANO**, Toshimichi GOKAN**,
Hayato YOSHIOKA** and Hidenori SHINNO**
**Precision and Intelligence Laboratory, Tokyo Institute of Technology,
4259-G2-19 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan
E-mail: sawano@pi.titech.ac.jp

Abstract
Demands for measurement of three dimensional (3D) micro-geometries over a large area have recently increased in a variety of industries. In order to meet such requirements, it is necessary to realize a novel coordinate measuring machine (CMM) with a three-dimensional nano-motion system which has high resolution, high response and large measuring area. In this study, a three-dimensional nano-motion system was developed for a scanning probe microscopy (SPM) based CMM with nanometer spatial resolution. The system developed is composed of an X-Y planar nano-motion table system driven by voice coil motors (VCMs), a Z axis nano-motion system driven by a hybrid actuator and a probe holder that equipped with SPM probes. Performance evaluation results confirm that the system simultaneously achieves a long travel range, a high positioning resolution and a high stability.

Key words: Nano Motion, Micro Geometry, Coordinate Measuring Machine, Voice Coil Motor, Piezoelectric Actuator, Scanning Probe Microscopy

1. Introduction

Demands for machining of three-dimensional complicated geometries with 10 mm scale size and nanometer scale accuracy have recently increased in the various industrial sectors [(1)-(2)]. In order to meet such requirements, it is necessary to realize not only a machining system with nanometer scale machining accuracy and 10 mm scale working area, but also a coordinate measuring machine (CMM) with nanometer scale measuring resolution and 10 mm scale measuring range. A scanning probe microscopy (SPM) such as a scanning tunneling microscopy (STM) or an atomic force microscopy (AFM) is capable of measurement with nanometer scale vertical resolution [(3)-(4)]. However, the measuring range of conventional SPM is limited to sub-millimeter scale. In order to realize a measuring system with nanometer scale measuring resolution and larger than 10 mm scale measuring range, it is necessary to remove all existing error factors in the measuring system and to build up an ideal machine structure.

This study presents a newly developed three-dimensional nano-motion system for an SPM-based CMM. The three-dimensional nano-motion system developed has a long travel range with nanometer spatial resolution.

2. Structural concept of an SPM-based CMM

In order to realize an SPM-based CMM with nanometer scale measuring resolution and 10 mm scale measuring range, it is important to develop a stable machine structure. Fig.1

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shows a basic design concept of thermally and dynamically stable measuring machine structure. Based on the proposed design concept, an innovative compact CMM can be realized as shown in Fig.2. The system has three laser interferometers to measure the positions in the X, Y and Z directions. Measurement of a 3D profile can be made by controlling the position of the probing system to keep the distance constant between the probe and the specimen surface and by measuring the Z position during X-Y scanning. The X-Y planar nano-motion table and the Z axis nano-motion system are guided by aerostatic bearings. In order to enlarge the stroke limitation of a piezoelectric actuator (PZT) for the Z axis driving, a main body is driven by the voice coil motor (VCM) with a long stroke. In addition, the Z axis nano-motion system has a gravity compensator using a vacuum cylinder. Then, the X-Y planar nano-motion table and the Z axis nano-motion system are guided and driven in a perfect noncontact condition, and various nonlinear phenomena can be reduced from the machine structure.

The overall machine structure is symmetrically designed with respect to the vertical motion axis so as to minimize Abbe offset. Furthermore, in order to improve stability, the overall nano-motion system is installed in a temperature-controlled enclosure and the machine base is supported by an active vibration isolation system.

In consequence, various nonlinear phenomena can be reduced from the machine and all existing error factors in the machine structure can be successfully minimized.

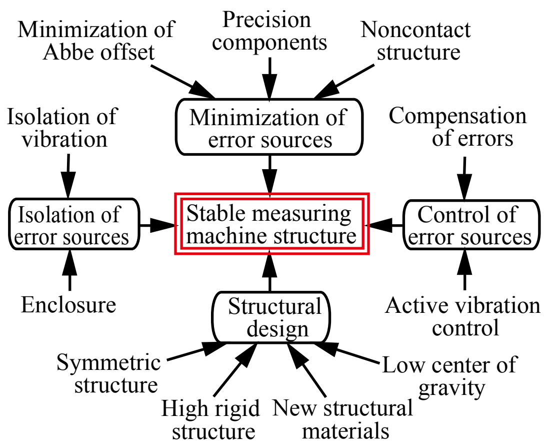


Fig.1 Ideal measuring machine structure

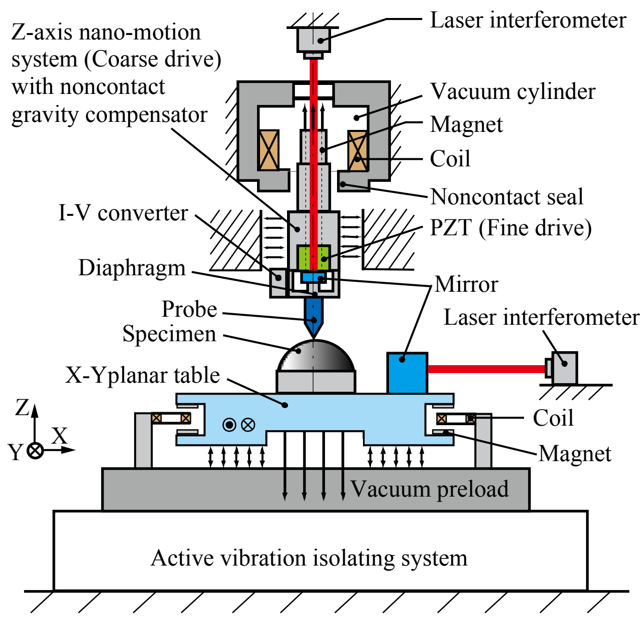


Fig.2 Structural concept of an SPM-based CMM

3. Three-dimensional nano-motion system for an SPM-based CMM

3.1 Structural configuration of a nano-motion system

Figure 3 shows the structural configuration of the three-dimensional nano-motion system and Fig.4 shows the photograph of the developed nano-motion system. The specification of the machine developed is given in Table 1. The fundamental structural modules, such as the X-Y planar nano-motion table system and the Z axis nano-motion system with gravity compensator, are made of alumina ceramics (Al_2O_3) whose coefficient of thermal expansion is 7.7×10^{-6}. Columns and a top beam are made of granite whose coefficient of thermal expansion is 5.0×10^{-6}. These structural materials are suitable for stable machine structure due to their low thermal expansion coefficient. SPM probes such as STM or AFM can be mounted on the probe holder.

Table 1 Specification of the 3D nano-motion system

Maximum driving range (X, Y)	18	mm
Maximum driving range (Z)	10	mm
Mass of the X-Y planar nano-motion table	4.1	kg
Mass of the Z axis nano-motion module	0.66	kg
Positioning resolution (X, Y, Z)	1	nm
Moment of inertia of the table about the Z-axis	0.025	kg•m^2
Sampling frequency	10	kHz

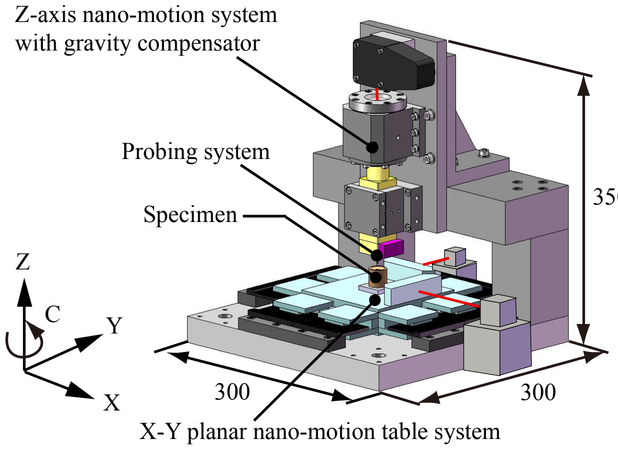


Fig.3 Structural configuration of motion system

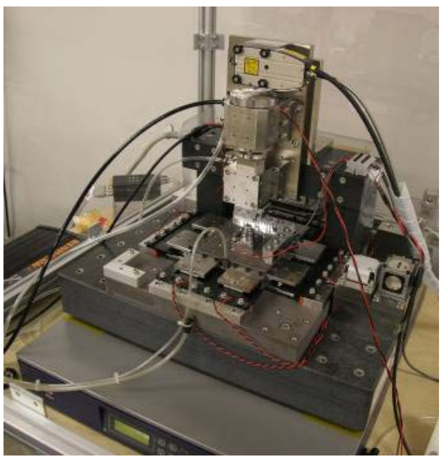


Fig.4 Photograph of developed motion system

3.2 Structure of an X-Y planar nano-motion table system

The structural configuration of the X-Y planar nano-motion table system is shown in Fig.5. This moving square table levitated with four porous air bearings can be driven by eight VCMs. In order to achieve both high motion accuracy and high rigidity, the vacuum attraction force preloads these aerostatic bearings. The X-Y planar nano-motion table system developed can be achieved sub-nanometer scale positioning capability [(5)-(6)].

Figure 6 shows a block diagram of the planar nano-motion control system. The table position on the X-Y plane can be measured by both a heterodyne laser interferometer and two plane mirrors fixed on the table. In this system, the full closed-loop control systems with the laser interferometer feedback are used together with the PID and the acceleration feedforward compensators, as shown in Fig.6.

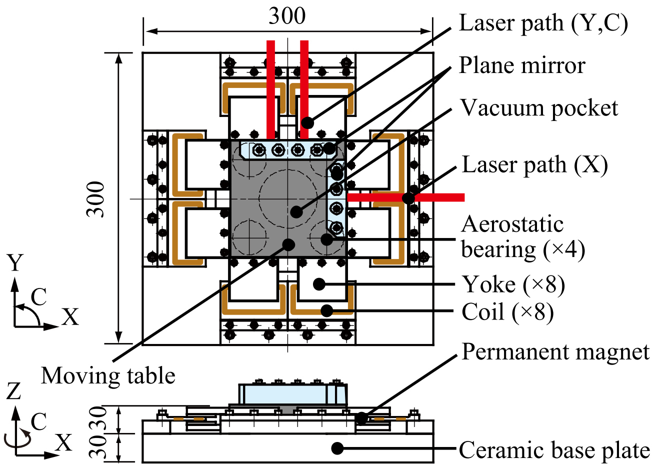
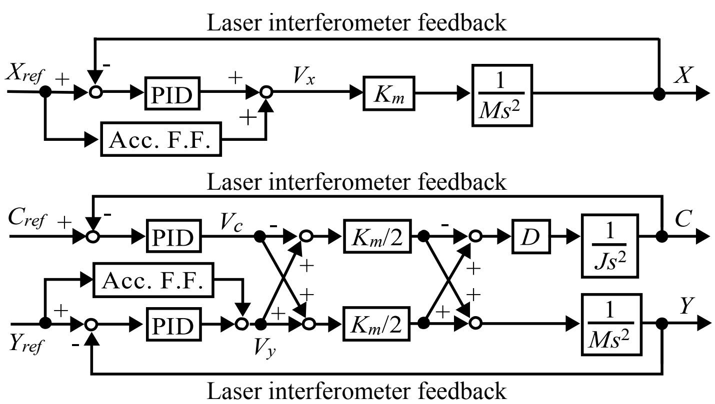


Fig.5 Structural configuration of the X-Y planar nano-motion table system



M : Table mass
J : Moment of inertia of the table about the Z axis
D : Distance between the axis of C motion and the center of gravity
K_m : Thrust constant of voice coil motor

Fig.6 Block diagram of the X-Y planar nano-motion control system

3.3 Structure of a vertical nano-motion system

Figure 7 shows a structural configuration of a Z axis nano-motion system. In order to realize the measuring machine with long measuring range and high measuring resolution, it is necessary to install the Z axis nano-motion system with long stroke and high response. Therefore, a hybrid actuator composed of a VCM with a long stroke and a PZT with a high response is applied to the Z axis nano-motion system.

In order to realize an effective vertical nano-motion control, the most important issue is to minimize gravity loading. In this study, a noncontact vacuum cylinder is used for the gravity compensator [7]. Furthermore, a through-hole at the center of the Z axis moving body enables to directly measure the position of the probe in vacuum environment without thermal deformation of the moving body.

Figure 8 shows a block diagram of the Z axis nano-motion control system. Both fine and coarse motion mechanisms are simultaneously driven by the full closed-loop control system with the laser interferometer feedback.

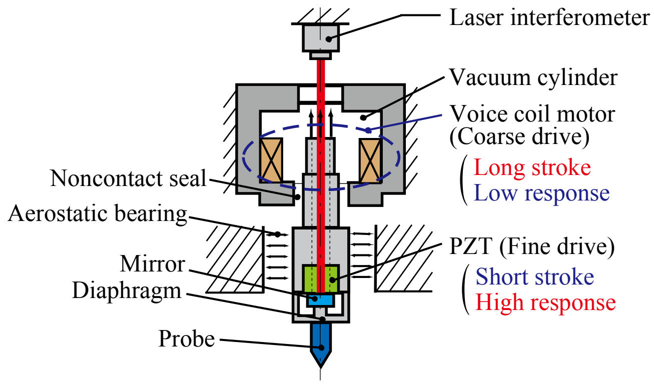
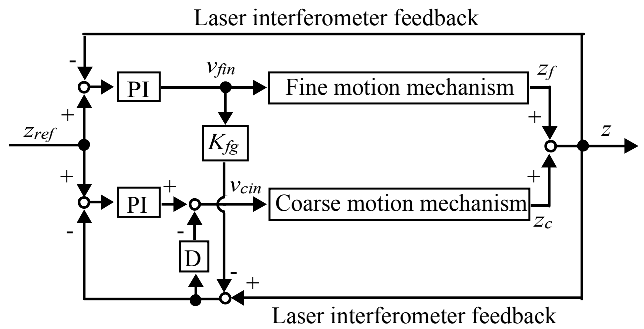


Fig.7 Structural configuration of the Z axis nano-motion system



z_{ref} : Reference for the Z axis nano-motion system
z_f : Displacement of fine motion mechanism
z_c : Displacement of coarse motion mechanism
z : Probe position
v_{fin} : Input voltage to fine motion mechanism
v_{cin} : Input voltage to coarse motion mechanism
K_{fg} : Gain of piezoelectric actuator (PZT)

Fig.8 Block diagram of the Z axis nano-motion control system

4. Performance evaluations

4.1 Positioning resolution

In order to evaluate performance of the nano-positioning system developed, a series of nano-motion experiments were performed.

Figure 9 shows the table response for stepwise positioning (1 nm on each axis) in simultaneous three axes control. The positions of each axis were measured by internal laser interferometers. A clear 1 nm stepwise positioning can be observed on each axis. It was clear that the developed system has high positioning resolution of 1 nm.

Figure 10 shows the table response for stepwise positioning (100 nm on each axis) in simultaneous three axes control. The overshoots of each step of the X axis and the Y axis were approximately 45 nm. In an actual measurement, the X-Y planar nano-motion table is driven with a constant velocity. So, these overshoots don't cause a problem in a profile measurement. The overshoots of each step of the Z axis were approximately 4 nm, because the Z axis nano-motion system had high response by hybrid actuator.

Furthermore, these figures show that there is no interdependence among the X, Y and Z axes. This result means the Z axis motion is not affected by X and Y axes motion.

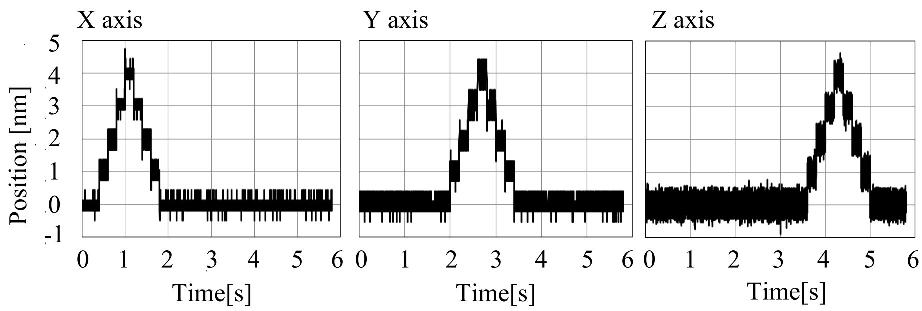


Fig.9 Response for 1 nm stepwise positioning

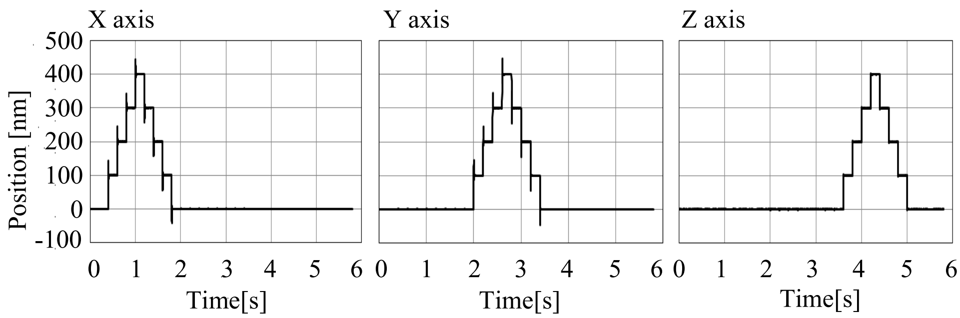


Fig.10 Response for 100 nm stepwise positioning

4.2 Evaluation of the Z axis nano-motion system with the hybrid actuator

In order to evaluate the Z axis nano-motion system with the hybrid actuator, a 100 nm step motion experiment was performed. Fig.11 shows the step response of the Z axis and each actuator which composes the hybrid actuator. The overshoot and settle time were approximately 4 nm and 5 ms, respectively. It is thought that these overshoot and settle time were sufficiently small for a profile measurement. For a start, the PZT moved quickly to a reference position. When the VCM position approached to a reference position, the PZT displacement became small. In addition, the PZT compensated the positioning error of the VCM and kept the Z axis position to a reference position.

Figure 12 shows the frequency response of the Z axis nano-motion system. By both actuators constructing the hybrid actuator, the stable frequency response of kHz order could be obtained.

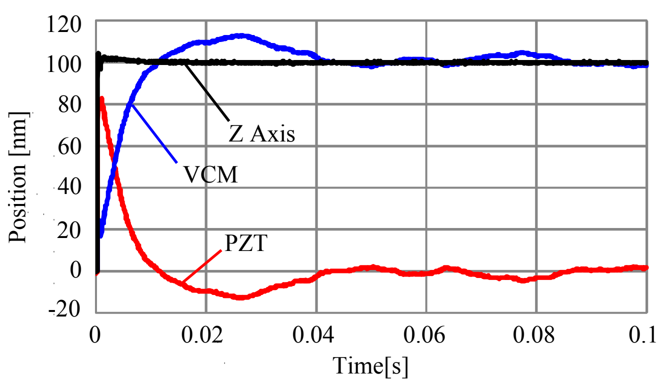


Fig.11 Response for 100 nm step motion of the Z axis nano-motion system

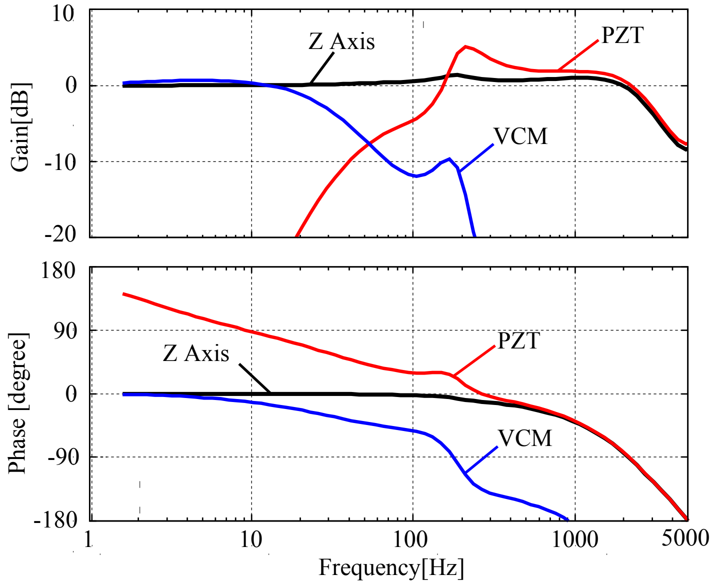


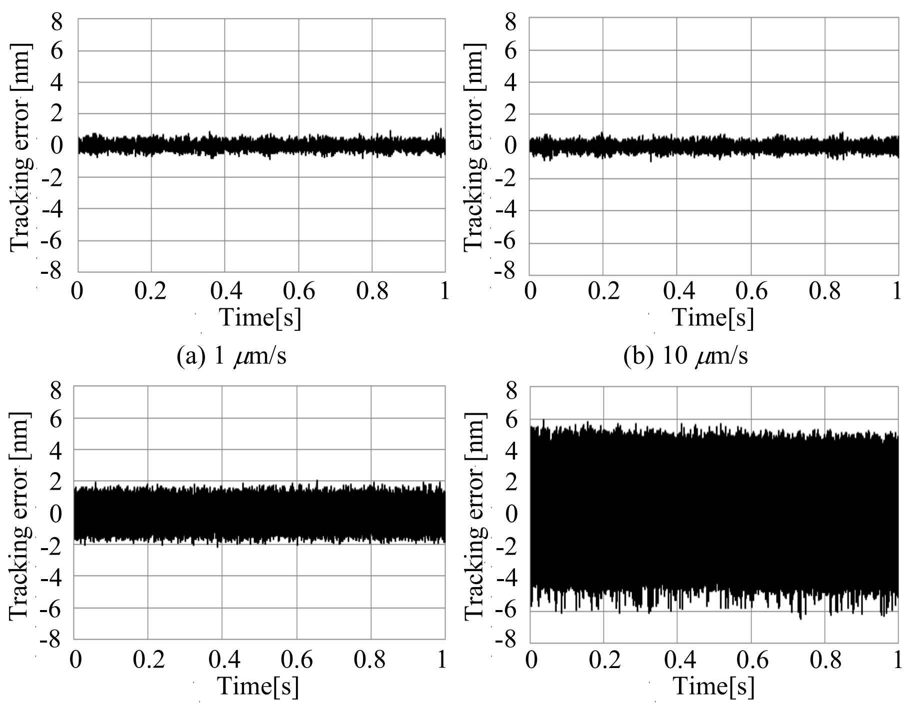
Fig.12 Frequency response of the Z axis nano-motion system

4.3 Relationship between the speed of Z axis and tracking error

The relationship between the speed and the tracking error of the Z axis nano-motion system was investigated. The Z axis nano-motion system was driven at a constant speed of 1 μm/s, 10 μm/s, 100 μm/s and 1000 μm/s, while each tracking error was measured.

Figure 13 shows the tracking error during moving at a constant speed. In addition, Fig.14 shows the relationship between the speed and the maximum tracking error.

In the case of the speed of 1 μm/s and 10 μm/s, the tracking errors were approximately ± 1 nm. Furthermore, even in the case of the velocity of 1000 μm/s, the tracking error was less than ±7 nm. These results confirm that the Z axis nano-motion system has high tracking capability. Furthermore, it is thought that these results can use for decision the measuring conditions, such as a scanning speed.



(a) 1 μm/s (b) 10 μm/s

(c) 100 μm/s (d) 1000 μm/s

Fig.13 Tracking error during at a constant speed

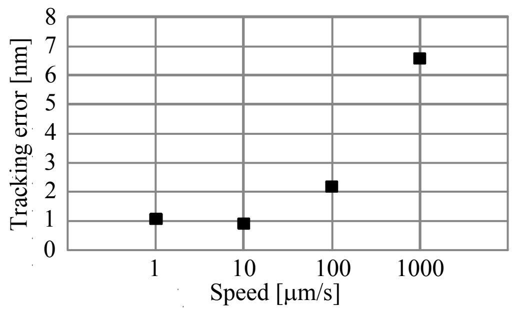


Fig.14 Relationship between the speed and the maximum tracking error

4.4 Tunneling current feedback experiments

In order to investigate the applicability of the developed nano-motion system to the proposed SPM-based CMM, the tunneling current feedback experiments were performed. An STM probe was used as the SPM probe and the Z axis nano-motion system was controlled to keep a constant tunneling current for 60 minutes as shown in Fig.15. The temperature variation around the system was within ± 0.1 degree during the measurement. An oxygen-free copper was used as the specimen. Fig.16 depicts the block diagram of the tunneling current feedback control system.

Figure 17 shows the response for the tunneling current feedback. The difference of the displacement in 60 minutes is approximately 50 nm, and the tunneling current is kept a constant successfully. These results show that the developed system has high stability and the applicability of the proposed SPM-based CMM.

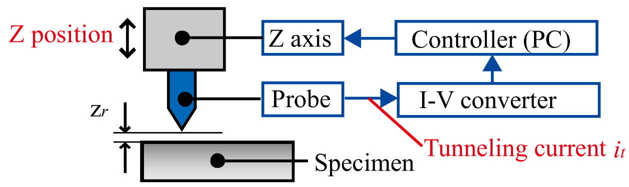
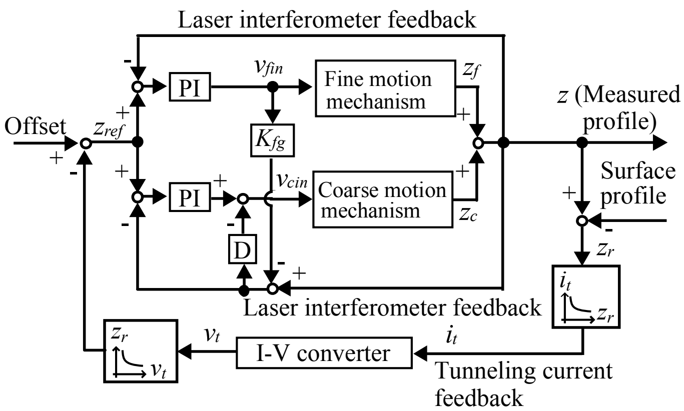
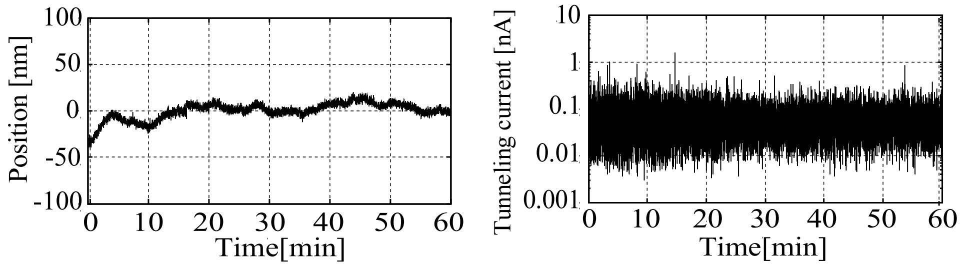


Fig.15 Scheme of the tunneling current feedback



z_{ref} : Reference for the Z axis nano-motion system
z_f : Displacement of fine motion mechanism
z_c : Displacement of coarse motion mechanism
z : Probe position
z_r : Relative displacement between probe and specimen surface
v_{fin} : Input voltage to fine motion mechanism
v_{cin} : Input voltage to coarse motion mechanism
K_{fg} : Gain of piezoelectric actuator (PZT)
i_t : Tunneling current
v_t : I-V converter output

Fig.16 Block diagram of the tunneling current feedback control system



(a) Position of Z axis z_r (b) Tunneling current i_t

Fig.17 Time response of the tunneling current feedback control

5. Conclusions

This paper presents a newly developed three-dimensional nano-motion system for an SPM-based CMM. In addition, performance evaluation experiments were performed. As a result, the following conclusions could be drawn:

1. An ideal structural concept of the SPM-based CMM was proposed and then the three-dimensional nano-motion system for the proposed CMM was actually developed.
2. The stepwise motion experiment results confirmed that the three-dimensional nano-motion system achieves high positioning resolution of 1 nm.
3. The evaluation results of the Z axis nano-motion system driven by the hybrid actuator confirmed that the developed system has the high response of kHz order.
4. The results of the Z axis nano-motion experiment at a constant speed confirmed that the Z axis nano-motion system has high tracking capability.
5. Tunneling feedback experimental results showed that the developed system has high stability and the applicability of the proposed SPM-based CMM.

Acknowledgement

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