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DEVELOPMENT OF NANO-METER POSITIONING IN JAPAN

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Abstract. *Production machines for next generation LSIs such as 4G-DRAMs and for large liquid crystal displays such as 0.5mx0.5m size, and information equipment such as magnetic hard disks and DVDs must have the positioning accuracy of a nano-meter order. To realize such a high degree of the positioning accuracy, not only precision machine elements and mechanisms but also high precision sensors, actuators and controller design techniques becomes crucial. This paper introduces recent topics of precision positioning and motion control technology in Japan.*

Keywords: *Precision Positioning, Nano-meter, Motion Control*

1. INTRODUCTION

Recently, many reports in Japan are being concerned with development of the nano-meter motion control (1nano-meter,1nm =0.001µm). The purpose of these reports is to establish production systems for next generation LSI semiconductors (for example, 4G-DRAM) , for a large and fine LCD (liquid crystal display) and/or for a high quality information equipment such as magnetic disk drives and digital video disks (DVD).

For example, Fig. 1 (originally made by Dr. M. Fukuda) shows changes of the LSI pattern width and overlay tolerance of wiring lines on silicon wafers. From the figure, pattern width of 1G-DRAM is becoming less than 0.2µm and overlay tolerance, less than 60nm, which have to be reached by the beginning of the 21st century. To achieve these, the accuracy of the motion measurement and control of machines and mechanisms which are used for LSI production must be at least 1/8 to 1/10 of the required accuracy.

Fig. 2 shows another example; the areal recording density of magnetic disks (by Prof. Y. Mitsuya). Recently, 10Gbit/in^2 recording density has been realized, which means 250nm bit spacing and 1.2µm track pitch. In the case of the track following control of reading heads for such disk drives, the accuracy has to be put 1/8 to 1/10 of the bit spacing and track pitch.

Fig. 3 is a typical positioning system consists of a DC motor, a ball screw and a laser interferometer used as a feedback sensor. To realize the accuracy of such high degree as above mentioned, there are some key fields. In Fig. 3, they are machine elements such as bearings and guide ways, mechanisms such as lead screws, actuators such as piezoelectric actuators or servo motors, measuring instruments such as laser interferometers and control algorithms. This paper introduces some examples of recent topics of nano-motion technology in Japan.

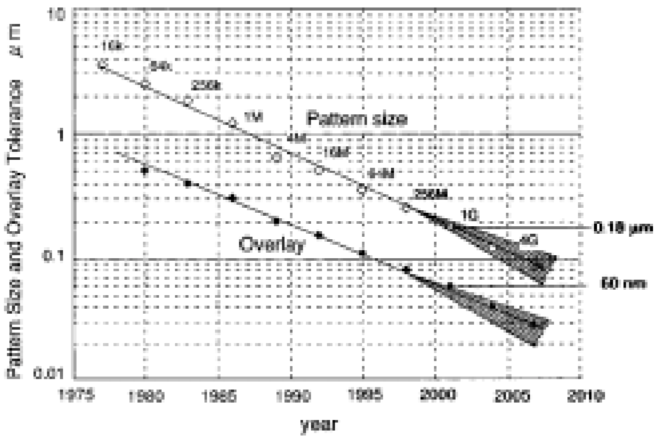


Fig.1 Minimum pattern size and overlay tolerance

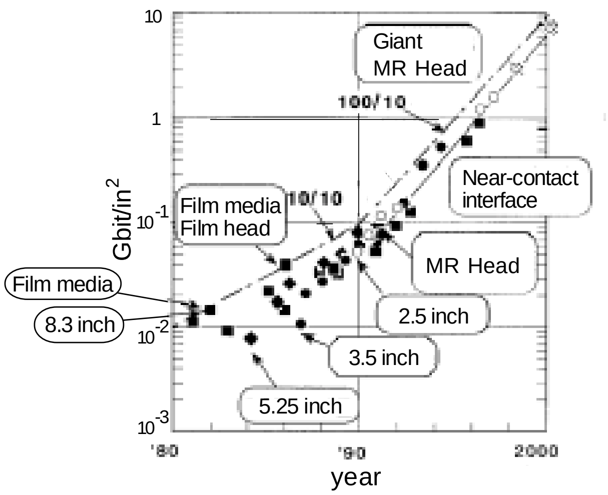


Fig.2 The areal recording density of magnetic disks

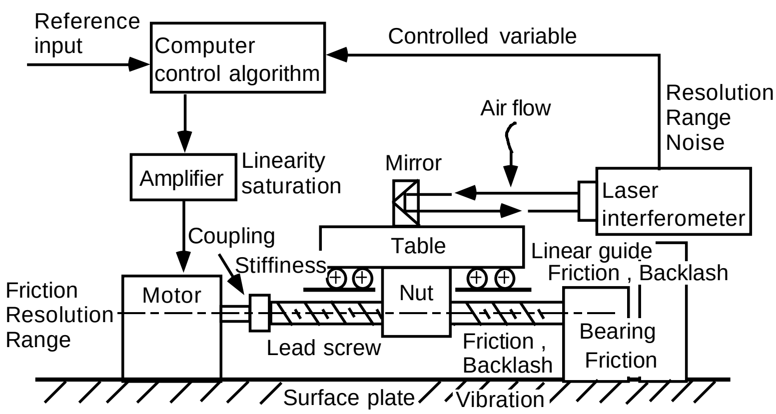


Fig.3 Positioning system model

2. NONLINEAR SPRING CHARACTERISTICS AND POSITIONING CONTROL

In Fig. 3, there are some mechanisms or elements in which mechanical contact is inevitable for their purpose. For example, in lead screws, the screw surface is always in contact with the nut surface. In such mechanisms or elements, when a small force is applied to one part (for example, to the table), it behaves as shown in Fig. 4. The force causes the displacement of the table but it moves back when the applied force is removed. Namely the table acts as if there are a nonlinear spring between the table and ground.

Fig. 5 is a schematic of a typical friction drive system and Fig. 6 is the nonlinear spring characteristics observed in the system(Kawamura et al., 1994). Fig. 7 is a positioning system using a steel belt mechanism and a DC motor. The obsereved nonlinear characteristics of the system is shown in Fig. 8. The system is controlled using a PI-D controller and achieved 3nm positioning resolution as shown in Fig. 9(Fujisaki et al., 1995).

Fig. 10 is a rotary type positioning system using a harmonic reducer. Fig. 11 shows the nonlinear spring characteristics of the rotary positioning system. Fig. 12 is a dynamic model of the system for a large rotation angle of the inertia load (a macro-dynamic model) and Fig. 13, for a small rotation angle (a micro-dynamic model). The load is positioned using a controller with disturbance observer as shown in Fig. 14. Fig. 15 shows the controller can cope with the various step input heights ranging from 40 to $4x10^5$ second of arc with a positioning error of 1 second of arc(Sato et al., 1999).

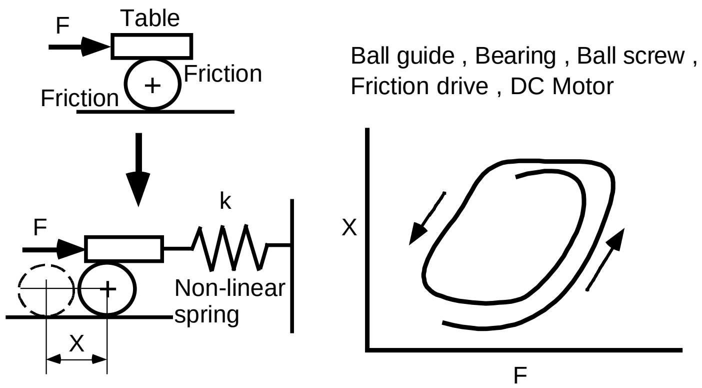


Fig.4 Nonlinear spring effect of mechanism with friction

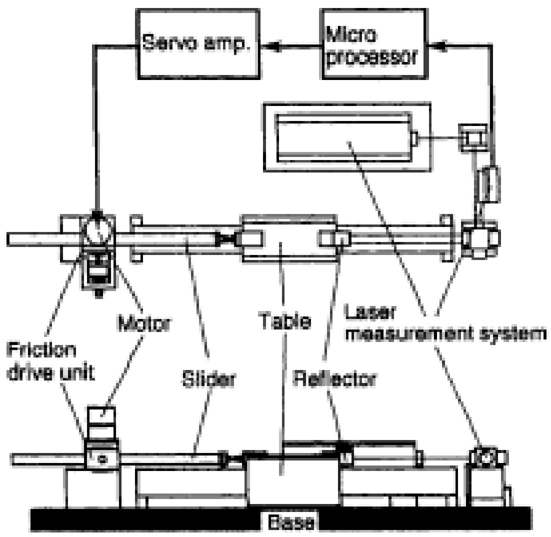


Fig.5 Positioning mechanism of friction drive

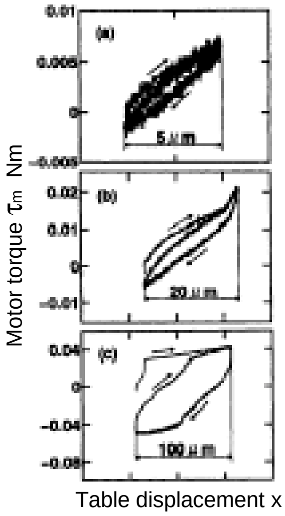


Fig.6 Nonlinear spring effect of friction drive mechanism

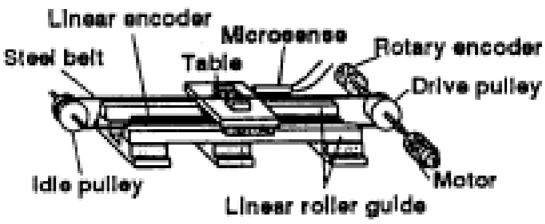


Fig.7 Steel belt positioning mechanism

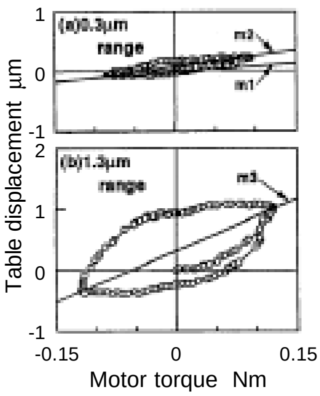


Fig.8 Nonlinear spring effect of steel belt mechanism

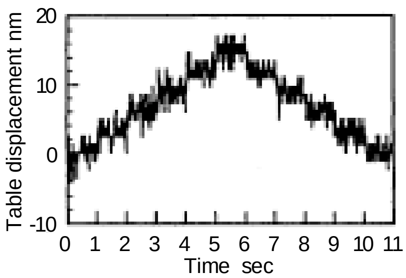


Fig.9 Positioning of steel belt mechanism (3nm stepwise input)

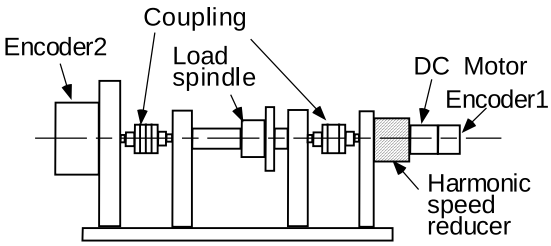


Fig.10 Rotational positioning mechanism

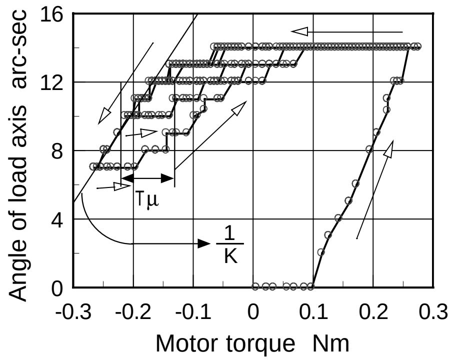


Fig.11 Nonlinear spring effect of rotational positioning mechanism

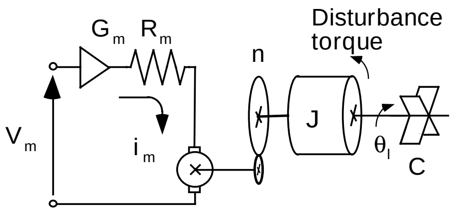


Fig.12 Macrodynamic model

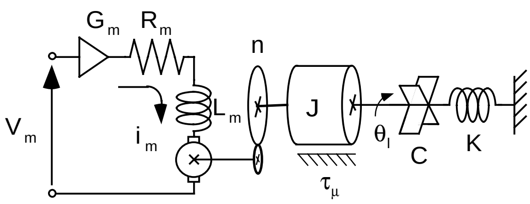


Fig.13 Microdynamic model

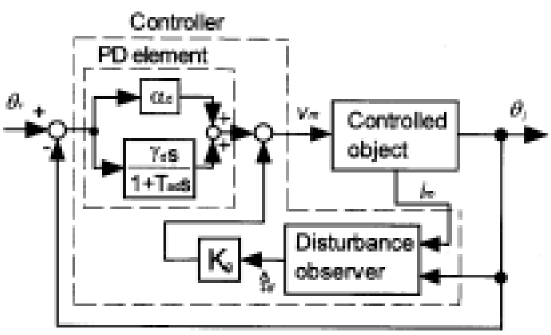


Fig.14 Control system with the disturbance observer

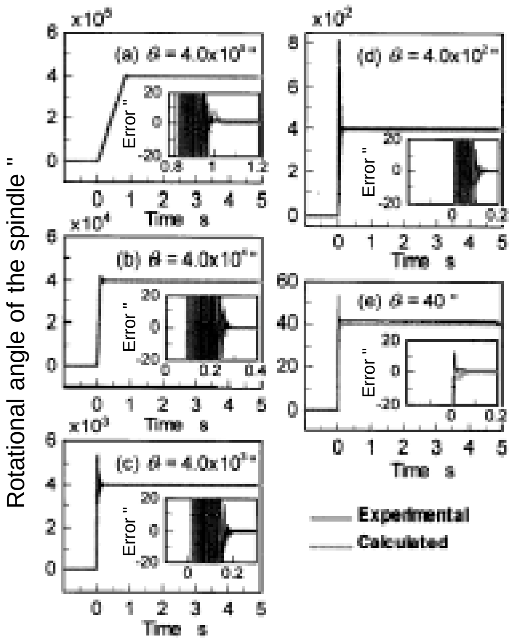


Fig.15 Step responses with the disturbance compensator

3. TWO-STAGE POSITIONING SYSTEM

One of the solutions to realize the nano-meter positioning accuracy as well as the high speed positioning is to use a two-stage positioning system. The system comprises a fine and a coarse positioning actuators. Though the fine actuator only has a short working stroke, it can drive an object (a fine table) with a high resolution and a high speed.

Usually the object and the fine actuator is put on a coarse table driven by the coarse actuator which is of a long stroke but of a low resolution and low speed. Such two-stage systems are expected to have a long stroke, a high positioning resolution and a high positioning speed. However it is difficult to control such two-stage positioning systems because they are redundant and each actuator has its own dynamic characteristics.

Fig. 16 is an example of the two stage positioning system in which a piezoelectric actuator is used as the fine actuator and a DC motor with a ball screw, as the coarse actuator. There are some possible control method for the system. For example, the fine actuator drives the object after it reached the neighborhood of the target position. In another example, the error signal is divided into a low and high frequency parts, and the high frequency part is sent to the fine actuator via a fine controller and the low one, to the coarse actuator via a coarse controller.

Fig. 17 shows the case in which two actuators are always working without dividing the error signal. In Fig. 17-(a), two sensors are used; one for measuring the fine table position and the other, for the coarse table position. Such system is not preferable because precision sensors are expensive. Fig. 17-(b) uses one sensor which measures the position of the fine table and the motion of the fine actuator is estimated by using the proportional gain K. The coarse table position is calculated from the fine table position and the estimated motion of the fine actuator.

Fig. 18 is step responses of the system in Figs. 16 and 17. PID, Fuzzy, Neural, State feedback, Sliding mode, H infinity controllers are applied to the system. Almost same performances were obtained but enlarged view of the errors and some other experimental results showed Fuzzy and Neural controllers were much more robust than others(Sato et al., 1998).

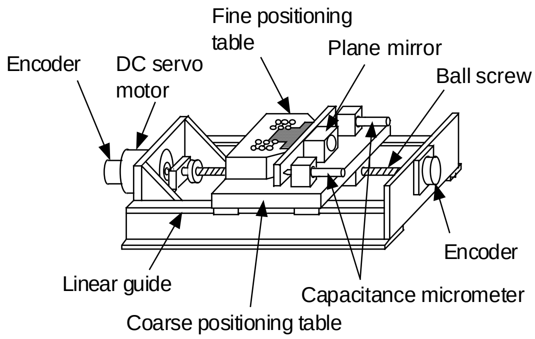
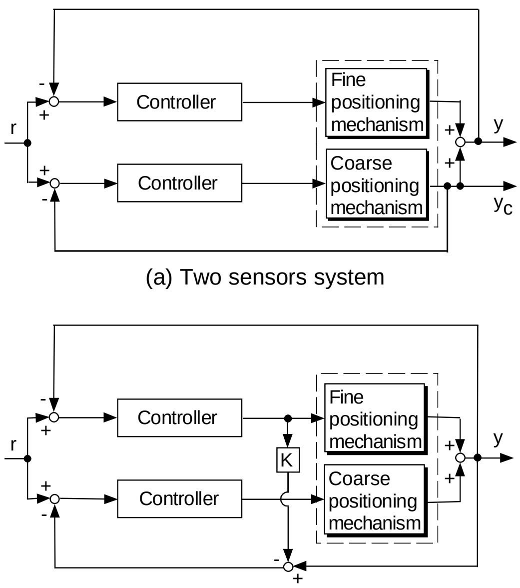


Fig.16 Two-stage positioning mechanism



(a) Two sensors system

(b) One sensor system

Fig.17 Control of two-stage positioning mechanism

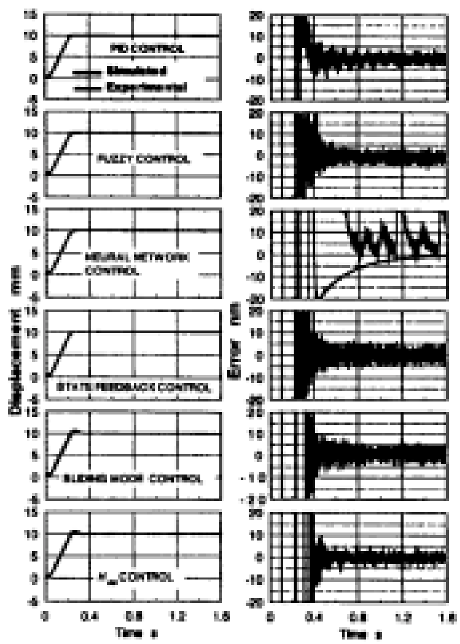


Fig.18 Step responses

4. ACTUATORS AND DRIVING MECHANISMS

Actuators as well as transmission mechanisms such as gears and lead screws are crucial in precision positioning. Stack type piezoelectric actuators (PEA) are often used but they have a short working range. Giant magnetostriction actuators (GMA) had been developed(Eda et al., 1995). Although GMA have a larger working range than PEA, the heat generation is so large that a built-in water cooling system is necessary to apply GMA to precision positioning at the moment.

High-power electrostatic linear actuators (ELAs) have been developed. ELAs have been considered to be useful in the micro-machine field, but a recent development has proved that ELAs are applicable to the field of precision positioning. For example, a 600g object has been positioned with 10nm resolution(Yamamoto et al., 1998).

New lead screw mechanisms has been developed such as an air lead screw(Tachikawa et al., 1997) and a magnetic lead screw(Shinshi et al., 1998) as shown in Figs. 19 and 20. Purpose of these lead screws is to eliminate the friction and backlash between the screw and nut. An experimental positioning system using the air lead screw has achieved a positioning resolution better than 10nm. In the system, air bearings and an air guideway are used to support the motor shaft, lead screw and the positioned table. Mechanical friction only exists between brushes and the commutator of the DC motor.

A system using the magnetic lead screw has also realized the positioning accuracy better than 10nm. In this case, an air guideway is used to support the positioned table but the motor and screw shafts are supported by conventional ball bearings.

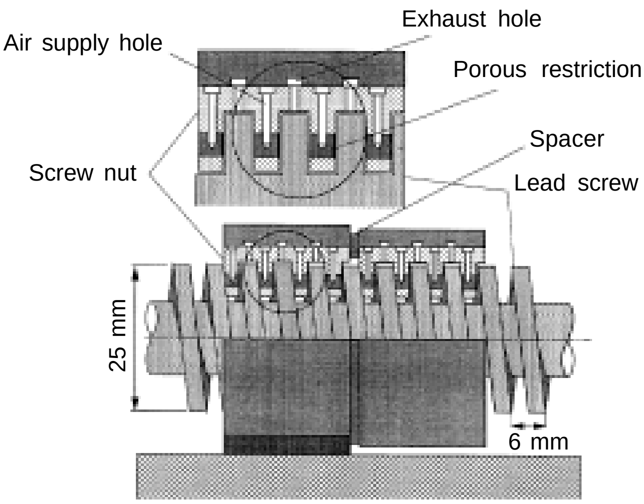


Fig.19 Construction of air lead screw

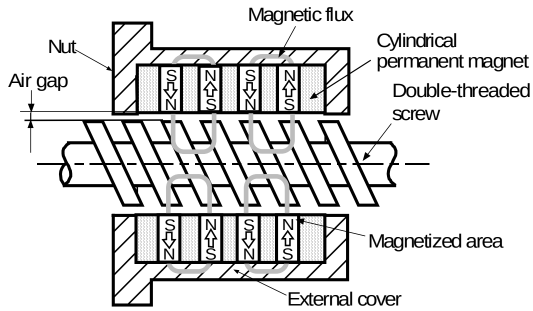


Fig.20 Principle of proposed magnetic lead screw

5. LINEAR MOTORS

There are some examples of linear motors applied to precision positioning. A stepper for exposure systems using KrF light beam has a table positioned by a linear motor (Fukuda, 1998). Linear motors usually can generate a large thrust force which is preferable for high speed positioning. But they generate a large heat generation which causes thermal deformation resulting in motion errors. So linear motors used for nano-meter positioning must be liquid-cooled.

A new linear motor driven table system was designed in which the table is supported by air linear guide (Hashizume et al., 1998). A brushless DC linear motor was arranged so as the thrust force to act on the gravity center of the table. The thrust force ripple as well as the base plate vibration was feed-forward-compensated. Fig. 21 is the mechanical configuration of the system and Fig. 22 is the control diagram. Fig. 23 shows 10nm and 2nm step responses which prove the system has the 2nm positioning resolution.

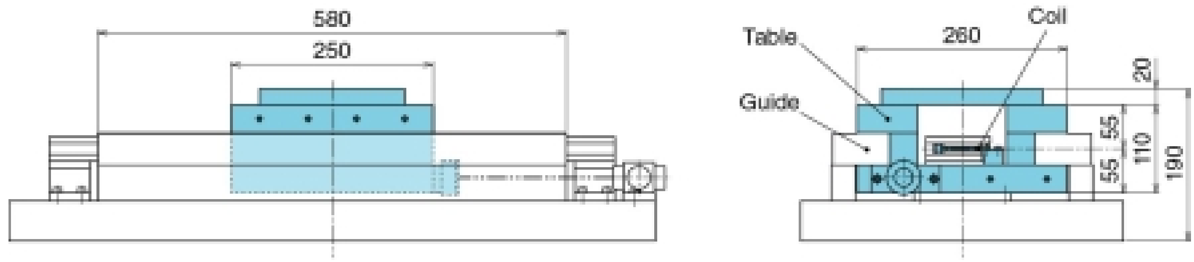


Fig.21 Mechanical configuration of the linear motor system

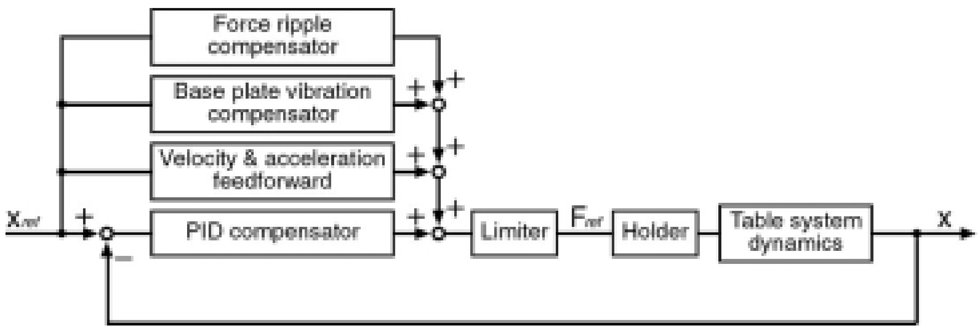
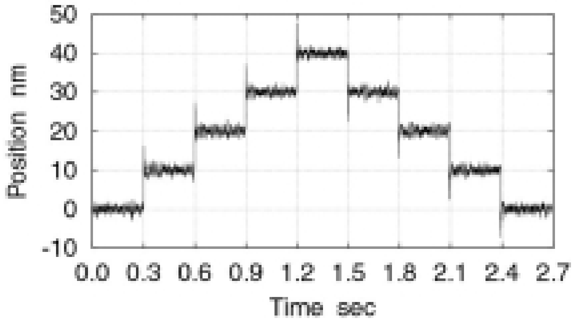


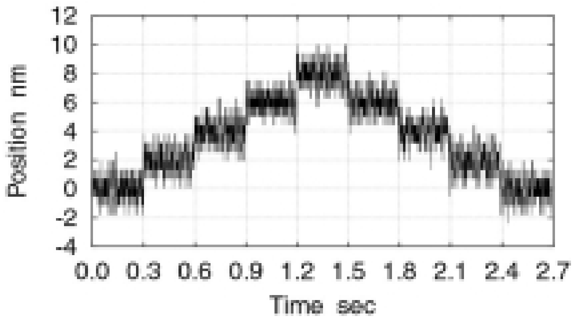
Fig.22 Control block diagram

6. CONCLUDING REMARKS

Precision positioning is a typical example of mechatronics. Engineers have to consider the precision positioning problem in its all aspects such as control, mechanism, electronics, measurement, data processing, ambient condition, etc. Especially, the attention have to be paid to the sensor accuracy. Positioning accuracy better than that of the feedback sensor is not attainable. Sensors not only of high resolution and wide dynamic range but also of wide bandwidth and low noise are undoubtedly necessary for precision positioning.



(a) 10nm stepwise positioning



(b) 2nm stepwise positioning

Fig.23 Stepwise positioning performance

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