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Laser Interferometer를 이용한 초정밀위치결정 피드백시스템의 컴퓨터 시뮬레이션 및 제어성능 평가

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Computer Simulation and Control performance evaluation for Feedback System of Ultra Precision Positioning by using Laser Interferometer

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Abstract

This system is composed of fine and coarse apparatus, measurement system and control system. Piezoelectric actuator is designed for fine positioning. We make a study of precision apparatus that is used in the various industrial machine. The study was carried out to develope a precision positioning apparatus, consisting of servo motor and piezoelectric actuator.Coarse positioning using lead screw is drived by servo motor. Control system output a signal from laser interferometer to amplifier of servo motor and piezoelectric actuator after digital signal processing(DSP). Resolution of this apparatus measure with laser interferometer.

In this study, design method and control system with ultra precision position apparatus are researched. As the first step, we have estimated for control performance and system stability before an actual apparatus is manufactured by MATLAB with SIMULINK including various functions those are composed of pre-design and system modeling.

Key Words: Laser interferometer, Piezoelectric actuator, Fine positioning, Coarse positioning, Resolution, DSP(digital signal processing), Simulation, Matlab Simulink, PID Controller

1. INTRODUCTION

Recently, high accuracy and high precision are required in various industrial fields that are composed of semiconductor manufacturing apparatus and ultra precision positioning apparatus and information system and so on. This technology has been rapidly developed, its field needs for positioning accuracy to high as submicron. It is expected that accuracy with 10 nm in precision working and accuracywith 1 nm in ultra precision working are reached at the beginning of 2000s. Also, high speed and low vibration are really needed for the same reason. Recently, to accomplish this positioning technology, many researches are concerned about it and make efforts it(Simokobe, 1998).

In this study, design method and control system with ultra precision position apparatus are researched. As the first step, we have estimated for control performance and system stability before an actual apparatus is manufactured by MATLAB with SIMULINK including various functions those are composed of pre-design and system modeling.

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2. Modelling of Ultra Precision Positioning Apparatus

This equipment is consisted with coarse apparatus and fine apparatus that fixed on the coarse apparatus. There are many style of coarse apparatus, in this journal. The lead screw is choice. The lead screw is consisted wit ball screw and double nut, and is driven by AC servo motor. The rotation movement of motor is changed to linear movement by double nut type ball screw(lead 5mm, outer diameter 19mm) and move coarse table. The moving distance is about 100mm, and AC servo motor is able to supply maximum about 2A, move coarse table with about 600mm/s. Fine apparatus is one of component of elastic hinge, and driven by PZT. The actuating range is ± 10 ㎛.

The object of coarse apparatus is positioning about aiming point with control object. In here, coupling, ball screw, spring effect between nut are ignored, model is simplification as considering coupling of motor axis and lead screw axis to one of rigid body, and frictional torque is ignored, too. Firstly, establishing kinetics equation of lead screw

$$J\ddot{\theta}+C_s\dot{\theta}=K_2 i_m+K_x\{K_n(x-K_x\theta)+C_n(\dot{x}-K_x\theta)\}-\tau_f \qquad (1)$$

Equation of coarse table is

$$M\ddot{x} = -K_n(x-K_x\theta)+C_n(\dot{x}-K_x\dot{\theta}) \qquad (2)$$

Relation of Rotation of Double nut and displacement of table is

$$K_x = \frac{\ell}{2\pi},\ x_C = \frac{\ell}{2\pi}\theta \equiv K\theta \qquad (3)$$

To flowing Motor current and occurred torque is

$$T = K_2 i_m \ \text{또는}\ \tan\theta=\frac{l}{\pi d} \qquad (4)$$

Circuit Equation of motor is

$$G_m v_m = R_m i_m + L_m i_m + K_1\dot{\theta} \qquad (5)$$

By equations (1)~(5), as state variable with x_c, $\dot{x}_c$, i_m input with input current of motor amp, state equation is established.

$$\begin{bmatrix} i_m \\ \theta \\ \dot{\theta} \\ x \\ \dot{x} \end{bmatrix} = \begin{bmatrix} -\frac{R_m}{L_m} & 0 & -\frac{K_1}{L_m} & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \frac{K_2}{J} & -\frac{K_n\cdot K_x^2}{J} & -\frac{(C_s+C_n\cdot K_x^2)}{J} & \frac{K_x\cdot K_n}{J} & \frac{K_x\cdot C_n}{J} \\ 0 & 0 & 0 & 0 & 1 \\ 0 & \frac{K_x\cdot K_n}{M} & \frac{K_x\cdot C_n}{M} & -\frac{K_n}{M} & -\frac{C_n}{M} \end{bmatrix} \cdot \begin{bmatrix} i_m \\ \theta \\ \dot{\theta} \\ x \\ \dot{x} \end{bmatrix} + \begin{bmatrix} \frac{G_m}{L_m} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} v_m \qquad (6)$$

$$y = [0\ 0\ 0\ 1\ 0]\begin{bmatrix} i_m \\ \theta \\ \dot{\theta} \\ x \\ \dot{x} \end{bmatrix} + [0]u \qquad (7)$$

Kinetics equation for fine apparatus shows like next.

The relation of displacement between displacement of fine table with piezo actuator is

$$m\ddot{x} + c_p(\dot{x} - \dot{x}_P) + K_p(x - x_p) = 0 \qquad (9)$$

and the relation of displacement between voltage of both pole with piezo actuator is

$$x_P = K_P v \qquad (10)$$

and the relation of voltage between input current of amp with both pole of piezo actuator is known to be as $G_P V_P = RC\dot{v} + v$ (11)

From equation (9)~(11), state equation expressed by state variable x, $\dot{x}$, v is

$$\begin{bmatrix} \dot{x} \\ \ddot{x} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ -\frac{k_P}{m} & -\frac{c_P}{m} & \frac{k_P K_P}{m}-\frac{c_P K_P}{RC_m} \\ 0 & 0 & -\frac{1}{RC} \end{bmatrix}\begin{bmatrix} x \\ \dot{x} \\ v \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{c_P G_P K_P}{RCm} \\ \frac{G_P}{RC} \end{bmatrix} v_P \qquad (12)$$

and if's output equation is

$$y = [\ 1\ \ 0\ \ 0\ ]\begin{bmatrix} x \\ \dot{x} \\ v \end{bmatrix} \qquad (13)$$

3. The Design of Control System

The dual servo system is composed by connection base of fine apparatus on slide. The actuator of dual servo is formed by processing that master slide compensate position error with fine apparatus PZT actuator as transferring fine stage or PZT actuator of fine stage compensate position error after transferring of coarse stage to aimed point.

On the fine stage slide and transferring of fine motion is measured at same time, caused by installation of laser optics for measuring displacement coarse servo is actuated by AC servo motor and ball screw with actuating signal that is output through the PC based controller. Because piezo actuator has many problems in accuracy and precision caused by internal hysteresis, drift as time and change of temperature, closed loop control is needed certainly. D/A converter decide driving fine stage, minimum transferring so, 12bit D/A converter is used. system will be going to realize resolution below submicron and need active closed loop control, so, PC based laser interferometer is used.

In tradition controlling method. It is able to divide with one the method of serial repetition of coarse positioning, fine positioning as dividing servo control method, another method that control coarse motion and fine motion at same time, as dual servo control method. In this research, design is based on the latter. Controller designed as PID controller is tested. Fig.1 shows block diagram of system

Ultra precision positioning apparatus is designed carefully for that displacement of fine apparatus do not over stroke in dual positioning caused by very small stroke about ±10㎛, and that control coarse motion and fine motion at same time. This apparatus is tested as supposing two actuator amp that is input control motion to one output system.

State equation and output equation of this control system is

$$\dot{x}_s = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} & 0 \\ 0 & 0 & a_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & a_{55} & a_{56} \\ 0 & 0 & 0 & 0 & a_{65} & a_{66} \end{bmatrix} x_S + \begin{bmatrix} 0 & 0 \\ b_{21} & 0 \\ b_{31} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & b_{62} \end{bmatrix} \begin{bmatrix} v_P \\ v_m \end{bmatrix} \quad (14)$$

$$x_S = [\; x \; \dot{x} \; v \; x_C \; x_C \; i_m \;]^T \quad (15)$$

$$\dot{y} = \begin{bmatrix} 1\,0\,0\,0\,0\,0 \\ 0\,0\,0\,1\,0\,0 \end{bmatrix} x_S \quad (16)$$

$$y = [\; 1 \; 0 \;] \; \dot{y} \quad (17)$$

$$a_{21} = -\frac{k_P}{m}, \quad a_{22} = -\frac{C_P}{m}, \quad a_{23} = \frac{k_P K_P}{m} - \frac{c_P K_P}{RCm},$$

$$a_{24} = \frac{K_P}{m}, \quad a_{25} = \frac{c_p}{m}, \quad a_{33} = -\frac{1}{RC},$$

$$a_{55} = \frac{-c_S}{J+k^2M}, \quad a_{56} = \frac{KK^2}{J+K^2M}, \quad a_{65} = -\frac{K_1}{L_m K},$$

$$a_{66} = -\frac{R_m}{L_m}, \quad b_{21} = \frac{c_P G_P K_P}{RCm}, \quad b_{31} = \frac{G_P}{RC}, \quad b_{62} = \frac{G_m}{L_m}$$

According to this, two apparatus is expressed by one state equation and It is able to think of designing that one apparatus has coarse motion control system and fine motion control system. Based on this, most appropriate servo system is designed.

4. Test of Ultra Precision Positioning and Investigation

4.1. Simulation

Fig.2 shows SIMULINK of coarse apparatus.

Generally, because if control system is designed with frequency response analysis rule after analyzing system in frequency domain, Performance of controller is guaranteed partly though there some errors in the processing of design or variables, It is able to make more robust control system than that designed in time domain. And, design of controller, though, is making closed loop transfer function to have need frequency response, eventually, caused by difficulty of it.

Open loop frequency analyzing of this system is appeared by Fm=96.589 dB, Pm=89.998 deg like Fig.3 gain margin over 60dB. on the other hang phase margin over 60 de. So, Design, for reducing phase margin is needed

In here, desirable stability spare are gain margin over 6dB and phase margin 30~60deg.

Adapting PID controller that was, designed before, It shows fine response in analyzing step response of time domain and Bode diagram of frequency domain likely Fig.3 and Fig.4

Analyzing close loop frequency including controller of this system is appeared by Gm=7.079 dB, Pm=42.054 deg gain margin is over 6dB and phase margin is 30~60 deg. And, In step response of time domain, fine response is showed such as Table 1 and Fig.5, also, and parameter value of PID controller that taken by simulation are $K_p = 0.97500[V/\mu m]$, $K_i = 4.00 \times 10^{-5}[V/\mu m]$, $K_d = 2.00 \times 10^{-2}[V/\mu m]$.

Accordingly, this system including PID controller is interpreted as stable. Fig.6 shows simulink of fine apparatus and Fig.7 shows frequency response of it.

Generally, The pole point of spring, damper, mass system different to zero point with 2 So, frequency specific curb is showed in Fig.7 as approximating the number of pole point to 3 and zero point to 1. At this, non-linearity absent amplitude of 0.1㎛ caused by one of output current of piezo AMP is used for watching movement. Static gain K_p of fine apparatus use 0.078㎛/v also, same as amplitude of 0.1㎛.

It is able to know that resonance frequency of fine structure system is about 1kHz~2kHz by Fig.7.

Fig.8 and Table 2 shows step response of time domain and it's analyzing. this shows that response of time domain is satisfactional response.

PID controller and system is interpreted as stable such as showing result of simulation. Table 3 is the value of parameter that adapting to fine apparatus.

As above, after simulation of coarse apparatus and fine apparatus, compositing simulink of ultra precision positioning apparatus combined with this formed, this is showed in Fig.9.

Fig.10 shows displacement of dual stage and coarse stage while performing dual positioning control of coarse and fine apparatus with simulating by simulink of Fig.9. In here, actuation of system as compensation errors coarse and fine stage each other is showed. This is proving that dual positioning control runs right.

The result of analysing simulink that stable Two system make to one system shows fine control efficiency like figure

Accordingly control efficiency and safety of system is verified by simulate ultra precision positioning apparatus with MATLAB, and choice of most adequate control efficiency and parameter is needed with comparing driving test in real apparatus with simulation.

4.2 Test of Ultra Precision Positioning

In ultra precision positioning apparatus, displacement measurement system for positioning use laser interferometer. Fig.11 shows figure of schematic diagram of this system.

Digital signal processing system(DSP) is used for controller. this changes signal from laser interferometer to A/D converting after calculating in main CPU of DSP.

As based on the parameter that is established in the simulation this system is constituted. As the result of operation, favorable parameters that are $K_p = 0.97410[V/\mu m]$, $K_d = 4.18\times10^{-5}[V/\mu m]$, $K_d = 2.12\times10^{-3}[V/\mu m]$ have been showed good capacity and we compared rotary encoder with laser interferometer as a feedback sensor, evaluated influence of resolution upon system with the difference of feedback sensor.

In the case that encoder used feedback sensor, there are ±5㎛ accuracy, and we found the problem of backlash. but by using laser interferometer, there are ±0.5㎛ accuracy, and the problem of backlash is compensated favorably.

After the experiment as above, positioning resolution of this system is tested with keeping up 0.5㎛ for 1 sec.

The result is shown by Fig.13. Consequently accuracy of this ultra precision positioning apparatus is ±0.5㎛ is confirmed.

While driving piezo actuator, high voltage amplifier that amplify actuating signal effect to actuating piezo actuator directly so it's output specificity is important so that. before positioning test of piezo actuator output specificity of high voltage amplifier is con firmed previously.

MPT693 of THORCABS is used for high voltage amplifier in this paper.

In next positioning test. 0.5㎛ step is given previously. then Fig.14, step response is confirmed this shows that it is similar to step response of simulation. In the point of only step response. Resolution of this system shows ±10nm accuracy.

At this, stroke test for more confidence of resolution is done with keeping up step 50nm for 1second. And to compare open loop with closed loop, and applying controller with not doting, open loop resolution test is done with step 1㎛.

Therefore Fig.15, it is able to be confirmed that resolution of fine apparatus is ±10mm.

In the result of positioning test with separating coarse and fine apparatus, like above. each apparatus shows satisfactional efficiency.

Next dual positioning control is performed, Fig.16 is the result of resolution experiment using dual positioning control. Comparing with the previous test of Fig.13, error are compensated greatly. Like this, the result of measuring resolution of this apparatus is about ±10nm through testing.

5. CONCLUSION

In this paper, A system is designed to make one output signals from two input signal by combining coarse and fine system in one system of ultra precision positioning apparatus. Separated coarse and fine apparatus were tested and positioning simulation with dual servo algorithm was also performed. To reduce performing errors, the result of test was repeated in computer simulation. The result of test was similar to that of simulation. The performance of apparatus including mass-spring-damper and designed PID controller was compared each other in computer simulation was confirmed that the PID controller had fine efficiency.

In the test of fine apparatus, the closed loop control was needed because of non-linearity specificity of piezo actuator itself. It's response was the most stable at frequency level, 1Hz and the closed loop control was proved to be essential with the test of open loop and closed loop control. And resolution ±10nm was gained by the positioning test.

These two systems showed superior performance, in the case of performing that dual positioning control of union have been showed good result in this paper.

In this through, fine capacity was need that confirming of control performance using variable algorithm. Further study for Ultra Precision Positioning Apparatus is also need to apply them to various industrial fields.

Table 1 Step response of Coarse Apparatus to Perform Simulation

Title	Parameter	Unit
Steady state error	0	
Maximum overshot	0.1(10%)	[%]
Rise Time	0.047	[s]
Setting Time	0.062	[s]

Table 2 The step Response Fine Apparatus to Perform Simulation

Title	Parameter	Unit
Steady state error	0	
Maximum overshot	0.1(10%)	[%]
Rise Time	0.005	[s]
Setting Time	0.0075	[s]

Table 3 Control parameters of PID controller in Fine Apparatus to Perform Simulation

P	β 0.01
I	γ 800
D	α 5×10^{-7}
	Tα 2.5×10^{-11}
Ks	7.9×10^{6} v/m
Q	0.707

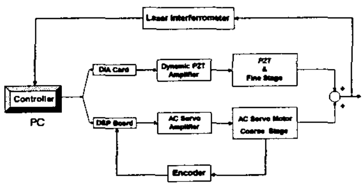

Fig.1 Block Diagram of Dual Servo Loop

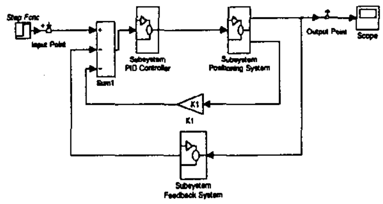

Fig.2 The Simulink of Coarse Apparatus

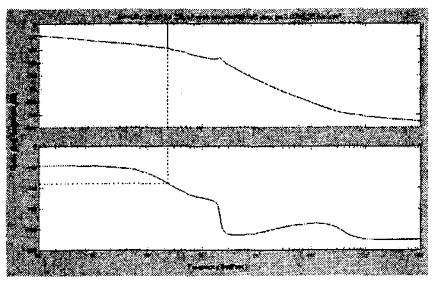

Fig.3 The Bode diagrams of Coarse Apparatus by Open Loop to Perform Simulation

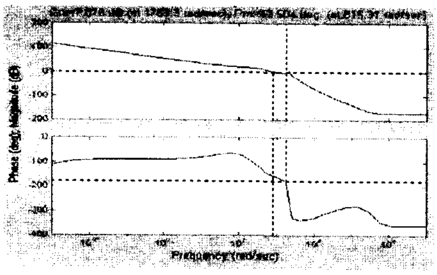

Fig.4 The Bode diagrams of Coarse Apparatus by Closed Loop to Perform Simulation

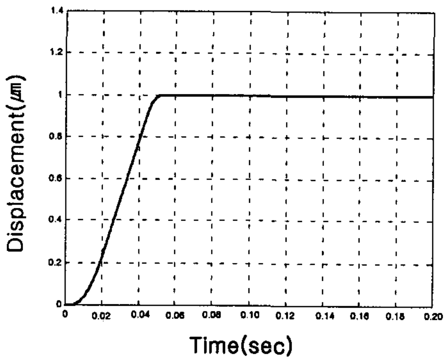

Fig.5 The Step response of Coarse Apparatus to Perform Simulation

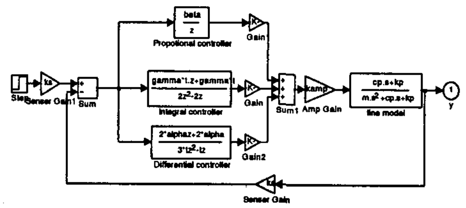

Fig.6 The Simulink of Fine Apparatus Apparatus to Perform Simulation

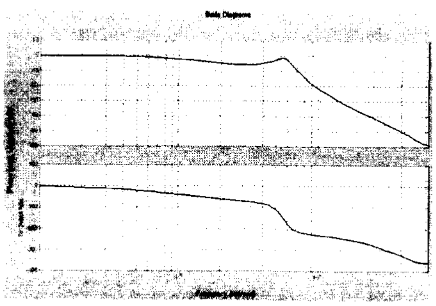

Fig.7 The Bode Diagram of Fine Apparatus by Closed Loop to Perform Simulation

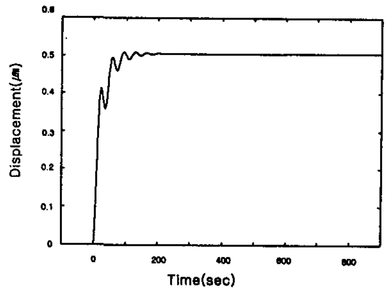

Fig.8 The step Response of Fine to Perform Simulation

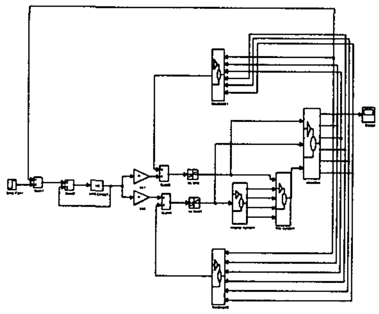

Fig.9 Simulink of Ultra Precision Positioning System

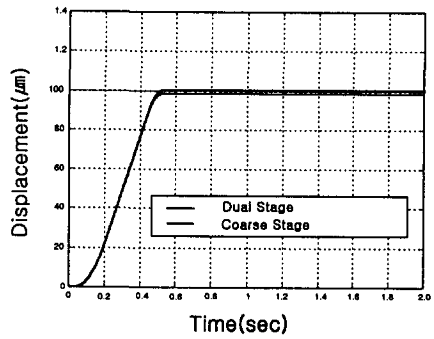

Fig.10 Step Response of Dual Stage to Perform Simulation

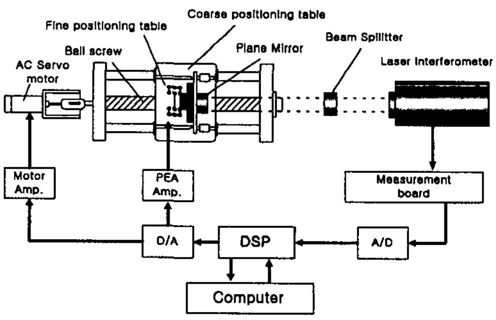

Fig.11 Schematic Diagram of Ultra Precision Positioning System

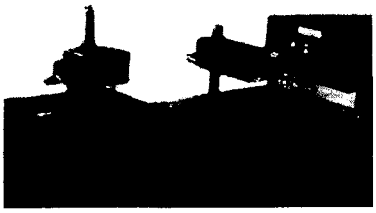

Fig.12 Photograph of Ultra Precision Positioning Apparatus

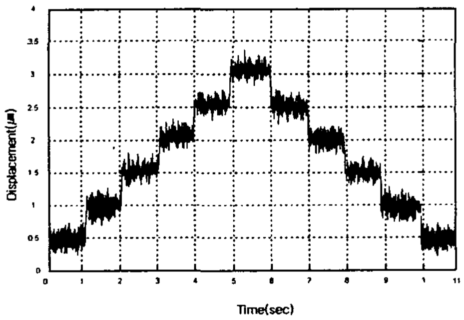

Fig.13 0.5㎛ Step response of feedback from Laser interferometer output

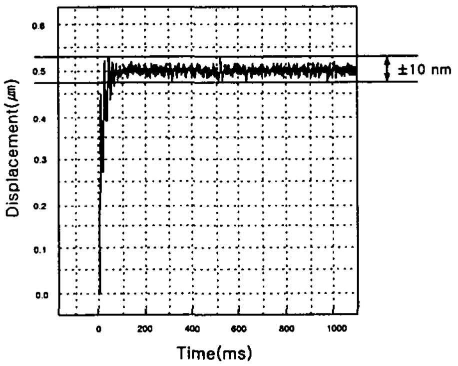

Fig.14 Step Response of Fine Apparatus

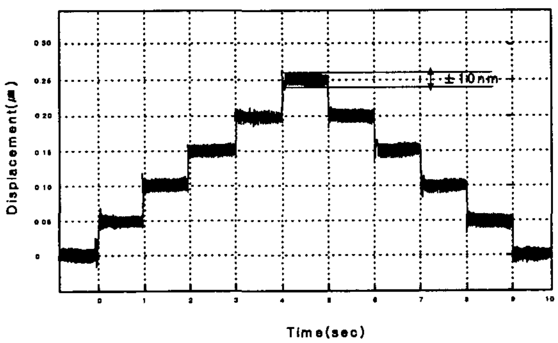

Fig.15 The resolution experiment of Ultra Precision Positioning System by Closed Loop

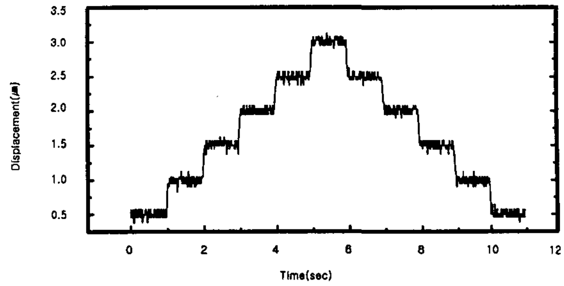

Fig.16 The resolution experiment of Dual positioning control

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