An Open-Loop Method for Point-to-Point Positioning of a Piezoelectric Actuator

Nobuhiko Henmi[1,#] and **Michihiko Tanaka**[1]

1 Faculty of Engineering, Shinshu University, Nagano, Japan
#Corresponding Author / E-mail: henmi@shonshu-u.ac.jp; TEL: +81-26-269-5153, FAX: +81-26-269-5145

KEYWORDS : Piezoelectric actuator, Open-loop control, Point-to-point positioning, Hysteresis, Creep

We describe how to control a piezoelectric actuator using the open-loop method for point-to-point positioning. Since piezoelectric actuators have nonlinear characteristics due to hysteresis and creep between the input voltage and the resulting displacement, a special method is required to eliminate this nonlinearity for an open-loop drive. We have introduced open-loop driving methods for piezoelectric actuators in the past, which required a large input voltage and an initializing motion sequence to reset the state of the actuator before each movement. In this paper, we propose a new driving method that uses the initializing state. This method also utilizes the overshoot from both the upward and downward stepwise drives. Applying this method, we obtained precise point-to-point positioning without the influence of hysteresis and creep.

Manuscript received: May 1, 2006 / Accepted December 6, 2006

1. Introduction

Stack type piezoelectric actuators are often used in precise positioning systems[1,2] because they easily generate precise motion with large amounts of force, but these actuators have nonlinear characteristics such as hysteresis and creep. Therefore, feedback control is usually applied for precise positioning by measuring position of objects directly.[3,4] However, closed loop feedback control cannot be always used in every application, and methods that eliminate nonlinearity or control the actuator without a closed-loop system have been investigated.[5,6] We propose a precise positioning system for actuators by using open-loop driving.

Previous papers have described the fundamental concepts and characteristics of the proposed open-loop driving method for a piezoelectric actuator[7], and submicron accuracy and repeatability for a 5-μm stepwise positioning system over a 30-μm motion range have been achieved.[8] Although the open-loop driving method can drastically reduce the influences of hysteresis and creep, previous driving methods use an initializing motion sequence to reset the actuator state. A large amplitude sinusoidal input voltage is applied to the piezoelectric actuator just before every stepwise positioning motion. By using the initializing motion sequence, the actuator is reset regardless of its position.

In the present paper, we propose a new driving method that does not use an initializing motion sequence, but instead utilizes the overshoot motion for both the upward and downward stepwise drives. Previous open-loop driving methods require the actuator to start every time from a fixed point before moving to its desired position. Furthermore, the actuator requires an initializing motion sequence before going to that initial starting point. The new driving method proposed in this paper uses downward overshoot to position the actuator to the starting point. Appropriate values of downward overshoot can precisely reset the actuator to where point-to-point positioning can be achieved without requiring a large initializing motion sequence.

2. Fundamental Characteristics of the Piezoelectric Actuator

2.1 Hysteresis characteristics

Fig. 1(a) shows hysteresis loops for a 10-Hz sinusoidal drive having different amplitudes. The amount of gain and hysteresis are different for each loop. Also, when the amplitude is large, the displacement of the center of the loop is high. In Fig. 1(b), each loop in Fig. 1(a) is redrawn so that the minimum point of each curve is the same. Fig. 1(b) shows that all of the curves on the increasing voltage side of the hysteresis loops are the same and do not depend on the amplitude of the driving voltage for a given frequency. Thus, the influence of hysteresis can be reduced if the actuator always initializes motion from the same starting point.

2.2 Creep characteristics

Fig. 2(a) and (b) show the creep behavior in the displacement of the piezoelectric actuator for different stepwise input waves. Fig. 2(a) indicates the response due to a normal step input and Fig. 2(b) shows the response due to a step input with overshoot. In Fig. 2(a), when normal stepwise voltage is applied to the actuator, the displacement changes gradually once the input voltage reaches a constant value. However, Fig. 2(b) illustrates that when a stepwise voltage with overshoot is applied to the actuator, the displacement remains constant once the input voltage reaches its constant value. Thus, the influence of creep can be eliminated by using a voltage drive with overshoot. It should be noted that an appropriate value of overshoot exists relative to the amplitude of the step voltage. Too large or too small overshoot values will not eliminate the influence of creep. We experimentally investigated the relationship between the overshoot and the creep behavior.

3. Results Using the Previous Driving Method

To explain the new driving method, we describe the previous driving method[7,8] and its results.

3.1 Outline of the previous driving method

According to the results in Fig. 1(b), the influence of hysteresis

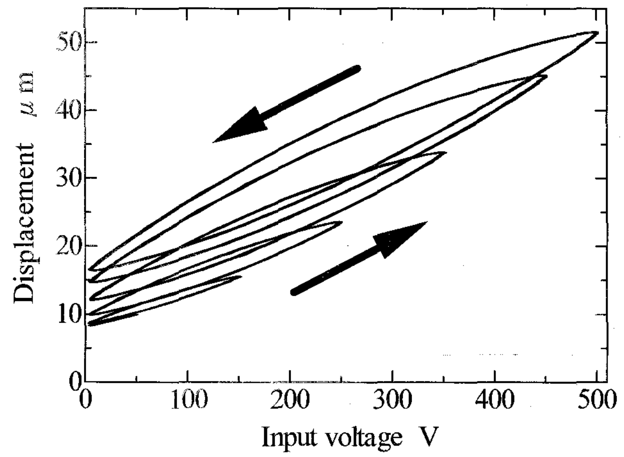

Fig. 1(a) Hysteresis loops for sinusoidal inputs of different amplitude

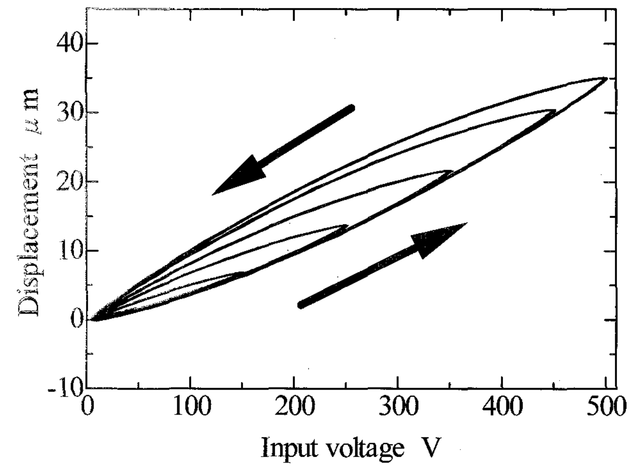

Fig. 1(b) Hysteresis loops drawn so that the lowest displacement coincides

can be reduced by elongating the actuator from one contracted position to the desired position. As shown from the results in Figs. 2(a) and (b), creep can be eliminated by using a stepwise drive with overshoot.

Fig. 3 shows the waveform of the input voltage to the actuator for stepwise point-to-point positioning using the previously proposed open-loop driving method. First, to reduce the influence of the difference in the initial condition of the actuator, the input voltage is raised up to a higher value called the initializing voltage (1 in Fig. 3). We call this motion the initializing motion. Next, the input voltage is brought down to 0 V at the beginning of every step and returned to some voltage that we call the initial standard voltage (2). Then, it is raised up to the desired step height, *3*, with some overshoot, 4. This unique driving motion is executed to eliminate both of the influences of hysteresis and creep. When the actuator moves to its next position, the voltage is brought up to the next initializing voltage and is changed in a way similar to that of the previous step.

This method has several driving parameters, the initializing voltage, the initial standard voltage, the step value and the overshoot value. The appropriate values of each parameter are determined according to the experimental results.

3.2 Positioning result using the previous driving method

Fig. 4 shows the results of a 5-μm stepwise positioning using the previous driving method. The actuator is driven at a constant step height by an open-loop drive and the influences of hysteresis and creep are reduced. The spikes shown just before each step position are due to the initializing motion sequence. The initializing driving voltage is a large-amplitude 10-Hz sinusoidal wave that is applied before every stepwise motion. For reference purposes, the

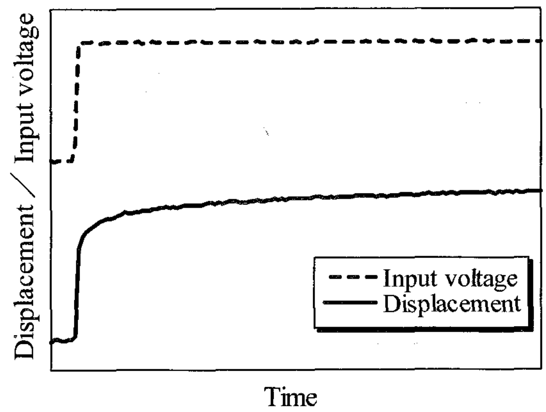

Fig. 2(a) Creep behavior of the piezoelectric actuator for a simple stepwise input voltage

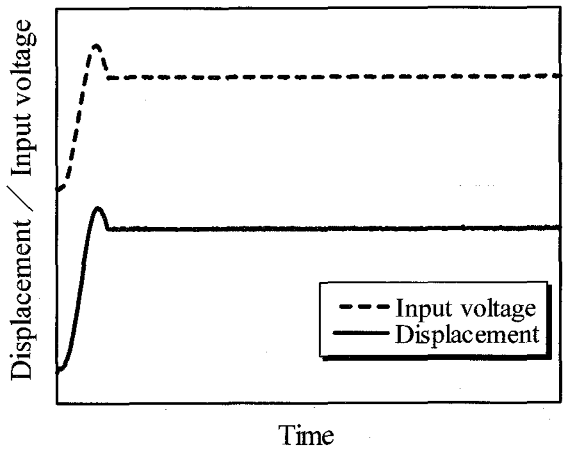

Fig. 2(b) Elimination of creep motion by overshoot drive

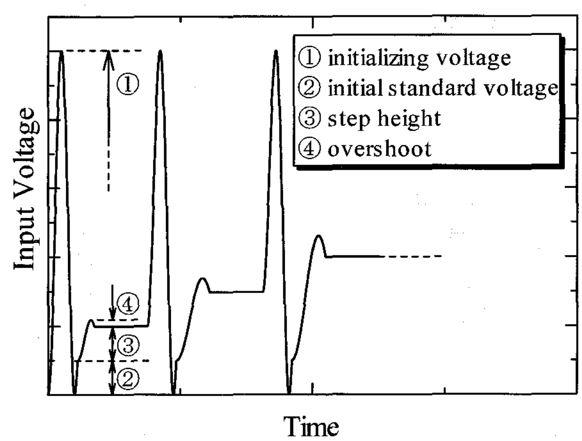

Fig. 3 Schematic of the input voltage wave for the previous driving method

displacement behavior due to the constant stepwise input voltage without the influence of nonlinearity is shown in Fig. 5. Although the step height of the input voltage is constant, the heights of each resulting displacement are different. Also, displacements for the same voltage in the step-up and step-down sides are different. Each step is not flat because of the influence of creep. By comparing the results in Fig. 4 and Fig. 5, it is clear that the previous method is not efficient for point-to-point positioning. Therefore, we propose a new open-

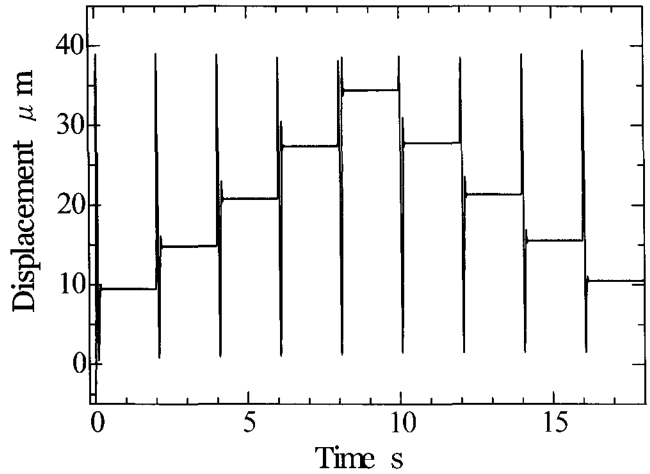

Fig. 4 Results of stepwise positioning by the previously proposed method

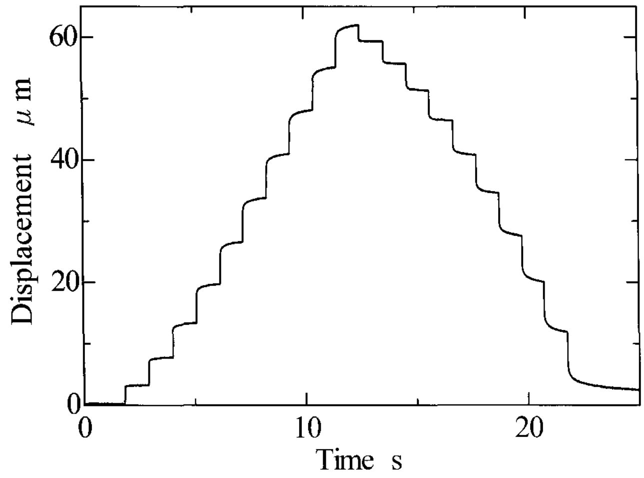

Fig. 5 Displacement behavior for a simple stepwise voltage input

loop driving method that does not use the initializing motion sequence.

4. The New Driving Method

4.1 Outline of the new driving method

As Fig. 2(b) shows, the actuator does not exhibit the effects of creep when an appropriate amount of overshoot is applied. Whenever the piezoelectric actuator is at rest and does not move due to creep, the molecular state of the piezoelectric actuator can remain under the same condition until a reversal of polarization occurs and the loads are applied. Therefore, the possibility exists that an appropriate amount of overshoot will result in a similar molecular state. Fig. 2(b) shows the case in which an upward overshoot is applied to the actuator. A downward overshoot can also eliminate the effects of creep. Thus, we propose a new driving method using an upward and downward overshoot drive.

Fig. 6 presents the concept of the waveform applied for point-to-point positioning using the new proposed method. The driving voltage starts from the initial standard voltage, *1*, and is raised to the desired step height, 2, with an upward overshoot, 3. Then, the voltage goes down to the initial standard voltage with some downward overshoot, as shown by 4. When the actuator moves to the next position, the voltage is brought up to the next step height with the upward overshoot in the same method shown in the previous step.

4.2 Influence of overshoot

Experimental results show that the appropriate values of both

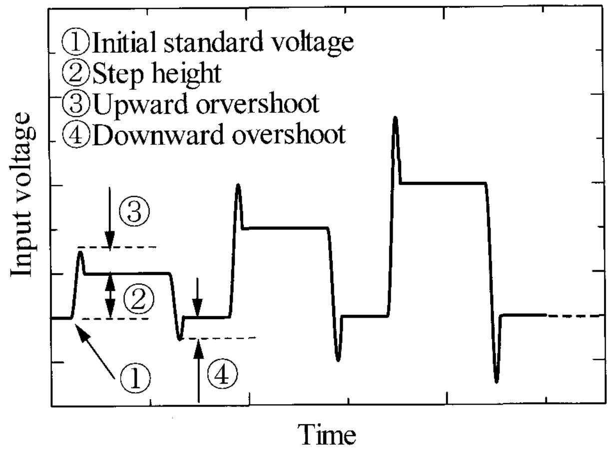

Fig. 6 Schematic of the input voltage of the newly proposed method for stepwise positioning

upward and downward overshoot exist. As discussed earlier, the amount of overshoot should not be too large or too small and depends on the step height. In our previous study[7], the percent step height was adopted to determine the amount of overshoot. However, the percentage of the step height is not enough information to achieve precise positioning over a large range of motion. We determined the appropriate values of both the upward and downward overshoot for several step heights experimentally.

Fig. 7(a)–(c) show the influence of the upward overshoot on the actuator displacement. These are the results for a (a) too large, (b) too small, and (c) the appropriate value of overshoot. The displacement behaviors shown are the actuator motions just after step input with overshoot is applied. When the overshoot value is too large, the actuator contracts after the input voltage remains constant. When the overshoot value is too small, the actuator gradually elongates. The appropriate value of the overshoot maintains a constant actuator motion. Although these results are for upward overshoot, it can also be shown that the actuator exhibits similar behaviors for downward overshoot. The appropriate value of overshoot is determined to keep the actuator displacement constant after step input. Fig. 8 shows the appropriate values of upward and downward overshoot for different step heights based on the experimental results. The overshoot values are not simply proportional to the step height, and the values of downward overshoot are a little smaller than that of upward overshoot.

4.3 Results using the new driving method

Fig. 9 shows the result of stepwise positioning driven by the new proposed method. The step heights of input voltage are 20, 30, and 40 V. These voltages result in about 3.0, 4.5 and 6.0 μm displacement, respectively. The actuator generates accurate displacements without the influence of hysteresis and creep. Both the upward and downward overshoot results in submicron order accuracy for point-to-point positioning using this new open-loop driving method.

Fig. 10 shows the result of stepwise positioning for a submicron step height using the new driving method. Step heights having an input voltage of 0.2, 0.4, 0.6, and 0.8 V are applied to the actuator. These voltages correspond to about 25, 50, 75, and 100 nm displacement, respectively. These results show that hysteresis and creep have almost been totally eliminated. However, the initial displacement waveform on the figure goes up gradually through the sequence. This gradual motion is less than 10 nm for 400 s and may be the result of thermal drift in the sensor and measurement system.

Fig. 11 shows the thermal drift in the output of the displacement sensor. The sensor is a capacitance, noncontact displacement sensor. Fig. 11 was obtained by measuring a steel block in a thermally insulated chamber.

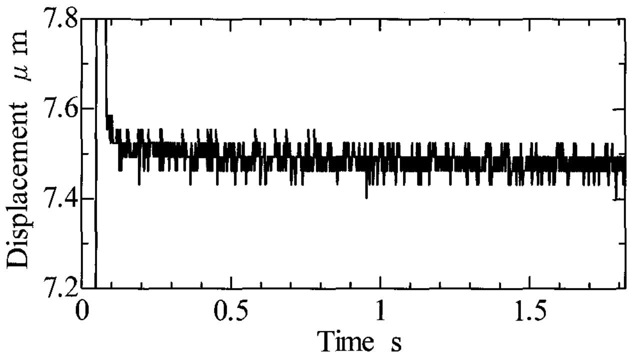

Fig. 7(a) Displacement behavior just after the stepwise input with a too large overshoot value

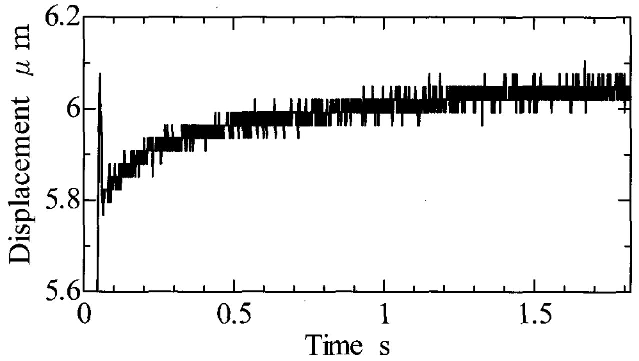

Fig. 7(b) Displacement behavior just after the stepwise input with a too small overshoot value

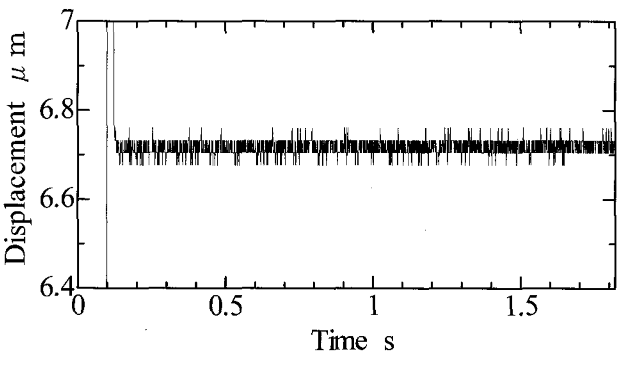

Fig. 7(c) Displacement behavior just after the stepwise input with the appropriate overshoot value

The temperature in the chamber was controlled, and ranged from 19 to 21 °C. The relative humidity in the chamber was also controlled and kept below 50%. The temperature shown in the figure was measured in the chamber. The change in temperature was about 0.4° C for 17 h. For the temperature change, the sensor showed about a 0.15 μm change in output. The sharpest displacement change in Fig. 11 is about 8 nm for 400 s, almost identical to the gradual displacement change observed in Fig. 10. In order to experimentally evaluate the proposed driving method more accurately and precisely, the quality of temperature control in the laboratory must be improved or a more accurate displacement sensor is needed.

5. Conclusions

We proposed a new open-loop driving method for a piezoelectric actuator. To explain the basic concept of the driving method, we first demonstrated the nonlinear behaviors of hysteresis and creep. Then, we introduced the new driving method, which did not require an initializing drive sequence before each stepwise positioning motion

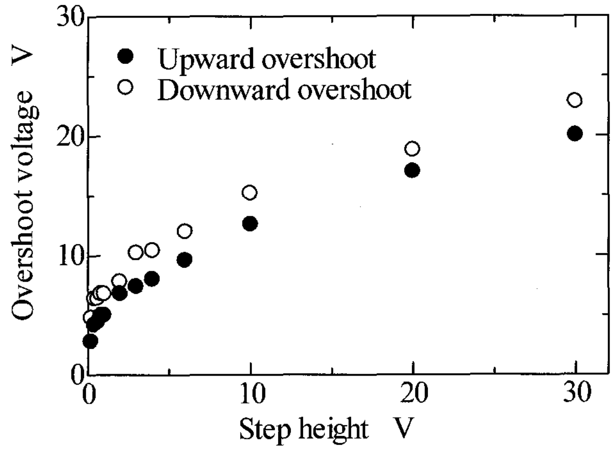

Fig. 8 Appropriate overshoot value for step height of input voltage

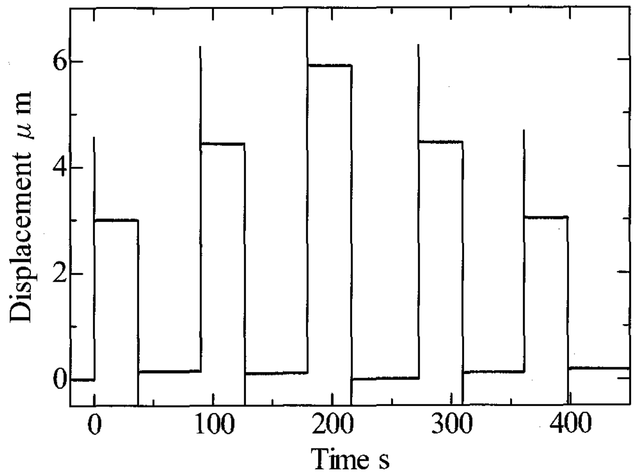

Fig. 9 Result of stepwise positioning by the new proposed method

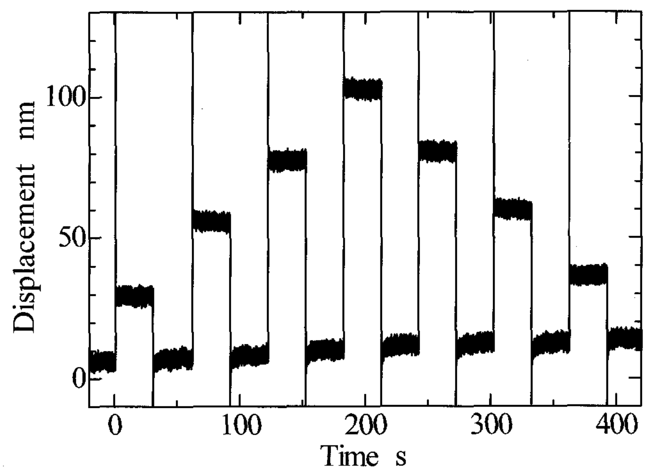

Fig. 10 Result of stepwise positioning for small step height by the new proposed method

but instead used overshoot in both the upward and downward directions. We next determined the appropriate value of the overshoot for various heights experimentally. Point-to-point positioning was

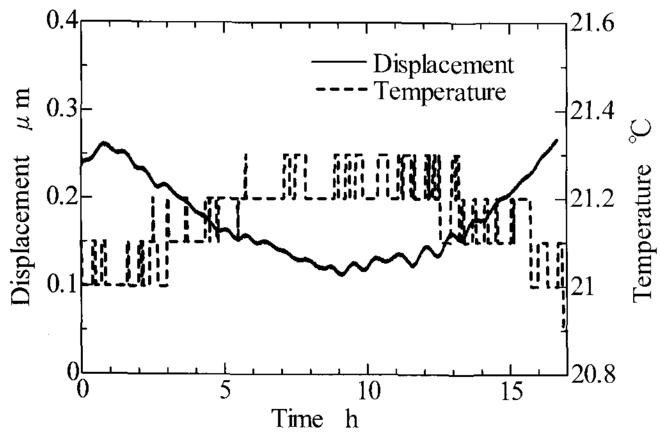

Fig. 11 Thermal drift of the sensor output and the temperature change in the experimental chamber

attained with submicron order accuracy without the influence of both hysteresis and creep. Submicron step height positioning was also achieved, which was as accurate as the thermal drift of the displacement sensor used in the experiments.

ACKNOWLEDGEMENTS

This study was financially supported by the Electro-Mechanic Technology Advancing Foundation. We thank Mr. Takeru Yotoriyama, an undergraduate student at Shinshu University, for providing assistance.

REFERENCES

1. Liu, Y. T., Fung, R. F. and Wang, C. C., "Precision Position Control Using Combined Piezo-VCM Actuator," Precision Engineering, Vol. 29, No. 4, pp. 411–422, 2005.

2. Li, Y., Guo, M., Zhou, Z. and Hu, M., "Micro Electro Discharge Machine with an Inchworm Type of Micro Feed Mechanism," Precision Engineering, Vol. 26, No. 1, pp. 7–14, 2002.

3. Chu, C. L. and Fan, S. H., "A Novel Long-Travel Piezoelectric-Drive Linear Nanopositioning Stage," Precision Engineering, Vol. 30, No. 1, pp. 85–95, 2006.

4. Henmi, N., "A Six-Degrees of Freedom Fine Motion Mechanism," International Progress in Precision Engineering (Proceedings of the 7th IPES), Butterworth–Heinemann, pp. 53–61, 1993.

5. Kaizuka, H. and Siu, B., "A Simple Way to Reduce Hysteresis and Creep when Using Piezoelectric Actuators," Japanese Journal of Applied Physics, Vol. 27, No. 5, pp. 773–774, 1988.

6. Furutani, K., Urushibata, M. and Mohri, N., "Displacement Control of Piezoelectric Element by Feedback of Induced Charge," Nanotechnology, Vol. 9, No. 2, pp. 93–98, 1998.

7. Henmi, N. and Tanaka, M., "A Study on Open-Loop Positioning Method for Piezoelectric Actuator," Proceedings of the 3rd International Workshop on Advanced Mechatronics, pp. 74–77, 1999.

8. Henmi, N., Matsusue, A., Tanaka, M. and Shinkai, D., "A Study on Open-Loop Drive for Piezoelectric Actuators—Improvement of Positioning Accuracy and Repeatability," Proceedings of the International Conference on Mechatronics and Information Technology, pp. 340–344, 2001.