Control Performances of a Fine Motion Stage using a Multilayer Electrostatic Actuator without Precise Balls for Lubrication

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Abstract

This paper describes the control performances of a multilayer electrostatic actuator, which is designed for a fine motion stage without precise balls for lubrication. The motion characteristics of the electrostatic actuator without precise balls depend on the input signal to the actuator, which consequently influences the frictional effect. First, the relationship between the working range and the input signal is explained. Next, based on the relationship, the actuator's control system is designed. The control system includes the PID compensator and the driving signal unit which generates the suitable signal for three driving modes in response to the working range; that is (1) fine driving mode for working range smaller than 120nm, (2) wide driving mode for working range wider than 120nm and (3) dual driving mode. The fine driving mode enables the actuator to be driven with a large holding force for limited working range. To ensure the full working range of the actuator, the wide driving mode is useful. Additionally, to permit the actuator to be driven with a large holding force under the full working range, the dual driving mode was introduced. The actuator exhibits high performances under these three driving modes with the positioning accuracy less than 15nm.

1. Introduction

Fine stages are typically used in systems such as semiconductor manufacturing systems, machine tools and scanning probe microscope systems. Often, these systems require high positioning accuracy in a short positioning time [1]. Furthermore, the designed actuator is preferred to be a simple structure, easy to maintain and be able to generate relatively low heat. Presently, actuators such as the piezoelectric actuators [2] and the electromagnetic actuators [1] are typically used for fine stages. However, the piezoelectric actuators typically need hinges for multi degree of freedom (DOF) motions in the fine stage [2]. These hinges result in the overall structure of the actuator being somewhat complex with a large stage size. In addition, hinges lead to greater vibration. A multi DOF is obtainable without hinges with the electromagnetic actuators, which additionally can generate large thrust force. The disadvantage of the electromagnetic actuators is that it generates a higher heat [4], which can lead to deformations in items on the fine stages.

The purpose of this research is to design and develop an electrostatic actuator for a fine motion stage. Unlike the piezoelectric actuators, the electrostatic actuators do not require hinges and also produces lower heat than the electromagnetic actuators. Up until today, several types of the electrostatic actuators have been designed. For example, the variable capacitance motors [5,6] and the induction motor [7] utilize precise balls to enable a reduction in the frictional effect and to keep the gap between electrodes [5,7]. A variable capacitance motor was developed by Ghodssi et al [6] in which the gap between the mover and stator layers is maintained with precise microball bearings. All these actuators exhibit good performances, but the use of such precise balls does however typically lead to a much more complex and costly system. For industrial purposes, it is much more desirable to have a simple structure with ease of maintenance. In [8], a multilayer electrostatic actuator which implements lubrication oil without precise balls has been designed and evaluated. It has been clarified that, low viscosity lubrication oil and the addition of high dielectric fillers to the lubrication oil shorten the response time and increase the thrust force of the actuator. Also, the signal on demand to drive the actuator was discussed.

In this paper, the control performances of the electrostatic actuator without precise balls are discussed. A brief description of the actuator's design is provided in Section 2. Section 3 discusses the effects of the driving signals on motion characteristics. Section 4 discusses the control performances of the actuator using the driving signals. Conclusions are summarized in Section 5.

2. Experimental electrostatic actuator

The electrostatic actuator in this paper is a variable capacitance motor type actuator which is useful for short working range motion. To examine the control performances of a multi-layer electrostatic actuator for a fine stage, a two-layer electrostatic actuator was designed [8]. Fig. 1 illustrates the side view of the experimental two-layer electrostatic actuator. The actuator consists of electrodes which are alternately stacked together. The electrodes are covered with Ethylene tetrafluoroethylene (ETFE) films as isolation films. The ETFE film is used so that the contact condition between the electrode layers causes low friction. To realize a bi-directional motion, voltages V_1 and V_2 are applied to Stator A and Stator B, whilst voltage V_3 is set to zero and applied to the mover shown in Fig. 1. The voltages V_1 and V_2 are out of phase by π. In order to reduce the frictional effect between the electrodes, lubrication oil is used without precise balls for easy fabrication and maintenance. Silicone oil with 10mPa.s viscosity is used as the lubrication oil. The dielectric constant of the 10mPa.s silicone oil is 2.65.

Fig. 2 illustrates the fabricated electrode. It is fabricated using a wire discharge machine. The electrode consists of many parallel beams. The beam pitch is 1.5mm. The structure of this electrode was adopted because it is expected not to cause dielectric breakdown in each layers of the actuator. Because of its simple structure, it is relatively easy to make. Table 1 shows the electrostatic actuator's model parameters.

Fig. 3 shows the overall view of the experimental setup. The setup includes a digital signal processing system, two high voltage power amplifiers and a capacitance displacement sensor.

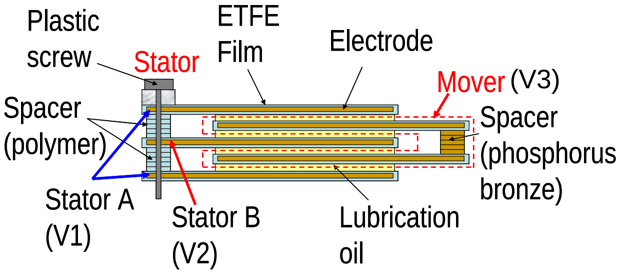

Fig. 1. Side view of the two-layer electrostatic actuator

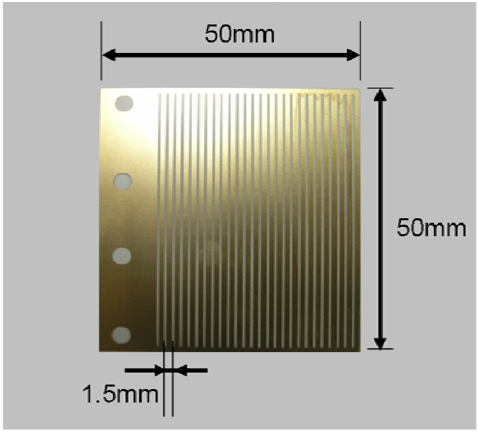

Fig. 2. Fabricated electrode

3. Open-loop driving characteristics

3.1 Basic dynamic displacement characteristics

The motion characteristics of this actuator with lubrication oil but not precise balls are greatly influenced by the applied voltage signal waveform to the actuator [8]. The long period of the applied voltage between the electrodes hugely reduces the produced thrust force, although the applied voltage produces the thrust force. Therefore, the appropriate signals to drive the electrostatic actuator without precise balls have been examined in detail.

Table 1: Electrostatic actuator's model parameters

Parameters	*Value*
Electrode, width & length (mm)	50.00 x 50.00
Beam pitch (mm)	1.5
Spacer (mm)	50.00 x 6.50
Electrode thickness (mm)	0.101
Spacer thickness, 4 pieces (mm)	0.420
ETFE film thickness (mm)	0.014
Electrode + ETFE film thickness (mm)	0.133
Thickness of assembled mover (mm)	0.835
Thickness of assembled stator (mm)	1.489
Gap between electrodes (mm)	0.218
Estimated silicon oil thickness (mm)	0.240
Mover mass (g)	5.22

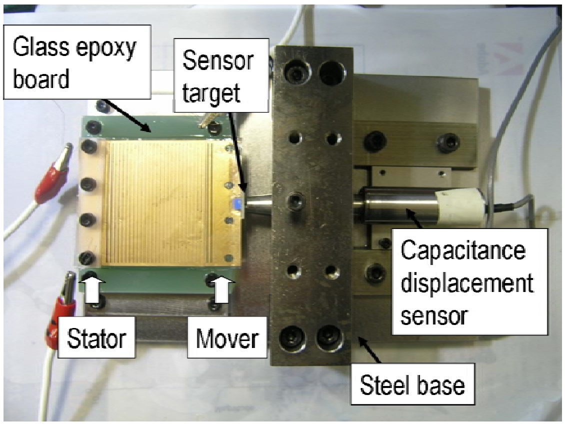

Fig. 3. Experimental setup

Fig. 4 shows that applying the periodic rectangular input signal to the actuator makes the displacement reduced step by step to approximately $2\mu m_{p\text{-}p}$, as introduced in [8]. Usual control signals include the direct current (DC) signal or the frequency of the components lower than the control bandwidth. In this paper, these signals are referred to as the normal signals. The periodic rectangular input signal is one of the normal signals. This figure signifies that the period of the normal signal is elongated enough to increase the friction force which limits the working range of the actuator. In this paper, the limited working range is defined as the fine working range. Hence, the normal signal is useful only for the fine working range. However, the advantage of the normal signal is that the holding force by the actuator is large because of the frictional effect between the electrodes. In order to benefit from this characteristic, the normal signal with the aid of a holding signal is evaluated. The holding signal is a constant 1kV voltage always applied to the actuator. The combination of the normal signal and the holding signal is referred to as the fine driving mode signal.

The relationship between the applied holding signals and the holding forces of the electrostatic actuator is shown in Fig. 5. The curve represents the average approximate line calculated using least square method based on Eq.(1). The displacement characteristic under the fine driving mode is shown in Fig. 6. This figure shows that under the 1kV holding signal, the actuator produces the displacement of 0.12μm$_{p-p}$. However, the displacement is shifted upward. This is because the frictional effect depends on the motion direction of the actuator.

$$F_{outputted} = k\left(V_{in}^{\ 2} - V_{\min}^{\ 2}\right) \qquad (1)$$

where,

$F_{outputted}$ = Outputted force by the actuator
k = Force gain
V_{in} = Applied voltage
V_{min} = Minimum voltage to move the mover

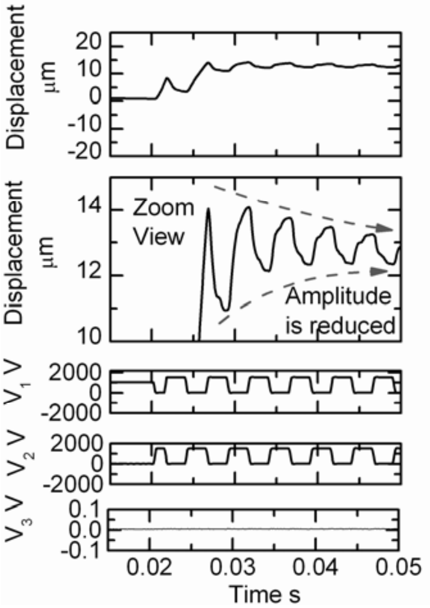

Fig. 4. Displacement response of the actuator to a periodic rectangular input signal using silicone oil with 10mPa.s viscosity.

3.2 Driving signal for full working range

As a signal to avoid the increase of the frictional effect and to ensure the full working range, the impulse signal has been introduced [8]. The full working range is defined as the wide working range. The impulse signal is used as the wide driving mode signal to ensure the full working range of the actuator. The open-loop displacement characteristic using the impulse signal whose duty cycle is (1/5) and the 10mPa.s silicone oil is shown in Fig. 7. This figure depicts that its initial displacement is almost the same as the initial displacement using the normal signal (see Fig. 4); however the displacement's amplitude is kept at approximately 20μm$_{p-p}$. This signifies that the impulse signal is useful for the wide working range.

4. Control performance

4.1 Control system structure

In this section, the control performances of the electrostatic actuator are examined to demonstrate the effectiveness of the actuator. Based on the PID controller, a control system was designed so that the system shows high precision positioning results. Fig. 8 shows the block diagram of the control system with the PID controller which includes the linearizer and the driving signal unit. The linearizer is used to cancel the nonlinear characteristics between the input voltage and the thrust force. The driving signal unit is added to control the driving mode discussed in this section. The tuned PID controller parameters are $K_p=15$, $K_i=1.8$ and $K_d=50$.

The control performances of the actuator are discussed independently based on three types of driving modes. First, the fine driving mode is evaluated using the normal signal and the holding signal. Next, the wide driving mode is examined using the impulse signal. Lastly, in order to improve the actuator's positioning performance, a driving mode based on the fine driving mode and the wide driving mode namely the dual driving mode is evaluated.

4.2. Fine driving mode

Fig. 9 illustrates the positioning performance under the fine driving mode using a 100nm step input (which is less than the fine working range shown in Fig. 6). For the fine driving mode, the normal signal and the 1kV holding signal are used as the driving signal. It can be depicted that, the positioning error is less than 15nm.

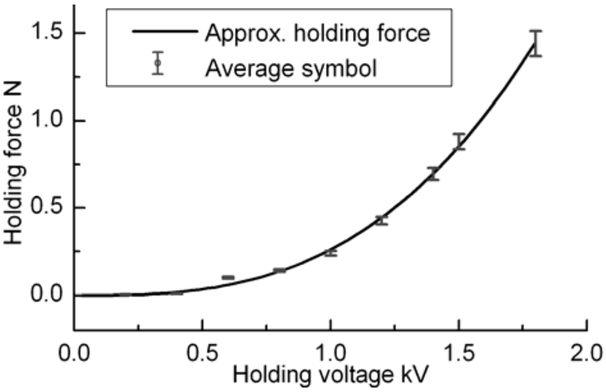

Fig. 5. Relationship between the applied holding voltages and the holding forces.

4.2 Wide driving mode

The impulse signal whose duty cycle is (1/5) is used as the driving signal for the wide driving mode. Fig. 10 shows the positioning result using a 100nm step input. The positioning error is less than 15nm which is identical to the fine driving mode (see Fig. 9). The experimental positioning results using step inputs with the step height of 1μm and 10μm are shown in Figs. 11 and 12, respectively. It can be depicted that the positioning error is less than 15nm for both step heights.

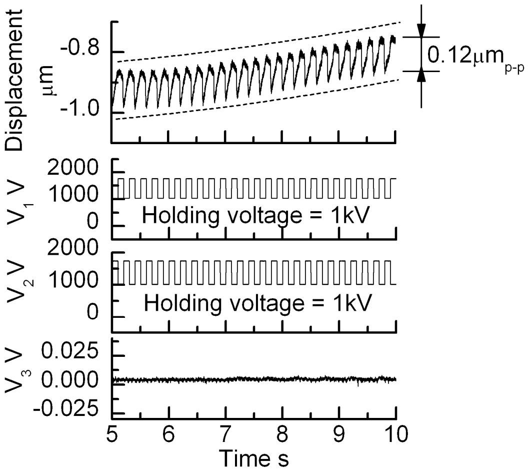

Fig. 6. Displacement characteristic under the fine driving mode.

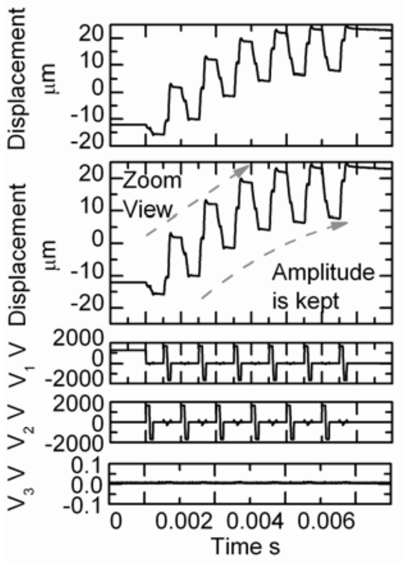

Fig. 7. Open-loop displacement characteristics using the impulse signal whose duty cycle is (1/5) and the 10mPa.s silicone oil.

4.3 Dual driving mode

In order to provide a large holding force in the wide working range, the dual driving mode is introduced. This mode consists of the fine driving mode and the wide driving mode. When the positioning error is larger than 500nm, the wide driving mode is used. Subsequently, when the positioning error is smaller or equal to 500nm, the fine driving mode is triggered. A time delay of 30ms is required to change from the fine driving mode to the wide driving mode. The time delay is added for restoring the gap due to the electrostatic attractive force between the electrodes. Figs. 13 and 14 show the positioning results of the dual driving mode using step inputs of 1μm and 10μm, respectively. In comparison with the wide driving mode (see Figs. 11 and 12), the positioning errors under the dual driving mode (see Figs. 13 and 14) are less than 15nm with smaller residual vibration. It can be depicted that, the percent overshoot for the step height of 1μm using the dual driving mode is reduced to 13.7% compared to the wide driving mode, 48%. For the step height of 10μm, the overshoot is reduced to 4% compared to the wide driving mode, 11%. However, the wide driving mode (see Figs. 11 and 12) exhibits shorter rise time compared to the dual driving mode for the both step heights. This indicates that the dual driving mode exhibits the better transient response in terms of the residual vibration and the percent overshoot.

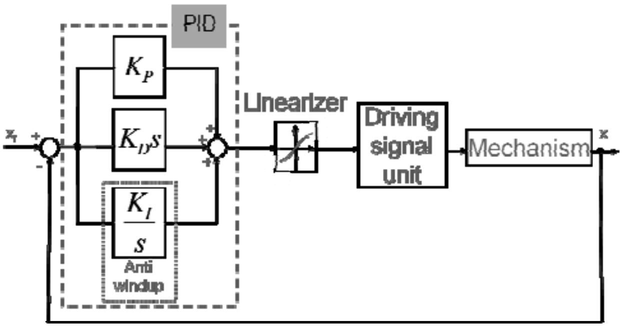

Fig. 8. Block diagram for the control system.

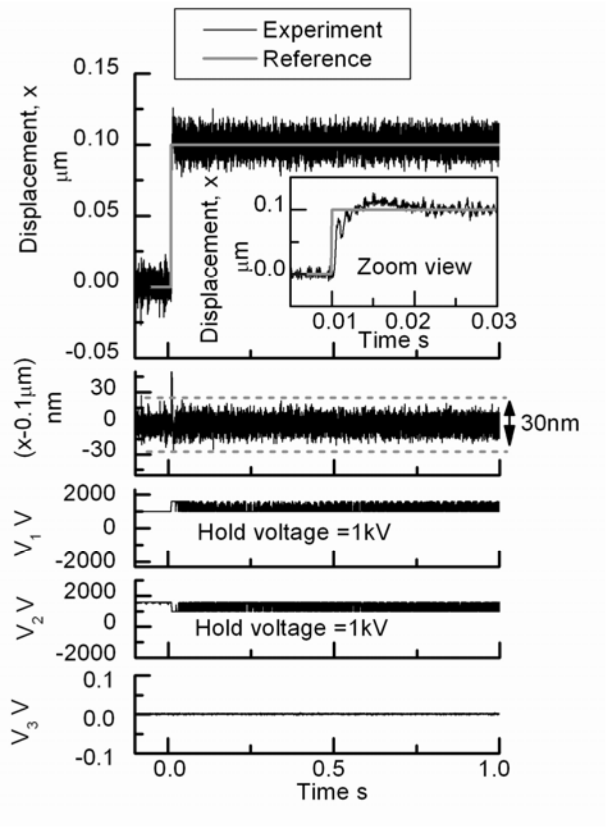

Fig. 9. Positioning performance using a 100nm step input under the fine driving mode.

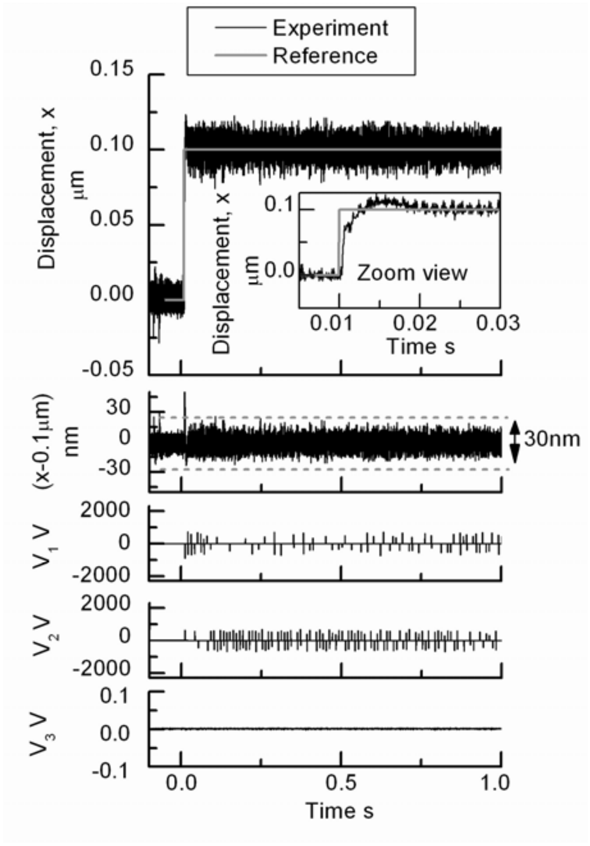

Fig. 10. Positioning result using a 100nm step input under the wide driving mode.

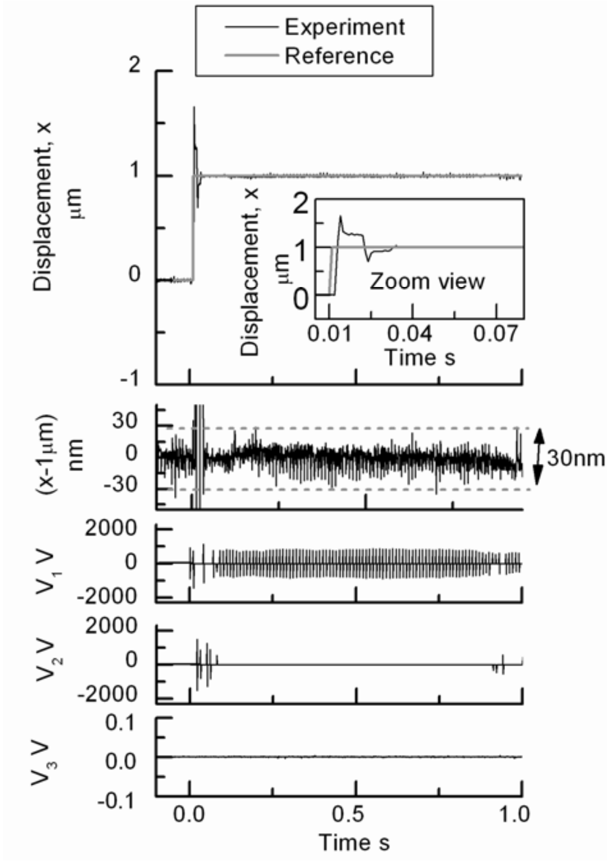

Fig. 11. Positioning results using a 1μm step input under the wide driving mode.

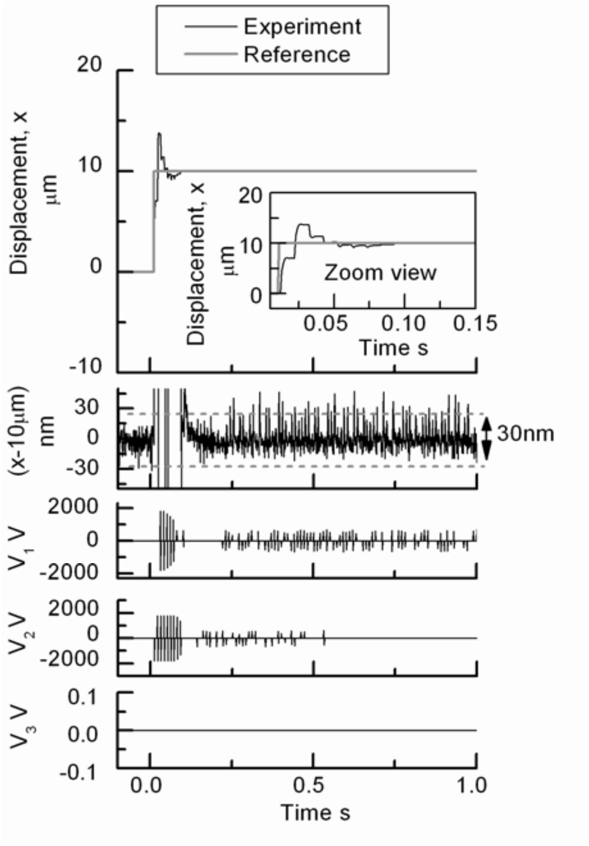

Fig. 12. Positioning results using a 10μm step input under the wide driving mode.

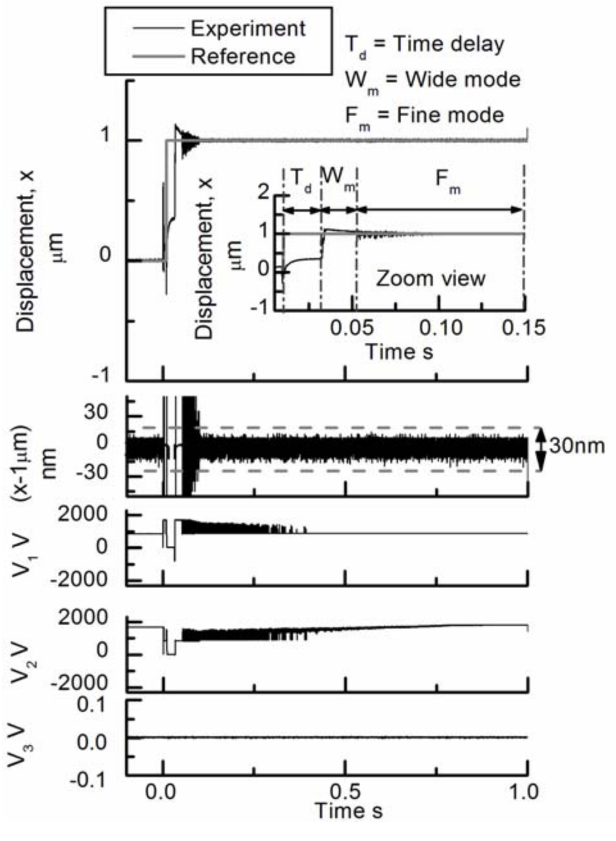

Fig. 13. Positioning results using a 1μm step input under the dual driving mode.

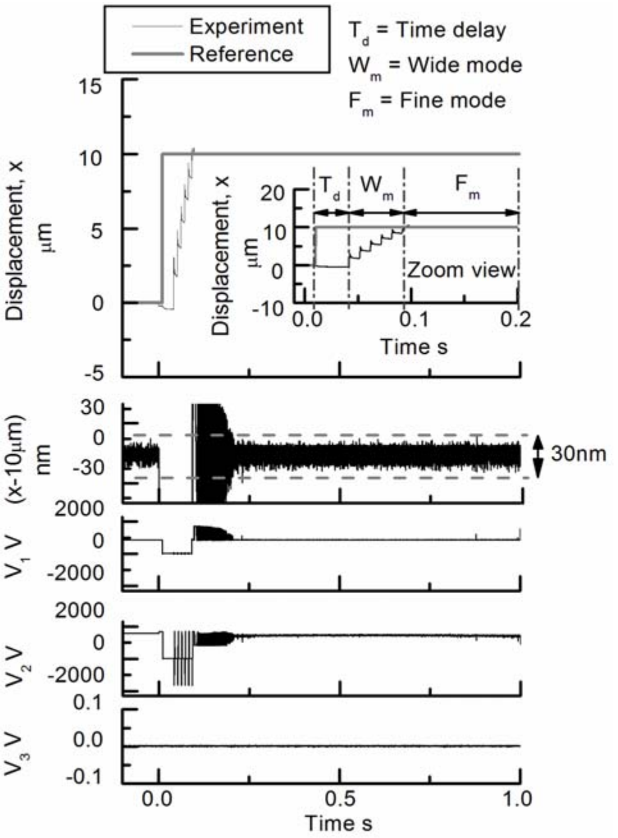

Fig. 14. Positioning results using a 10µm step input under the dual driving mode.

5. Conclusion

In summary, this paper briefly provides an overview of the control performances of a two-layer electrostatic actuator. Two types of driving signals were introduced; the normal signal and the impulse signal. In this paper, the control performances of the actuator have been examined based on these driving signals. For the working range shorter than 120nm, the control system with the fine driving mode was useful. It allows positioning performance with a large holding force and the positioning accuracy less than 15nm for the fine range motion. In order to enable the actuator to be driven for a wider working range without precise balls, the wide driving mode was introduced. It has been proven that the wide driving mode assisted in providing a positioning accuracy less than 15nm using the impulse signal. Additionally, to allow the actuator to be driven in the wide working range with the additional large holding force, the dual driving mode was examined. The results show that under the dual driving mode, the actuator exhibits the positioning accuracy less than 15nm with smaller residual vibration and the percent overshoot less than 13.7%.

References

[1] Won-Jong Kim and David L. Trumper, High-precision magnetic levitation stage for photolithography, Precision Engineering, Vol. 22, 1998, pp. 66–77.

[2] C.L. Chu, S.H. Fan, A novel long-travel piezoelectric-driven linear nanopositioning stage. Precision Engineering, Vol. 30, Issue 1, 2006, pp. 85-95.

[3] R.M. Seugling, T. LeBrun, S.T.. Smith, L.P. Howard, A six-degree-of-freedom precision motion stage, American Institute of Physics, Vol. 73, 2002, pp. 2462-2468.

[4] Shih-Kang Kuo and Chia-Hsiang Menq, Modeling and control of a six-Axis precision motion control stage, IEEE/ASME Transactions on Mechatronics, Vol. 10, no. 1, 2005, pp. 50-59.

[5] Zu Guang Zhang, Norio Yamashita, Masahiko Gondo, Akio Yamamoto and Toshiro Higuchi, Electrostatically actuated robotic fish: Design and control for high-mobility open-loop swimming, IEEE transactions on robotic, Vol. 24, No. 1, 2008, pp. 118-129.

[6] Mustafa ilker Beyaz, Matthew Mc Carthy, Nima Ghalichechian, Reza Ghodssi, Closed-loop control of long-range micropositioner using integrated photodiode sensors, Sensors an Actuators A, 2009, pp. 187-194.

[7] Norio Yamashita, Zu Guang Zhang, Akio Yamamoto, Masahiko Gondo, Toshiro Higuchi, Voltage-induction type electrostatic film motor driven by two- to four-phase ac voltage and electrostatic induction, Sensors and Actuators A, Vol. 140, 2007, pp. 239–250.

[8] Mariam Md Ghazaly, Kaiji Sato, Open-loop Characteristics of a Multilayer Electrostatic Actuator for a Fine Motion Stage. (Submitted to the Proceedings of the 14th International Conference on Mechatronics Technology, November 2010).