

Evaluation of a Multilayer Electrostatic Actuator for a Fine Motion Stage without Precise Balls for Lubrication

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ABSTRACT

This paper outlines the basic characteristics and the control performances of a multilayer electrostatic actuator utilized for a fine motion stage without precise balls. The research was undertaken in order to realize a practical and simple multilayer electrostatic actuator that produces high precision motion and sufficient force for a fine motion stage. For this purpose, a two-layer electrostatic actuator was developed and evaluated. Lubrication oils are used as lubricants in order to obtain low friction by maintaining the gaps between the stator and mover layers without precise balls for simplicity and easy maintenance. Each layer of the electrostatic actuator has one electrode, which consists of several beams. 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, this paper examines the resultant effects of the driving signals on the motion characteristics. Next, based on the driving signal, the control system for the actuator is designed. The control system includes the PID compensator and the driving signal unit which generates the suitable signal for full working range motion. The actuator exhibits the positioning accuracy better than 15nm.

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 have a simple structure, be 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 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. Multi-DOF stages without hinges are obtainable using the electromagnetic actuators, which additionally can generate large thrust force. The disadvantage of the electromagnetic actuators is that it generates a higher

heat, which can lead to deformations in objects on the fine stages.

The purpose of this research is to design and develop a simple and user-friendly 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 [4,5] and the induction motor [6] utilize precise balls to enable a reduction in the frictional effect and to keep the gap between electrodes [4,6]. A variable capacitance motor was developed by Ghodssi et al [5] 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 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 this paper, a multilayer electrostatic actuator which implements lubrication oil without precise balls has been designed and evaluated [7,8]. A brief description of the actuator's design is provided in Section 2. Section 3 discusses the basic open-loop characteristics of the actuator. Section 4 discusses the control performances of the actuator. Conclusions are summarized in Section 5.

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 basic open-loop characteristics and the control performances of a multi-layer electrostatic actuator for a fine stage, a two-layer electrostatic actuator was designed [7,8]. 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 fabricated using a wire discharge machine. 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

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applied to the mover shown in Fig. 1. The voltages V_1 and V_2 are out of phase by π . In this actuator, the working range depends on the pitch of the beam. The working range is $500\mu\text{m}$ which is determined by the beam pitch. In order to reduce the frictional effect between the electrodes, lubrication oil is used without precise balls for easy fabrication and maintenance. Several silicone oils whose viscosity differs are used as the lubrication oil. Fig. 2 shows the overall view of the experimental setup. The setup includes a digital signal processing system as a controller, two high voltage power amplifiers and a capacitance displacement sensor. The sensor measuring range is $50\mu\text{m}$ and the evaluation range of the actuator characteristics is smaller than the sensor range. For force measurement, a load cell is used which is replaced by the capacitance displacement sensor. The dynamic model of the actuator can be expressed as Fig. 3. Its model parameters are shown in Table 1. This dynamic model is used for force estimation in Section 3.

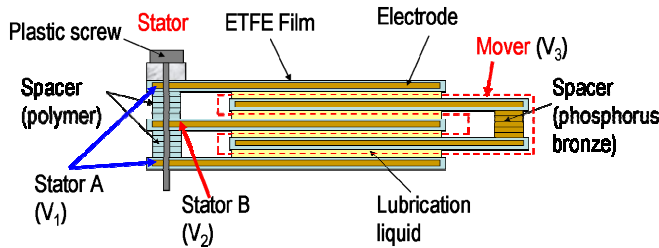


Fig. 1: Side view of the two-layer electrostatic actuator

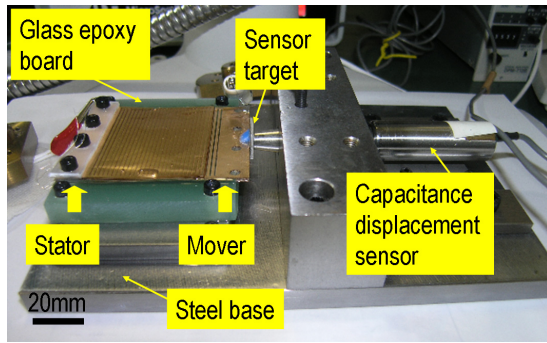


Fig. 2: Overall view of the experimental setup.

OPEN-LOOP 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 due to the attractive force. 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 to ensure the full working range motion [7,8].

In this paper, silicone oils are used as lubricant. Several silicone oils are used with different viscosity in this experimental actuator. The viscosity is considered to

influence lubrication characteristics of the actuator and then change the displacement and force characteristics.

High response is often important for fine stages and influenced by the oil viscosity. It is anticipated that a higher viscosity silicone oil has a higher ability to be maintained inside the gaps thus reducing the frictional effect. Also, it is expected that a lower viscosity silicone oil would be able to provide low damping characteristics in the traveling direction for high response.

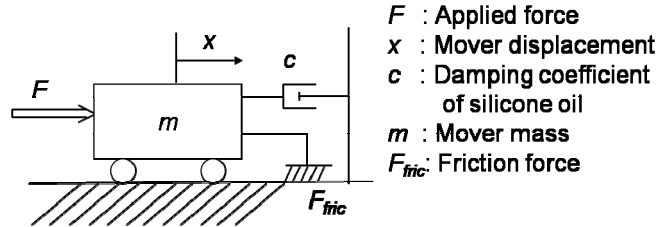


Fig. 3. Dynamic model.

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

A. DISPLACEMENT CHARACTERISTICS

Fig. 4 illustrates the influence of the silicone oil viscosity on the open-loop step responses as introduced in [7,8]. The dielectric constant of the 10mPa.s, 50mPa.s and 100mPa.s silicone oils is 2.65, 2.72 and 2.74 respectively. For each of the response, similar experiments were conducted 20 times. Each line represents the typical displacement response for each silicone oil when the actuator was applied with a 2kV voltage. In this paper, the response time refers to the $50\mu\text{m}$ displacement. When comparing the 10mPa.s, 50mPa.s and 100mPa.s silicone oils, the 10mPa.s exhibits the shortest response time, which shows that the low viscosity oil is better suited for higher response as shown in Fig. 4.

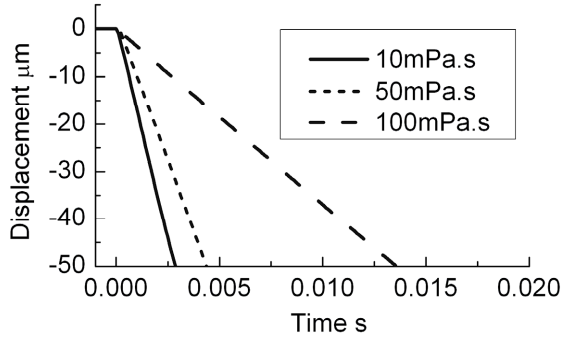


Fig. 4. Influence of silicone oil viscosity on the open-loop step response using a 2kV voltage.

B. FORCE CHARACTERISTICS

In comparison with the electrostatic actuators that are maintained by precise balls, the electrostatic actuator which is only maintained by lubrication oil is greatly influenced by the electrostatic attractive force. The attractive force will change the gap and the frictional effect which consequently influences the horizontal force characteristics of the actuator. In this subsection, the force characteristics of the experimental actuator were analyzed. This action was taken to clarify the effect of the oil viscosity on maintaining the gap between the electrodes and also on the horizontal force characteristics. The effect of the attractive force depends not only on the oil viscosity and but also the applied signal pattern to the electrodes. The change of the gap influences the frictional effect in the force response, although it was not possible to measure the gap directly.

Two different approaches were utilized to assess the force characteristics, that is the force estimation from the open-loop step displacement response (referred to as the estimated force), and the force measurement using a triangular input signal whose period is 1s (referred to as the quasi-static signal force) as discussed in [7,8]. Load cell was used for the force measurement using the quasi-static signal force. The dynamic model in Fig. 3 was utilized using Eq. (1), to determine the estimated force with the least square method. The minimum voltage which can move the mover is named V_{min} . The minimum voltages were measured by applying a stepwise input voltage to the experimental actuator.

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

where

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

The results in Fig. 5 show the relationship between the input voltage and the thrust force with the 10mPa.s and 50mPa.s silicone oil. Two force derivation approaches are

also shown in this figure. The average force values for each condition are signified by each symbol. Each symbol indicates the average of four experimental results. Each curve was calculated with the Eq.(1) and the least square method, where each of the curves are in agreement with the Eq.(1).

The results shown in Fig. 5 depict that the 10mPa.s silicone oil leads to the production of a much greater thrust force than the 50mPa.s silicone oil for both assessed approaches. On the other hand, even though the lubricant oil with a high viscosity was expected to lower the effect of friction, no specific reduction was observed. Thus, it is clarified that low viscosity oil is better suited for the electrostatic actuator.

Results in Fig. 5 also show that the estimated force is much higher than the quasi-static signal forces. In comparison with the measured force, the displacement of the actuator immediately after the voltage input was used for the estimated force. Thus, the estimated force is least influenced by the electrostatic attractive force which increases the frictional effect between the electrodes. The effect of friction is increased by the reduction in the gap attained by the attractive force between the electrodes. In conclusion, the estimated force is decided as the sensible thrust force independent of friction

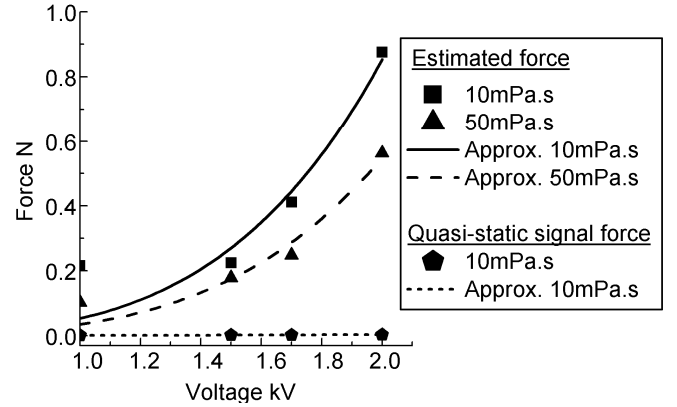


Fig. 5. Relationship between the input voltage and the thrust force.

C. DRIVING SIGNALS OF THE ACTUATOR

The results in Subsection B suggest that when the period of applying the voltages between the electrodes is elongated, it vastly decreases the thrust force, although it is the voltage that generates the thrust force. Therefore, it is necessary to determine the suitable signals to drive the actuator.

Fig. 6 show the actuator's displacement response to a periodic rectangular input signal, as introduced in [7,8]. The periodic rectangular input signal is one of the signals that have frequency lower than the control bandwidth. This figure also shows the voltages V_1 and V_2 which are applied to the Stator A and Stator B, and also voltage V_3 to the mover which is grounded as shown in Fig. 1. The voltages V_1 and V_2 are out of phase by π . This input signal is referred to as the normal signal in this paper. From Fig. 6, it can be seen that the initial displacement is relatively large. However, the amplitude of the displacement is reduced to roughly around

$2\mu\text{m}_{p-p}$. This result indicates that the input signal period is long enough to increase the friction force, which limits the working range of the actuator. This leads to the conclusion that the normal signal is not suitable for the actuator because it limits the working range. Therefore, a suitable signal which is applied in a short period need to be clarified which does not influence the working range of the actuator.

D. DRIVING SIGNAL FOR FULL WORKING RANGE

As described in Subsection C, the long period for applied voltage to the actuator greatly reduces the 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 in [7,8]. The time in the applied signal for the non-zero voltage is shorter than the normal signal for reducing the effect of the attractive force between the electrodes.

The impulse signal is used as the driving signal to ensure the full working range of the actuator. The sampling period of impulse signal is 1ms. 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. 6); however the displacement's amplitude is kept at approximately $20\mu\text{m}_{p-p}$. This signifies that the impulse signal does not influence the working range of the actuator and is useful for the full working range motion.

CONTROL PERFORMANCES

A. CONTROL SYSTEM STRUCTURE

In this section, the control performances of the electrostatic actuator are examined to show the usefulness of the actuator. Based on the PID controller, a control system was designed so that the system showed high precision positioning results. Fig. 8 shows the block diagram of the control system with the PID controller which includes a linearizer and a driving signal unit. The linearizer is used to cancel the nonlinear characteristics from the input voltage to the thrust force. The driving signal unit is added to translate the linearizer output into the impulse signal. The impulse signal whose duty cycle is (1/5) is used as the driving signal to ensure the full working range motion. The tuned PID controller parameters are $K_p=25$, $K_i=7.5$ and $K_d=15$.

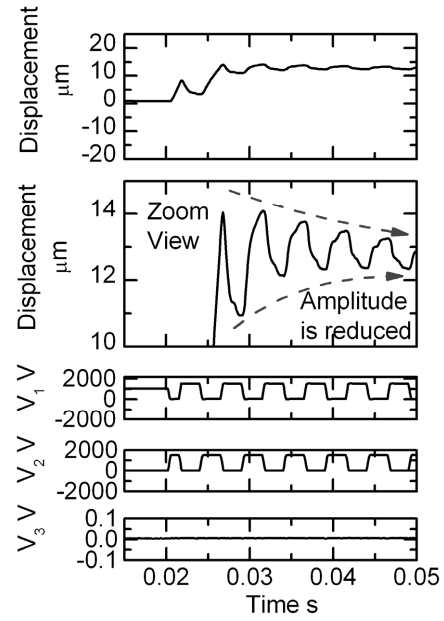


Fig. 6. Displacement response of the actuator to a periodic rectangular input signal using silicone oil with 10mPa.s viscosity.

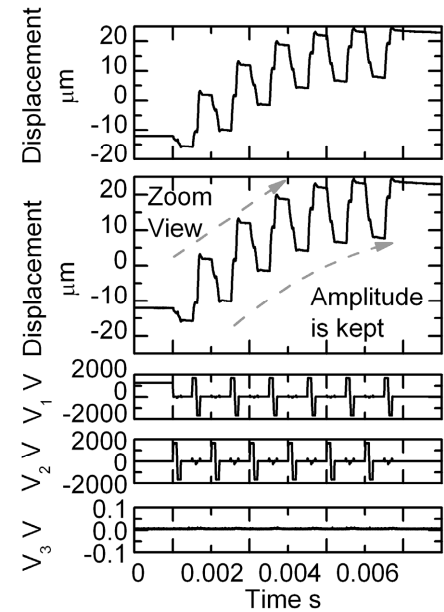


Fig. 7. Open-loop displacement characteristic with the impulse signal whose duty cycle (1/5) and the 10mPa.s silicone oil.

B. PERFORMANCE EVALUATION

Fig. 9 shows the positioning result using a $10\mu\text{m}$ step input with the impulse signal whose duty cycle is (1/5) and with a 0.5ms control period. It can be depicted that the impulse signal with the 0.5ms control period gave a maximum average positioning error which is better than 15nm. This error is smaller than the error in reference [8]. Additionally, the impulse signal with the 0.5ms control period exhibits a fast rise time less than 0.5ms compared to the results in reference [8].

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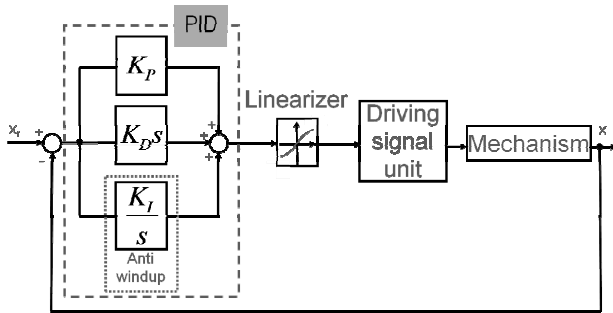


Fig. 8: Block diagram of the control system.

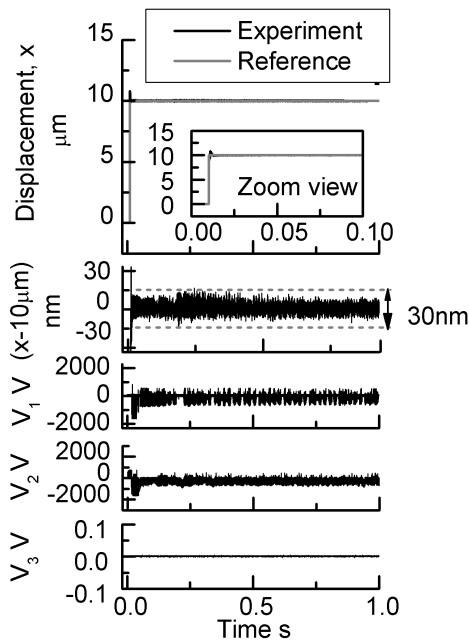


Fig. 9: Positioning result using $10\mu\text{m}$ step input under impulse signal with 0.5ms control period.

CONCLUSIONS

As a conclusion, this paper briefly provides an overview of the evaluation of a multilayer electrostatic actuator for a fine motion stage without precise balls for lubrication. To clarify the open-loop characteristics of the actuator, the actuator was examined in detail. The effects of the lubrication oil viscosity on the displacement and force characteristics were evaluated. Results of the open-loop characteristics show that low viscosity oil produces a much faster response and large thrust force. For the multilayer electrostatic actuator without precise balls, the suitable driving signals were clarified. The impulse signal was clarified as the suitable signal to ensure the full working range motion of the actuator supported by lubrication oil without precise balls. It has been verified that the impulse signal with the 0.5ms control period assisted in providing a positioning accuracy better than 15nm and with a short rise time less than 0.5ms .