

# The evaluation of a locking function for a vertical stage electrostatic actuator

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## Abstract

The present paper validates the effectiveness of the characteristic switching as a locking function for a vertical motion multilayer thin electrostatic actuator supported by only lubricating oil. In the electrostatic actuator, the friction forces often deteriorate the response and positioning accuracy of a control system, especially when the lightweight electrode layers are supported by only lubricating oil. However, the contact condition between the electrode layers can be changed by the attractive forces resulting from the driving signal waveforms, which consequently influences the frictional effect. The large frictional effect that is generated is useful as a locking function which is needed to precisely maintain the stage position especially in vertical motion stages. In this paper, suitable driving signal waveforms for switching between two frictional conditions (i.e., low friction for the wide and fast motion and high friction for the fine motion with a large holding force) are examined and clarified for the vertical motion stage. First, the working principles and experimental setup of the electrostatic actuator in the vertical motion stage are discussed. Then, the open-loop characteristics under the vertical motion stage are discussed based on the frictional effect. Lastly, the resultant effects of the driving signals on the vertical motion characteristics were evaluated, which concluded with the discussion in the signal selection on demand as the locking function.

**Keywords** : Multilayer electrostatic actuator, Lubricating oil, Locking function, Holding force and Vertical motion stage.

## 1. Introduction

In microscope systems, optical systems and semiconductor manufacturing systems (Hwang, et al., 2006); high response and high positioning accuracy are critical. In microscope systems, samples need to be finely positioned and precisely held in vertical stages for precision motion. In optical systems, mirrors and optical fibers must be aligned, tilted, and held with precision. Additionally, in micro electric discharge machining large thrust capability and high positioning and tracking accuracy is desired with use of a clamping mechanism with force magnifying structure as a locking function (Lin, et al., 2002). To satisfy this requirement, the stages often have mechanisms that generate the holding force. In (Lin, et al., 2002), a self-locking mechanism with a piezoelectric actuator produces the frictional effect needed to hold the object. In (Cueffli, et al., 2010), additional holding mechanisms have been implemented to maintain precise positioning. These holding mechanisms with the aid of holding signals enable the fine stages to hold and precisely position objects, and are beneficial especially in vertical motion stage. As a resolution, an electrostatic actuator supported by only lubricating oil has been proposed that has a locking function without any additional mechanism to a horizontal motion stage (Ghazaly and Sato, 2013). The mover has a simpler structure and is cost effective. The electrode layers of the actuator are lightweight enough to maintain the gap and reduce the frictional force between the layers without applying voltage. In the actuator, the motion characteristics depend on the driving signal since the frictional force is changed by the driving signal. The frictional force exhibited by the electrostatic actuator is used to continuously generate the holding force, which acts as a locking mechanism. The driving signal waveforms for

adjusting two types of frictional force have been proposed; i.e. (a) high friction force for the limited working range motion with a large holding force and (b) low friction force for full working motion. Therefore, in this paper, the usefulness of the electrostatic actuator supported by lubricating liquids with a locking function is demonstrated using a vertical motion stage.

In Section 2, the structure, working principles, and experimental setup of the electrostatic actuator in the vertical motion stage are described. In Section 3, the open-loop characteristics under the vertical motion stage are discussed based on the relationships between the driving signals, the working ranges and the frictional effect. Finally, the conclusions are presented in Section 4.

**2. The structure of the vertical motion stage**

The electrostatic actuator presented in this paper is a variable-capacitance motor type actuator that has two mover layers (Ghazaly and Sato, 2013). Fig. 1 shows a schematic diagram of the experimental two-layer electrostatic actuator. Only lubricating oil is used to reduce the friction between the electrode layers for easy fabrication and maintenance. Silicone oil with a viscosity of 10 mPa·s and a dielectric constant of 2.65 is used as the lubricating oil. Fig. 2 shows the front and side view structure of the experimental two-layer electrostatic actuator in the vertical motion for examining the locking function. The material used for the electrodes is phosphorus bronze. The electrodes are laminated with 30µm thickness low density polyethylene flat films as isolation films to reduce the friction between the electrode layers. This film is selected due to the high wettability of the film. The lubricating liquid is expected to easily be maintained between the electrode layers using high wettability film in the vertical setup. The mover mass is 5.43g. The nominal silicone oil thickness inserted in the gap is 0.123mm. To realize bidirectional 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. Stator B is set to be shifted by 500µm to Stator A. Under this condition, the initial condition of the mover is set to be shifted by 250µm to Stator A and Stator B in the z-direction. The working range is equal to the length between the beam centers of Stators A and B in the z-direction, i.e. 500 µm. Only lubricating oil is used to reduce the friction between the electrode layers for easy fabrication and maintenance. Silicone oil with a viscosity of 10 mPa·s and a dielectric constant of 2.65 is used as the lubricating oil.

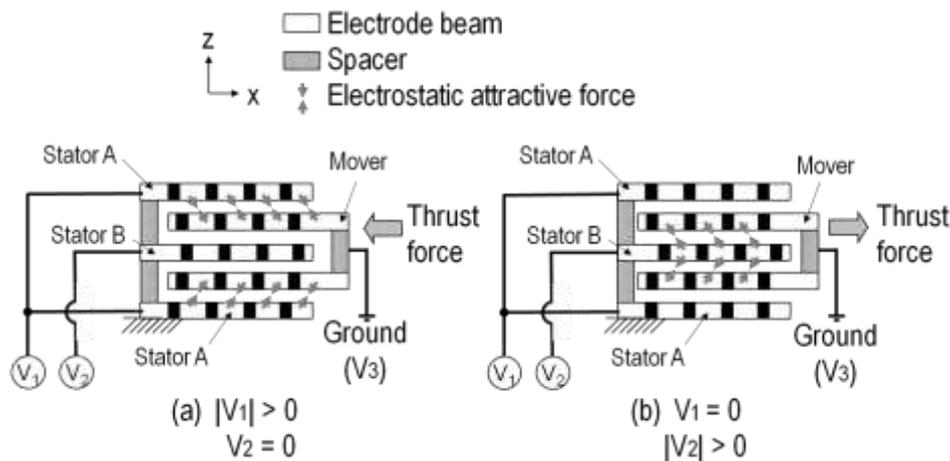


Fig. 1: Driving procedure for the bi-directional motion of the electrostatic actuator (Ghazaly and Sato, 2012).

In comparison to the horizontal setup (Ghazaly and Sato, 2013), the stator is aligned and screwed parallel to the z- axis and spacers are inserted between the stator electrode layers to maintain the gap at each side of the actuator. Extra film at each side of the laminated stator electrodes is used for fixing each side of the electrode layers of the stator to the base in order to prevent the thin electrodes from bending. Fig. 3 shows the displacement measurement setup of the experimental two-layer electrostatic actuator in the vertical motion for examining the motion characteristics. The stator is aligned and screwed parallel to the z- axis and spacers are inserted between the stator electrode layers to maintain the gap at each side of the actuator. The measurement range of the sensor is 50 µm, and the evaluation range of the actuator is less than 500 µm. Thus, in the present study, the full working range-of-motion characteristics are examined within a range of 40 µm. Wires are used to hold the mover position without any applied signal and to prevent the mover from descending due to gravity. Table 1 shows the specifications of the electrostatic actuator.

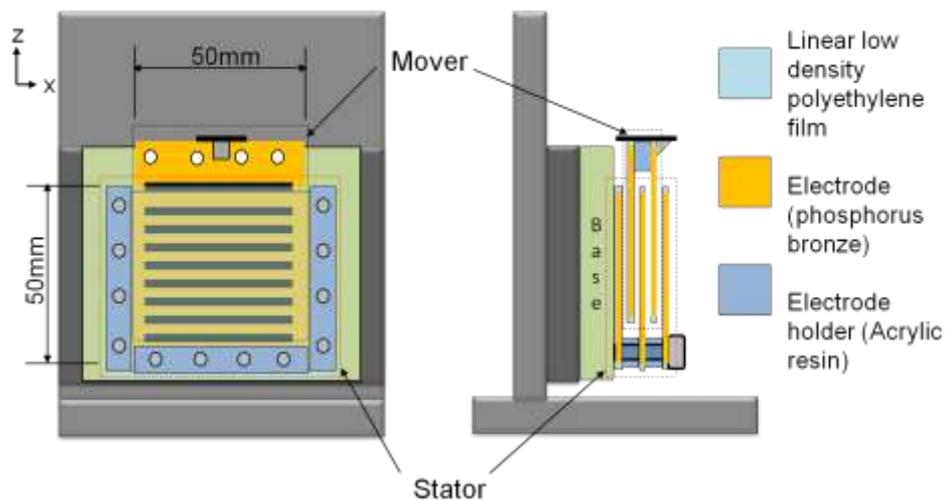


Fig. 2: Structure of the electrostatic actuator in the vertical motion stage

### 3. The locking function & the driving signal characteristics

In this section, the motion characteristics of the electrostatic actuator with the linear low density polyethylene film as the isolated film are discussed in detail in order to validate the suitable driving signal for the vertical motion stage. In the experimental actuator, the 10mPa.s silicone oil is used as the selected lubricating liquid with the dielectric constants of 2.65. The attractive forces resulting from the driving signal influence the contact condition between the electrode layers (i.e., the frictional effect), when the lightweight electrode layers are supported by only lubricating oil. When the driving signal is applied to the electrode layers, the applied voltage signal between the electrode layers provides the charge to the electrode layers and the attractive force between them. The attractive force reduces the gap between the electrode layers and causes the mechanical contact between them. This behavior increases the frictional force, which is useful as a locking function. Hence, a suitable driving signal has the potential to adjust the frictional effect for fine motion with a large holding force and a wide and fast motion.

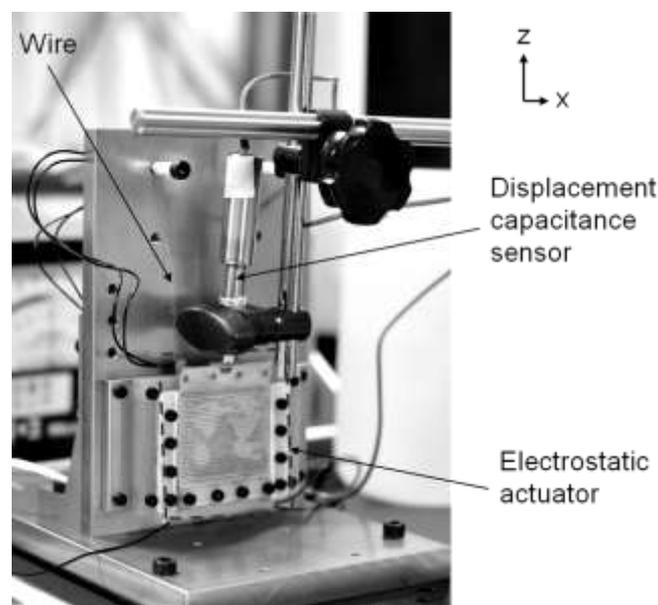


Fig. 3: Overall view of the displacement measurement setup for the vertical motion stage

Table 1: Specifications of the electrostatic actuator

Parameters	Value
Electrode width and length (mm)	50 × 50
Beam pitch (mm)	1.5
Spacer (mm)	50 × 6.5
Electrode thickness (mm)	0.1
Spacer thickness (mm)	0.4
ETFE film thickness (mm)	0.014
Electrode + ETFE film thickness (mm)	0.128
Thickness of assembled mover (mm)	0.656
Thickness of assembled stator (mm)	1.184
Gap between electrodes (mm)	0.244
Estimated silicon oil thickness (mm)	0.244
Mover mass (g)	5.22

In (Ghazaly and Sato, 2013), two driving modes has been proposed for the horizontal motion stage and the driving signal profiles for adjusting the frictional effect have been discussed; i.e. (a) fine driving mode using the fine driving mode signal for the fine motion with a large holding force and (b) wide driving mode using the wide driving mode signal for wide and fast motion. For adjusting the frictional effect for fine driving mode with a large holding force, the normal signal is useful, although the working range is limited. In this paper, the limited working range is referred to as the fine working range. In order to benefit from the large holding force, the normal signal with a continuous constant voltage (referred to as the holding signal) is applied to the actuator which is introduced in (Ghazaly and Sato, 2013). Fig. 4 shows the displacement characteristics using the fine driving mode signal under the vertical stage. Fig. 4 shows that the displacement is kept at  $1\mu\text{m}_{p-p}$  after the period of 4s.

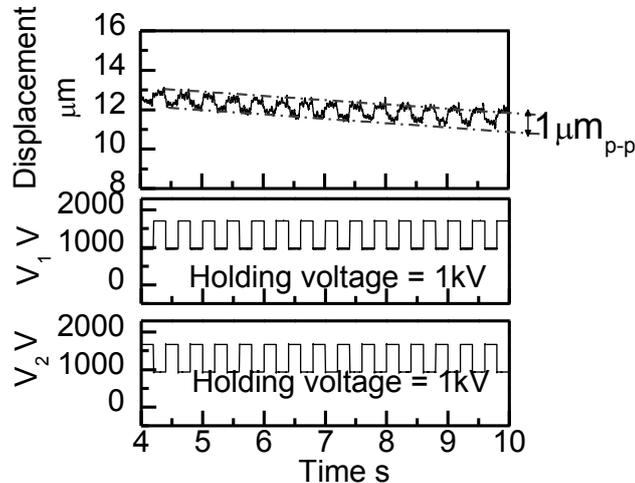


Fig. 4: Displacement characteristics using the fine driving mode signal under the vertical stage; motion characteristic is kept at  $1\mu\text{m}_{p-p}$ .

In order to avoid an increase in the frictional effect and also to ensure the full working range of the actuator, the negative impulse signal with a duty cycle of 1/5 has been proposed, as introduced in (Ghazaly and Sato, 2012). In this paper, the full working range is referred to as the wide working range. The negative impulse signal is used as the wide driving mode signal with a 1kV holding voltage to ensure the full working range of the actuator and enables additional locking function for the vertical motion stage. The motion characteristics using the negative impulse signal are examined and discussed in the vertical motion stage. Figs. 5 (a) and (b) shows the motion characteristics for the upward-unidirectional motion and downward-unidirectional motion using 1.8kV applied voltage with a 1kV holding voltage, respectively and Fig. 6 shows the reciprocating motion using applied voltage 1.5kV with a 1kV holding

voltage. It can be depicted that the upward is approximately  $20\mu\text{m}_{\text{p-p}}$  which is slightly larger than the downward motion  $18\mu\text{m}_{\text{p-p}}$ . This difference is considered to be caused by the effect of gravity. In the upward motion, the center of gravity of the mover is shifted upward, which result in a larger displacement. In addition, during the upward motion the wires holding the mover becomes contracted which indirectly helps to produce large displacement in compared with the downward motion. In the downward motion, the wires are extended and constrained by the stiffness of the wire, which limits the displacement range.

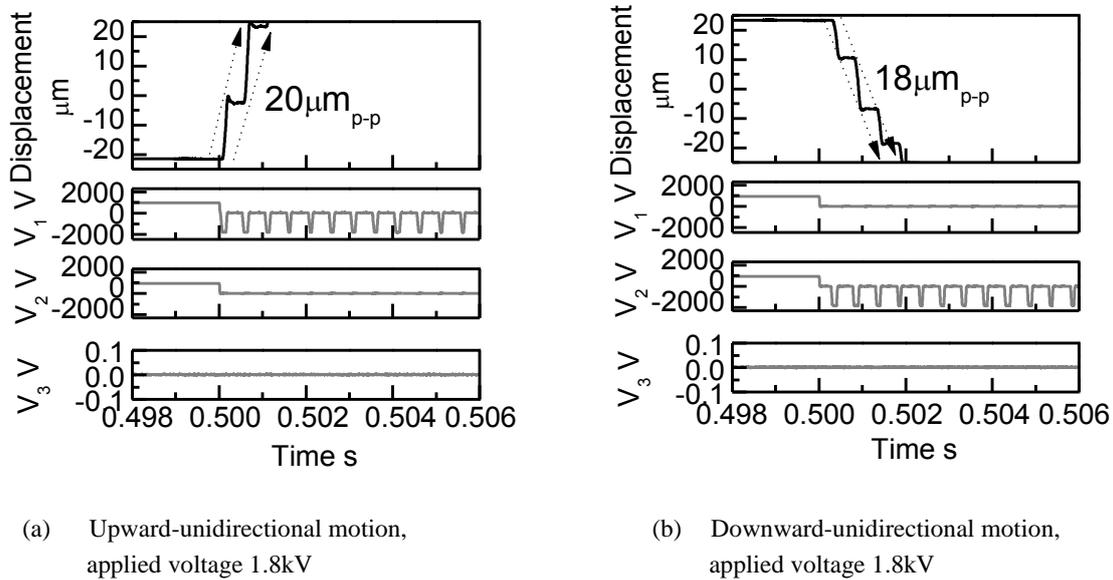


Fig. 5: Motion characteristics of the actuator in the vertical stage using negative impulse signal; control period,  $T_{cs}=0.5$  ms after applying the 1kV holding signal.

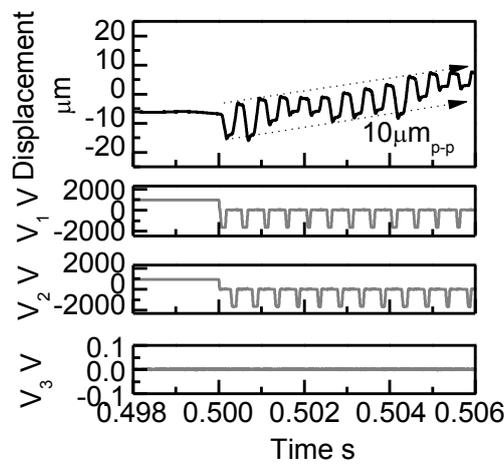


Fig. 6: The reciprocating motion characteristics of the actuator in the vertical stage using negative impulse signal with an applied voltage 1.5kV; control period,  $T_{cs}=0.5$  ms after applying the 1kV holding signal.

**4. Conclusions**

In summary, this paper focused on validating the effectiveness of two driving signals: i.e. (a) fine driving mode signal and (b) wide driving mode signal i.e the negative impulse signal with the 1kV holding signal to a vertical motion stage which enables a locking function for the vertical motion stage. In the vertical motion stage, the holding function is crucial for maintaining precise motion due to the influence of gravity. Both the driving signals are useful for the control of the precision positioning stage based on these characteristics; i.e. working range and frictional effect. As a result, the suitable driving signal has the potential to adjust the frictional effect for fine motion with a large holding force which acts as a holding function; and a wide and fast motion. The two driving modes; i.e., the fine driving mode

for fine motion with a continuous holding force and the wide driving mode with the 1kV holding voltage for the full working range of motion have been examined in detail. The open-loop experimental results show that the two driving modes can be derived and switched using suitable driving signals. As a conclusion, these prove the negative impulse signal with the 1kV holding voltage was useful to reduce the frictional effect due to the attractive force and to drive the actuator in the vertical motion under the wide working range.

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