ELECTROSTATIC SUSPENSION IN 3-DOF BY USING A VARIABLE CAPACITOR

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ABSTRACT
A control system of electrostatic actuators using by variable capacitors has been proposed as one method of avoiding the use of high-speed and high-voltage amplifiers. This control system is applied to electrostatic suspension in this paper. An experimental apparatus is fabricated for demonstrating the feasibility of electrostatic suspension. The experimental results show 3-DOF electrostatic suspension is achieved with the proposed control system using variable capacitors.

INTRODUCTION
Non-contact suspension can be achieved by using magnetic force or electrostatic force. Since electrostatic suspension can suspend more various objects than magnetic suspension, it can meet demands in many industrial fields such as semiconductor manufacturing. Electrostatic suspension systems for silicon wafer [1] and hard disk media [2] have been developed. Electrostatic force per unit area is, however, smaller than magnetic force so that high voltage must be applied to the electrodes for suspension. Such high voltage must be changed quickly for achieving stable non-contact suspension. Therefore, high-speed and high-voltage amplifiers have been used in previous works. It sometimes raises the cost. As one method of avoiding the use of such amplifiers, a control system using variable capacitors has been proposed [3]. This system can control the electrostatic force without high-voltage amplifiers.

This paper applies this control system to a manufactured electrostatic suspension system. Experimental results on 3-DOF control are shown to demonstrate the efficacy of the control system.

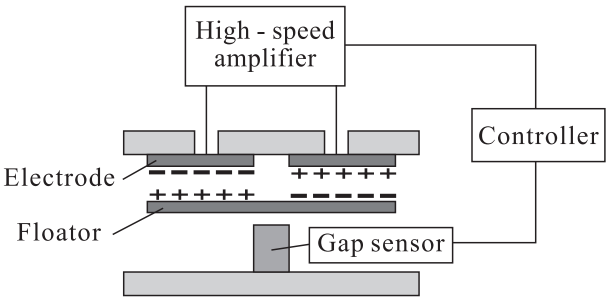


Figure 1: Basic concept of electrostatic suspension

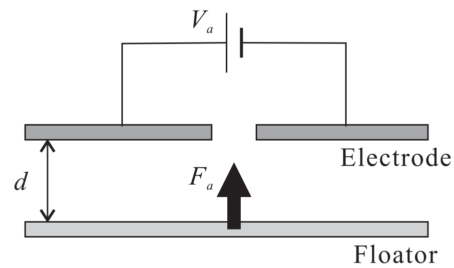


Figure 2: Electrostatic suspension

PRINCIPLES
Figure 1 shows a basic model of the electrostatic suspension in this system. The electrodes and the object to be suspended (commonly called floator) comprise a capacitor. The electrodes are electrified by applying voltage across the electrodes. When the floator is dielectric, the surface of floator is electrified due to electrostatic induction. Therefore, electrostatic

attraction is generated. The electrostatic force F_a is approximately given by

$$F_a = \varepsilon \frac{S}{8}\left(\frac{V_a}{d}\right)^2 , \qquad (1)$$

where ε : permittivity, S : area of electrode, d : gap between the floator and the electrodes (see Fig. 2). Equation (1) indicated that the force can be changed by voltage V_a.

Figure 3 shows an equivalent circuitry of proposed control system using a variable capacitor for electrostatic actuators [4]. The electrostatic actuator is treated as a capacitor C_a. A variable capacitor C_v is connected with this in series. A constant high voltage E is applied to this connection. The voltages across C_a and C_v are denoted by V_a and V_v, respectively. The voltage across the electrostatic actuator is given by

$$V_a = \frac{C_v}{C_v + C_a} E . \qquad (2)$$

Equation (2) shows that the voltage applied to the electrostatic actuator can be adjusted by changing the capacitance of the variable capacitor. In the case of electrostatic suspension, the capacitor consisting of the electrodes and the floator can be treated as the capacitor C_a. Substituting Eq (2) into Eq. (1) gives

$$F_a = \frac{\varepsilon S}{8d^2}\left(\frac{C_v}{C_v + C_a}\right)^2 E^2 . \qquad (3)$$

Equation (3) indicates that electrostatic force can be controlled by the variable capacitor.

VARIABLE CAPACITOR

There are various types of variable capacitors. They are classified according to

- Shape of electrode
- Motion of movable electrode
- Actuator for moving an electrode

In a parallel-plate capacitor, the capacitance is given by

$$C = \varepsilon \frac{S}{d} . \qquad (4)$$

The capacitance can be varied by changing the following three physical quantities.

(a) Gap d
(b) Area S
(c) Permittivity ε

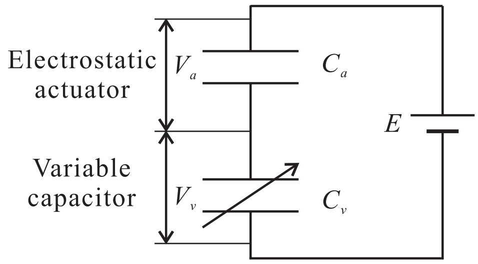
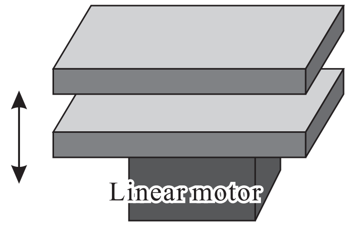
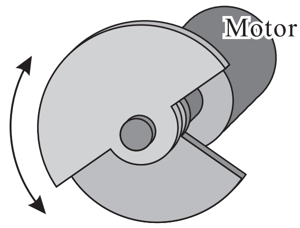


Figure 3: Equivalent circuit of the proposed system



(a) Variable gap.



(b) Variable area.

Figure 4: Examples of the variable capacitor

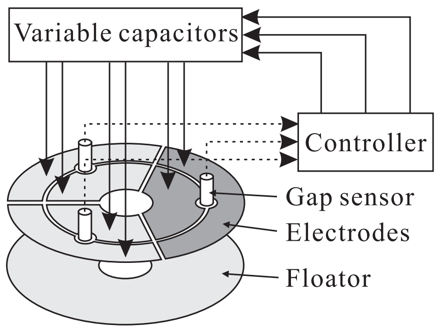


Figure 5: Schematic view of the experimental system

Figure 4 shows examples of the first two cases. In the example (a), it composed of two rectangular electrodes. One is fixed, and another one is movable in translation. A linear motor is used for changing gap between the electrodes. In the other example (b), electrodes are semicircular. A rotary motor is used for changing the area. In this work, the method (a) is adopted because of simplicity of structure.

EXPERIMENTAL APPARATUS

Figure 5 shows a schematic view of an experimental apparatus. This system can be divided into a suspension system and a voltage control system. The apparatus for suspension is mainly composed of electrodes, a floator, positioners for setting an initial position of the floator and sensors as shown by Fig. 6. Electrodes are divided into six parts as shown by Fig. 7. Each pair of electrodes (E_1, E_2) (E_3, E_4) and (E_5, E_6) operates as an electrostatic actuator. They are denoted by Act1, Act2, and Act3. To prevent short-circuits when the floator contacts with the actuator, an insulating tape is paste on this surface. This apparatus can control the three degrees of freedom of motions of the floator by using these three actuators. The vertical displacements of the floator are detected by three optical sensors mounted on the top. There are three holes for the beams of the optical sensors to pass through the electrodes.

Figure 8 shows a disk-like floator made of aluminum whose mass is 18 g. The external diameter is 95 mm, the internal diameter is 25 mm, and the area is 6600 mm^2. The thickness is 0.8 mm.

Figure 9 shows a fabricated variable capacitor. There are two circular electrodes. They are same shape as the floator. An insulating tape is pasted on the surface of the fixed side electrode. A voice coil motor (VCM) is used as an actuator for changing the gap between the electrodes. The gap is detected by a gap sensor mounted on the top. The fixed electrode can be made the horizontal with the adjustment screw.

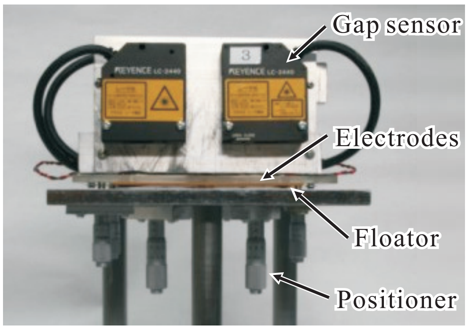


Figure 6: The experimental apparatus

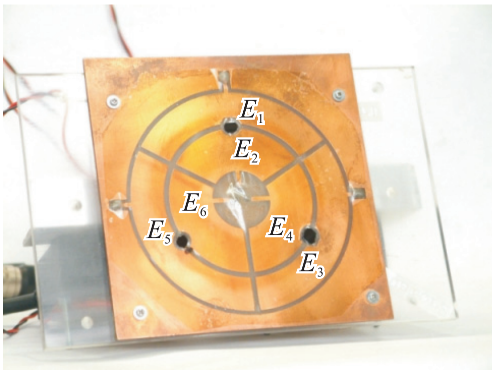


Figure 7: Electrodes of actuator

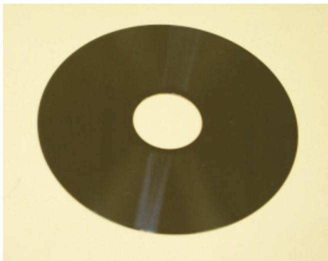


Figure 8: Photo of the floator

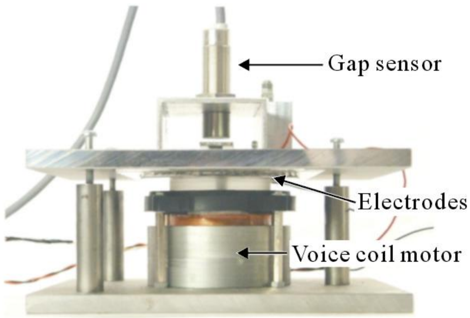


Figure 9: Fabricated variable capacitor

CHARACTERISTIC OF THE VARIABLE CAPACITOR

The controllability of the voltage control system depends much on the response of the variable capacitors. High-voltage must be changed quickly for achieving stable electrostatic suspension. Figure 10 shows a frequency response of the variable capacitor in the open loop. It has a peek at 60 Hz. The other two variable capacitors have similar characteristics. Because no time delay is expected between the variable capacitors and the control voltage, the electrostatic suspension can be achieved with the variable capacitors.

ELECTROSTATIC SUSPENSION

First, one of the three actuators is controlled by the proposed control method, and the others are controlled by high-voltage amplifiers. Figure 11 shows the step response of the floator and variable capacitor. It is confirmed that the position of the floator can be adjusted, and the response is well damped.

Next, all the three actuators are controlled by the proposed method. The voltage applied to each actuator is varied by using the variable capacitor. Figure 12 shows the displacements of the floator. At start, the floator was on the positioners, and target position is set to 0.15 mm from the surface of the insulating tape. The applied DC voltage is approximately 2 kV, and the voltage is applied at t=0. The displacements of the floator change from 0.25 mm to 0.15 mm. It is confirmed that the floator can follow the command signal and the transient response is well damped. These results demonstrate the realization of electrostatic suspension by using a variable capacitor.

To improve the controllability, the gap between electrodes of the variable capacitor is detected, and fed back. Figure 13 shows a frequency response of the variable capacitor with this loop. Comparing Fig. 13 with Fig. 10, we find that the response of the variable capacitor is improved. Figure 14 shows the displacement of the floator and the gap of the variable capacitor. It demonstrates that the position of the floator can be adjusted more quickly.

SUMMARY

This paper described the principle of electrostatic actuator control system using a variable capacitor and reported the results of the experiment of electrostatic suspension controlled by proposed method. The experimental results showed the realization of non-contact electrostatic suspension with 3-axis control.

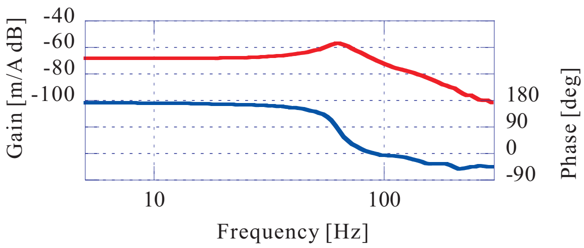
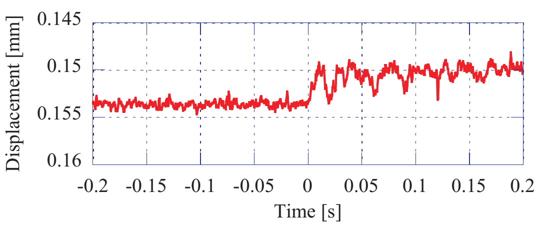
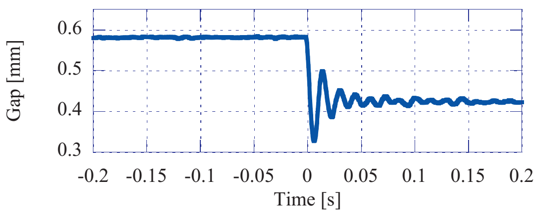


Figure 10: Frequency response of the variable capacitor



(a) Floator.



(b) Variable capacitor.

Figure 11: Step response

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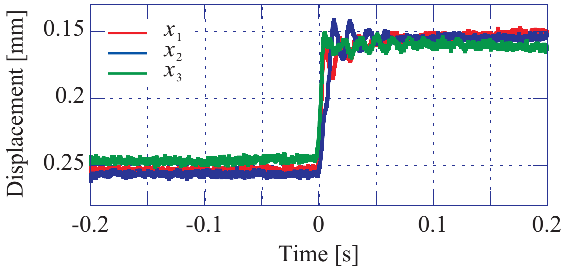

Figure 12: Displacement of the floator; x_k is displacement in Act k (k = 1,2,3)

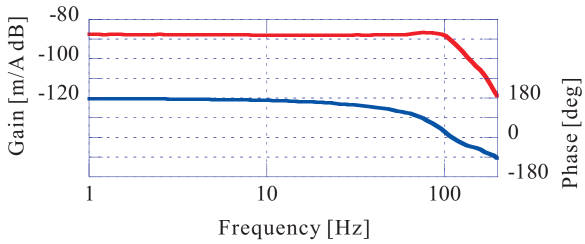

Figure 13: Frequency response of the variable capacitor

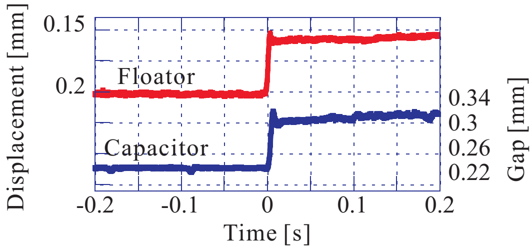

Figure 14: Displacement of the floator when the controller has the local loop