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ELECTROSTATIC SUSPENSION OF GLASS PLATE

°Jong Up Jeon*, Shao Jü Woo*, and Toshiro Higuchi*,**

*Kanagawa Academy of Science and Technology, East Block 405, KSP, 3-2-1 Sakado, Takatsu-ku, Kawasaki 213, JAPAN
Tel: +81-44-819-2093; Fax: +81-44-819-2095; E-mail: jeon%naeba@intellect.pe.u-tokyo.ac.jp

**Dept. of Precision Machinery Eng., The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113, JAPAN
Tel:+81-3-3812-2111 ext. 6449; Fax:+81-3-5800-6968; E-mail: higuchi@intellect.pe.u-tokyo.ac.jp

Abstract This paper reports about the successful suspension of a glass plate by electrostatic forces. In order to implement a stable suspension, the electrostatic forces exerted on the glass plate are actively controlled on the basis of the gap lengths between the glass plate and the stator electrodes. In this paper, the dynamic model of the suspension system and the influence of the resistivity of glass on the system stability are described, followed by stator electrode design, the experimental apparatus and a stabilizing controller. Experimental results show that the glass plate can be suspended at a gap length of about 0.3 mm. The influence of air humidity on the suspension initiation time, and the lateral dynamic characteristic are also described.

Keywords Electrostatic Force, Electrostatic Suspension, Glass Plate Suspension

1. INTRODUCTION

In thin glass plate related industries, particularly in the manufacture of liquid crystal display (LCD) devices, glass plates are mainly being handled through direct mechanical contact. However, for specific types of glass plates, there is a trend that the surfacial area/thickness ratio is becoming larger and consequently the manipulation by physical contact causes deformation of them. In addition, physical contact with the glass panel in LCD devices leads to surface contamination and particle generation restricting the product quality. Thus, there is a strong necessity to develop contactless handling systems for glass plates. Electromagnetic forces can not be utilized to directly support a glass plate since glass is not a ferromagnetic material. Electrostatic suspension provides us with a solution to solve the problems mentioned above.

Electrostatic suspension has already been utilized to implement a contactless support of a 4-inch silicon wafer [1]. It has also been employed in electric vacuum gyros [2] and to support a rotor in microbearings [3]. In these applications, the suspended object consisted of conductive materials or semiconductors. Electrostatic suspension of objects made of dielectric materials such as glass has not been reported yet.

This paper proposes a support device for the contactless suspension of glass plates by electrostatic forces. By using electrostatic forces to support the glass plate, the deformation of the glass plate can be prevented since the electrostatic forces are exerted uniformly on its entire surface.

Glass can be regarded as a highly resistive material. In this paper, the influence of the resistivity on the system stability will be analyzed. The resistivity of glass is strongly dependent on the environmental humidity so that the suspension system characteristics, such as the suspension initiation time, system stability and lateral dynamics, are influenced by it. Here, the suspension initiation time is defined as the time needed for the glass plate to start to being lifted upwards after applying the control voltages to the stator electrodes. The influence of the air humidity on the suspension initiation time has also been investigated experimentally.

2. DYNAMIC MODEL AND STABILITY ANALYSIS

The dynamic model and stabilizing method of the electrostatic suspension system, where the suspended object is made of conductive or semi-conductive materials, have already been analyzed [1]. In this paper, for objects made of highly resistive materials, the influence of the resistance on the system stability will be analytically investigated. Fig. 1 shows a one degree of freedom model that will

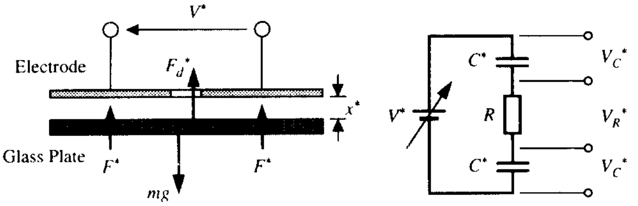

Fig. 1. Model of electrostatic suspension system with one degree of freedom and its equivalent circuit.

be used for the subsequent analysis. It is assumed that the energy of the electric field is concentrated in the airgap between the stator electrodes and the glass plate. Glass can be treated as a highly resistive material so that the glass plate can be replaced by a resistor in an equivalent electric circuit. With the assumption stated above, the electrostatic force F^* can be expressed in terms of the gap length x^* and the potential difference V_C^* between the electrodes and the glass plate:

$$F^* = \frac{1}{2}\varepsilon A\left(\frac{V_C^*}{x^*}\right)^2 \tag{1}$$

where ε and A denote the permittivity and the area of each electrode, respectively. Eqn. (1) shows that the force F^* is inversely proportional to the square of the gap length x^*. This implies that the motion of the glass plate will exhibit an unstable behavior without any active control of the force F^*.

Any vertical motion of the glass plate experiences air friction as the air between the stator and the glass plate gets pushed out or sucked in. Since the gap length is significantly smaller than the area of the glass plate, the air in the gap can be modeled as a squeeze film when the glass plate moves vertically. Assuming that the compressibility of air can be neglected and considering an one-dimensional case, the damping force F_d can be approximately expressed as

$$F_d = \frac{\eta B L^3}{x^{*3}}\dot{x}^* \tag{2}$$

where η is the viscosity of air, B and L are the width and the length of the glass plate, respectively.

With the forces F^* and F_d derived above, the dynamic equation of motion of the glass plate is described as follows:

$$m\ddot{x}^* = -2F^* - F_d + mg \quad (3)$$

Referring to the equivalent circuit in Fig. 1, the voltage equation is given by

$$V^* = 2V_C^* + R\frac{d}{dt}(C^* V_C^*) \quad (4)$$

where V^* is the electrode voltage, C^* is the capacitance between the electrode and the glass plate which is defined as $C^*=\varepsilon A/x^*$, and R is the resistance of the glass plate.

A linearization technique is applied to eqns. (3) and (4) to obtain a linearized equation of motion. Let F_0, V_0, V_{C0}, C_0, x_0 be the values at the equilibrium state and F, V, V_C, C, x be the linearized values. Then the variables F, V, V_C, C, x are defined by $F^*=F_0+F$, $V^*=V_0+V$, $V_C^*=V_{C0}+V_C$, $C^*=C_0+C$, $x^*=x_0+x$. Linearization of the eqns. (1), (2), (3) and (4), yield the following relations at the equilibrium state:

$$F_0 = \frac{mg}{2}, \quad V_0 = 2V_{C0} \quad (5)$$

where $F_0=(C_0/2)(V_{C0}^2/x_0)$ and $C_0=\varepsilon A/x_0$. The bias voltage V_0 can be obtained from eqn. (5).

Next, the linearized equation of motion is given by

$$\begin{aligned} m\ddot{x} &= 2k_s x - 2k_V V_C - b\dot{x} \\ RC_0\dot{V}_C + 2V_C &= (RC_0 V_{C0}/x_0)\dot{x} + V \end{aligned} \quad (6)$$

where k_s, k_V are the linearization constants and b is the damping constant which are given by

$$k_s = C_0(V_{C0}/x_0)^2, \quad k_V = C_0(V_{C0}/x_0), \quad b = \eta BL^3/x_0^3 \quad (7)$$

Using the Laplace transform of eqn. (6), the open-loop transfer function of the system is obtained as follows:

$$\frac{X(s)}{V(s)} = \frac{-2k_V}{[mRC_0 s^3 + (2m + RC_0 b)s^2 + 2bs - 4k_s]} \quad (8)$$

Clearly, this system possesses an unstable open-loop dynamic characteristics. To stabilize it, a PID feedback control law is utilized:

$$V(s) = (K_P + K_D s + K_I/s)X(s) \quad (9)$$

where K_P, K_D and K_I are the proportional, derivative and integral gains, respectively. Upon substituting eqn. (9) into (8), the characteristic equation of the closed-loop system can be obtained:

$$mRC_0 s^4 + (2m+RC_0 b)s^3 + 2(b+k_V K_D)s^2 + 2(k_V K_P - 2k_s)s + 2k_V K_I = 0 \quad (10)$$

The effect of the resistance of glass on the system's stability can be investigated by applying Routh's stability criterion to the characteristic equation. For the case that only PD feedback control is considered, the stability conditions for the PD gains can be derived as follows:

$$K_P > \frac{2V_{C0}}{x_0}, \quad K_D > \frac{mRC_0(K_P - 2V_{C0}/x_0)}{2m + bRC_0} - \frac{b}{k_V} \quad (11)$$

It can be observed that the P gains which assure system stability are independent from the resistance R while the D gain has to be increased as the resistance R increases. Despite the high resistivity of glass, the D gains can be set to low values, or even to zero depending on the P gains. The reason for this lies in the fact that the damping force due to the squeeze film, which possesses the same function as the D gains, has the same order of magnitude as the mass of the glass plate and is relatively high. As a numerical example, consider m=17.6 g, B=L=100 mm, x_0=0.3 mm and $K_p=\alpha(2V_{C0}/x_0)$, where α=2~100. Then the minimum D gain to stabilize the system is calculated as $(K_D)_{min} \approx -10^5$. This implies that the system can be stabilized without D control independent from the resistivity of the suspended object. Without any squeeze film damping, the necessary D gain required to stabilize the system can be computed as

$$K_D > (10^{-4} \sim 10^{-2})R \quad (12)$$

Eqn. (12) shows that the stabilizing D gain is proportional to the resistivity of the suspended object. Practically a limit exists to increase the D gain implying a limit for the resistivity of the object to be suspended.

3. EXPERIMENTAL SYSTEM

3.1 Stator Electrode Design

In the following, the structure of the stator electrode to fully suspend a glass plate in six degrees of freedom will be described. Through preliminary studies, it was found that it is advantageous for the characteristics of the suspension system to form many boundaries between electrodes having different potentials. Fig. 2 depicts

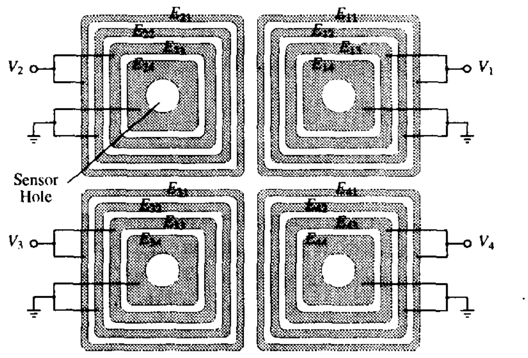

Fig. 2. Stator electrode pattern.

the design of the stator electrode pattern based on this fact. The stator electrodes are divided into four sections, each of which acts as an independent actuator of force. Each section i consists of four electrodes which are denoted as E_{ij}, where i, j=1~4. All the electrodes have the same area and are connected as shown in Fig. 2. The electrodes E_{i2} and E_{i4} are grounded while the electrodes E_{i1} and E_{i3} are supplied with the actively controlled voltages V_i. To measure the gap lengths between the electrodes and the glass plate, four fiber optical sensors are mounted at the geometrical centers of the most inner electrodes E_{i4}.

3.2 Experimental Apparatus

The schematic diagram of the experimental apparatus that was developed for suspending a glass plate is shown in Fig. 3. The sta-

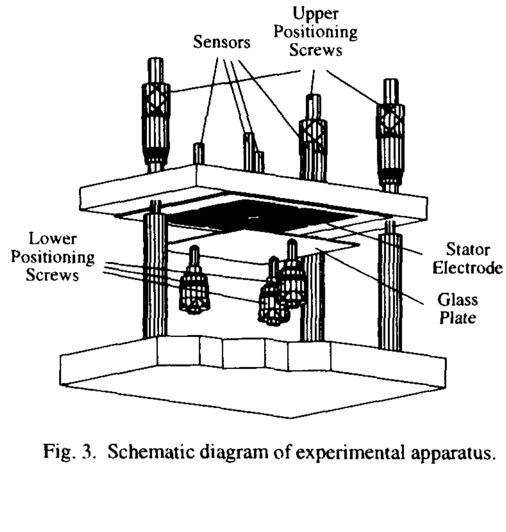

Fig. 3. Schematic diagram of experimental apparatus.

tor electrodes are etched from a 35 μm thick copper layer on a glass-epoxy base. The four sections of the stator electrode together form a square-shaped pattern of which the length of each side is 100 mm. The area of each individual electrode is 3.6 cm^2. Fig. 4 depicts a

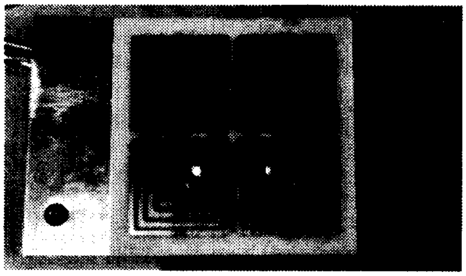

Fig. 4. Photograph of stator electrode.

photograph of the stator. The suspended object is a polished soda-lime glass plate measuring 100 mm×100 mm and has a 0.7 mm thickness and 17.6 g mass. The volume resistivity of this glass plate is approximately 10^{13} Ω·cm. The surface resistivity is strongly dependent on the air humidity and varied from 10^{12} Ω to 10^{16} Ω as the air humidity varied from 70 %RH to 30 %RH. By adjusting the heights of upper and lower micropositioning screws, the stator electrode is leveled and the initial gap length is set.

3.3 Stabilizing Controller

To stabilize the movement of the glass plate, we need to control its movement in six degrees of freedom. Among them, the movements in horizontal plane and the rotational motion are passively stabilized through a restriction force [4]. The remaining vertical, pitching and rolling motions are actively controlled as follows.

Fig. 5 shows the block diagram of the control system. The gap lengths between the stator electrodes and the glass plate are measured using the displacement sensors. Subsequently, the error signals in vertical, pitching and rolling movements are computed from the measured gap lengths and the desired position/attitude signals. The error signals are then fed back to a PID compensator and control voltages in each degree of freedom are generated. These control voltages are then transformed to the stator electrode control voltages by a pre-compensator. After being added to the four bias voltages, the electrode control voltages are sent to the limiter and amplified by the high voltage amplifiers which have a amplification ratio of 1000. These amplified voltages are supplied to the four stator electrodes to stabilize the motion of the glass plate. Note that a limitation is imposed on the voltages to prevent electric discharge which is caused by the breakdown of the electric field.

4. EXPERIMENTS AND DISCUSSION

Suspension experiments have been performed with a polished soda-lime glass plate. The proportional, derivative and integral gains for the vertical movement of the glass plate were respectively 1.5×10^5 kV/m, 120 kV·s/m and 5×10^5 kV/(m·s), and those for pitching and rolling were 40 kV/rad, 0.025 kV·s/rad and 5×10^2 kV/(rad·s), respectively. A bias voltage of 1.56 kV and a limit voltage 3 kV was utilized. The initial and reference gap length were set at 350 μm and 300 μm, respectively.

Fig. 6 shows the recorded gap length and voltage variations after

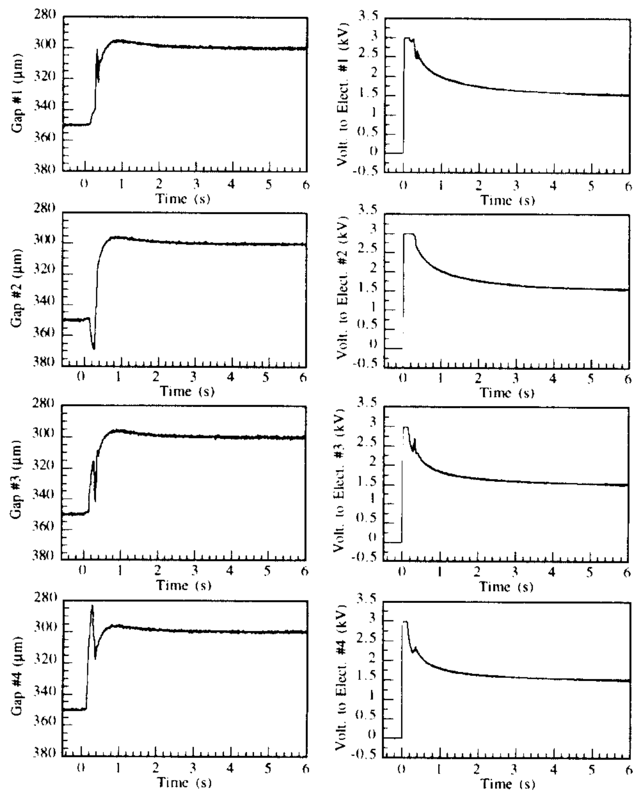

Fig. 6. Gap and voltage variations during suspension process.

the PID compensator was switched on. It shows that a period of time of approximately 0.3 seconds was needed for the glass plate to reach a state of suspension. Note that since glass is a material having a high resistivity, a certain period of time is needed to accumulate sufficient induced charges on the glass surface facing the electrodes in order to pick up the glass plate. This period of time is strongly dependent on the air humidity since the surface resistance of the glass plate is strongly influenced by the air humidity. The data shown in Fig. 6 was recorded under an air humidity of 50 %RH.

Fig. 6 also shows that during the state of stable suspension, the actively controlled voltages are slowly decreasing. A physical explanation for this drift phenomenon is that the charge built-up on the glass surface had not yet reached a steady state and indicates that the process of charge accumulation was progressing continuously during suspension. The voltages after 9 seconds from the control start were respectively 1.49 kV, 1.51 kV, 1.49 kV, and 1.46 kV. Fig. 7 is a photograph of the glass plate under stable suspension.

To explore the influence of air humidity, the suspension initia-

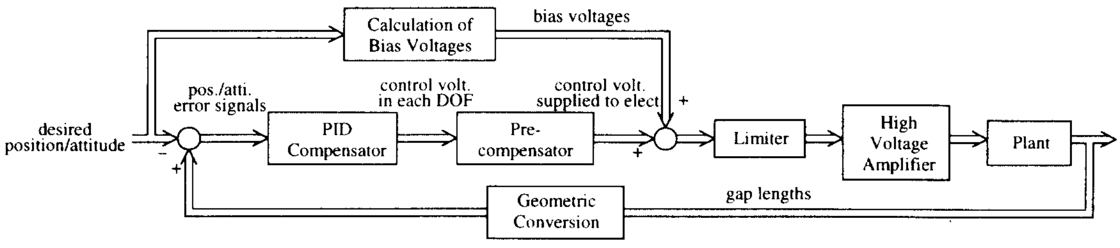

Fig. 5. Block diagram of control system.

Fig. 7. Photograph showing glass plate under suspension.

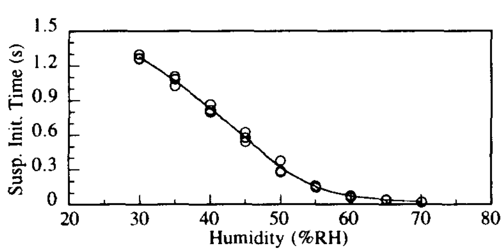

Fig. 8. Humidity influence on suspension initiation time for soda-lime glass.

tion time was measured as a function of the air humidity. Fig. 8 shows the measured experimental data. These data reveal that the suspension initiation time varied from 1.3 seconds to 0.02 seconds for an air humidity variation from 30 %RH to 70 %RH..

Additional suspension experiments were carried out using polished quartz glass plates which have a higher resistance than that of soda-lime glass plates. The quartz glass plates also have been suspended successfully at a gap length of 300 μm. However, the suspension initiation time of the quartz glass plate was longer than that of the soda-lime glass plate due to its higher resistance. Fig. 9 shows

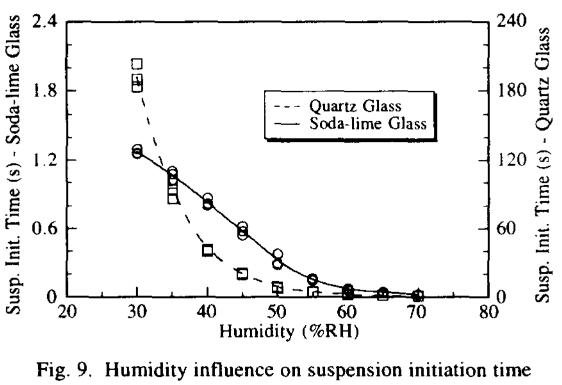

Fig. 9. Humidity influence on suspension initiation time for soda-lime and quartz glass.

the recorded suspension initiation time for the quartz glass plate for an air humidity variation from 30 %RH to 70 %RH. For comparison, the suspension initiation time for the soda-lime glass is also shown. The experimental data show that the suspension initiation time of the quartz glass plate varied from 3 minutes to 0.8 seconds for an air humidity variation from 30 %RH to 70 %RH.

The dynamic characteristics of the non-actively controlled lateral motions were investigated by using the impulse response method [5]. Fig. 10 shows the lateral translation of the soda-lime glass plate after an impulse was imposed on it. It is assumed that for small amplitudes of lateral translation, the lateral restriction force can be approximated as a linear function of the lateral translation. As a consequence, the estimation algorithm for linear systems can be

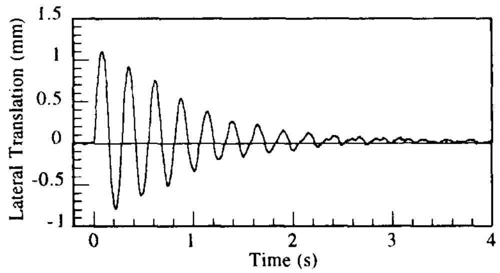

Fig. 10. Impulse response.

applied which gives an estimated stiffness of approximately 0.86 gf/mm. This value is almost 20 times bigger than the case of the suspended objects made of conductive or semi-conductive materials such as silicon wafers. It is known that for conductive materials, the lateral restorative forces are generated due to the edge effect. However, in case of objects made of highly resistive or dielectric materials like glass, it was observed that these edge effects are small and the lateral restriction forces are mainly generated in the vicinity of the boundaries of the electrodes having a potential difference. This indicates the dependence of the lateral dynamic characteristics on the environmental humidity. The data shown in Fig. 10 was recorded under an air humidity of 43 %RH. From our experiments, it was found that the lateral stiffness became higher as the air humidity decreased. Moreover, the lateral motion of the glass plate reveals a hysteretic-like characteristic so that in the event of an lateral disturbance, the glass plate does not return back to its original position even after removing the disturbance. As evidenced from Fig. 10, a steady state error can be observed.

5. CONCLUSIONS

A contactless glass plate suspension system based on electrostatic forces is proposed in this paper. By actively controlling the electrostatic forces acting on it, a polished glass plate has been suspended successfully at a gap length of about 0.3 mm. The dynamic response of the non-actively controlled lateral motion has been experimentally investigated using the impulse response method. The influence of the resistance of the glass plate on the system stability was analyzed based on the fact that glass can be regarded as a slightly conductive material. The air humidity has a strong influence on the resistivity of the glass plate and hence on the suspension system characteristics such as suspension initiation time, system stability, and dynamic behavior. We have experimentally explored the influence of the air humidity on the suspension initiation time for two types of glass; polished soda-lime glass and polished quartz glass.

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