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Design and Control of the Electrostatic Suspension System for Flexible Objects

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Abstracts **Electrostatic suspension is a method to levitate an object by using electrostatic forces. Its main advantage is to levitate objects without any mechanical contact which fulfills the requirement of an object handling in ultra clean environment. In this paper, the electrostatic suspension system for film-like thin plate ,such as aluminum sheet, is designed and controlled. In contrast with the conventional electrostatic suspension system which requires the costly and bulky high-voltage amplifiers, it is suggested to use the switching voltage control method in consideration of real industrial application for the handling of such flexible bodies. Some experimental results show that the developed electrostatic suspension system shows good performances to levitate flexible film-like thin plate.**

Keywords **Electrostatic suspension, Electrostatic forces, Ultra clean environment, Flexible body suspension**

1. Introduction

In the latest developments of the technology, with requests for ultra-precision, ultra-accuracy, and ultra-integration, the necessity of manufacturing in ultra clean environment is becoming influential.[1] Especially, in semiconductor industry and LCD production process, the transportation of silicon wafer or glass plate for liquid crystal display panel is needed in this clean environment, and the development of non-contact transportation system has been proposed as a countermeasure.[2]

As an example of the non-contact transportation, the system with electro-magnetic levitation can be also considered. However, the transported objects should be loaded on the levitated carriage, which makes the object have minimum contacts with the carriage. And the limitation to levitate only ferro-magnetic material arises in this conventional magnetic levitation system.

The electrostatic suspension system described in this paper is the levitation system using the electrostatic attractive force and having the advantage to levitate bodies without any mechanical contact, and also having the advantage to levitate nonferromagnetic material directly. Previous research results show the examples of levitating system for wafer of semiconductor industry [3][4], flat glass of LCD [5] and aluminum disk for HDD[6] using the principle of electrostatic suspension.

However, in the existing electrostatic suspension system, thin plate-shape rigid bodies were mainly used as the object to be suspend. Namely, the levitating bodies in previous works could be treated as rigid bodies.

Differently, in this paper, we present the electrostatic suspension system for flexible thin plate-shape objects such as film and metal sheet.

The flexible film-like objects can be levitated by controlling with much more d.o.f. according to flexibility of levitating objects.

This system is designed and investigated for an aluminum sheet with 100μm thickness.

For control of the electrostatic suspension system, PID(Proportional-Integral-Derivative) based feedback control is the most commonly used conventional method. Additionally, other different control methods have been used as well. However, due to the characteristic of the control method, a certain number of high-voltage amplifiers which are expensive and bulky system components are needed in the conventionally controlled system. Considering the characteristic of the system, in case of the electrostatic suspension system for the flexible thin film-like levitating bodies which can be modeled by multi-d.o.f., the large number of high-voltage amplifiers would be needed and the numbers of the high-voltage amplifiers is proportional to the numbers of electrodes in conventional control method. Practically, it makes the embodiment of industrial application of electrostatic levitating system be non-realistic.

Therefore, we use the switched-voltage control method for control of electrostatic suspension system in this paper.[7] The high-voltage amplifiers are not needed any more and only high-voltage power supplies are utilized. Therefore, the system can be designed very simple, and the cost-effective electrostatic levitation system can be constructed.

In this paper, we investigated the design and control of the electrostatic suspension system for the flexible film-like objects using the switched voltage control method.

2. Principle of the electrostatic suspension system for flexible objects

The electrostatic suspension system is to support the object contactless using electrostatic forces.

The electrostatic attractive force acts between two charged bodies having different polarities. Therefore, we can design a system of the basic 1-degree of freedom as shown in Fig.1 which can form the electrostatic attractive force.

As shown in Fig.1, the electrostatic suspension system has two charged electrodes of positive(+V) and negative(-V) polarity respectively. Under the electrodes, there exists a flexible thin plate-shape levitating object which possesses positive or negative polarity according to the polarity of its adjacent electrode. However, if the electrodes are designed to have the same surface area, the electric potential of the levitating object is zero.

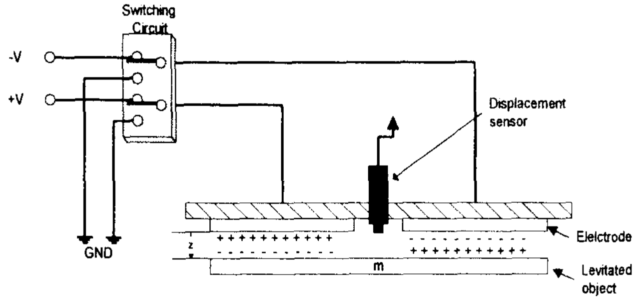

Fig. 1 Principle of the electrostatic suspension system

In this suspension system, the position of the levitating bodies are sensed by a displacement sensor located as shown in Fig.1 and the electrodes repeat 'charge-discharge' by on-off action of the switching circuit according to the sensor signal. This electrostatic suspension system can be expressed by simple mathematical model as follows.

$$m\frac{\partial^2 z}{\partial t^2} = mg - 2F^* + F_d - F_s(x,y,t) \qquad (1)$$

where, F^* is the electrostatic force, F_d is the external disturbance force , and $F_s(x,y,t)$ is the squeeze air damping force caused by the existence of small air gap between the electrode and the levitating object. F^* and $F_s(x,y,t)$ can be expressed as follows,

$$F^* = \frac{1}{2}\varepsilon A\left(\frac{V}{z}\right)^2 \qquad (2)$$

where, $\varepsilon = 8.85971 \times 10^{-12}$[farad/m]

A : Surface area of whole electrode

V : Electrode applied voltage

z : air gap

$$F_s(x,y,t) = \iint_{x,y} p(x,y,t)\,dxdy \qquad (3)$$

where, p(x,y,t) : Pressure

Here, the damping force, $F_s(x,y,t)$ of the system is determined according to the size and shape of the air gap between the electrode and the levitating object, and it effects the stability of the system immensely .

In case of the flat film-like levitating object in this paper, the air damping force by a squeeze film effect is large enough to make the suspension system be stable which will be verified and revealed from the experimental results in the following section.

Since the electrostatic attraction force,F^* is about 0.4g_f/cm^2 and much smaller than the electromagnetic force used in the conventional magnetic levitation system, the electrostatic suspension system must have large active surface area which the electrostatic force acts on.

Therefore, the ratio of the surface area to the thickness of the levitating body used in electrostatic suspension system needs to be large such as wafer, glass plate and thin film-like plate in this paper. Equation (2) also shows that it has to set in more small air gap between the electrodes and levitating body because the electrostatic attractive force is inversely proportional to the square of the air gap.

3. Design of the electrostatic suspension system for flexible object

The electrode pattern used in the electrostatic suspension system is designed as shown in Fig.2. It is made of glass epoxy PCB using etching process. Total size of the electrodes is 280mm x 80mm which is the same size with the levitating body and it has fourteen channels as shown in Fig.2. Displacement sensors are located at the center of each electrode.

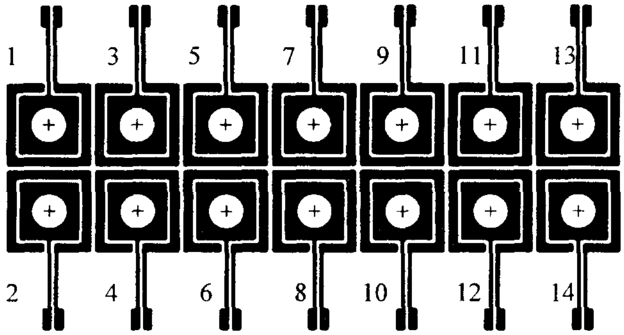

Fig. 2 Electrodes pattern

Fig.3 shows the configuration of the electrostatic suspension system for the flexible object suggested in this paper.

Sensor signals detecting air gap at each channel are sent to 'on-off switching control circuit' shown in (B) and compared with the air-gap reference which is set by 'air gap adjustment potentiometers' shown in (A). On the basis of this comparison, high voltage amplifiers in (C) supply ±1kV or zero voltage to the electrodes to implement 'charge-discharge' action. Fig.3(G) shows the levitating aluminum sheet having a thickness of 100μm.

4. Experimental results

The objective is to suspend a flexible aluminum sheet at a stable equilibrium position under the electrode plates.

The mass and size of the levitated object are 5.7g and 280mm× 80mm×0.1mm respectively. The applied high voltages are ±1kV. The air-gaps are set at 600 and 750 μm. Eddy-current type non-contacting displacement sensors are used in the experiment.

Experimental procedure is as follows.

(1) The plate with electrodes and sensors is leveled by three micrometer positioning screws.

(2) The flexible aluminum sheet supported by a insulating plate is leveled by three micrometers and is placed under the electrode with 1mm air gap.

(3) The DC high-voltage amplifier are switched on and the bias voltages of +1kV and -1kV are ready to be applied to the electrodes.

(4) By switching on the control circuits, the control voltages are applied to the electrodes depending on the sensor signals, and the flexible sheet is levitated subsequently.

Fig.4,5,6,7 and 8 show the sensor signal which represent the air gaps between the electrodes and the levitating object, and also the high-voltage signals applied to electrodes during levitation of the flexible aluminum sheet.

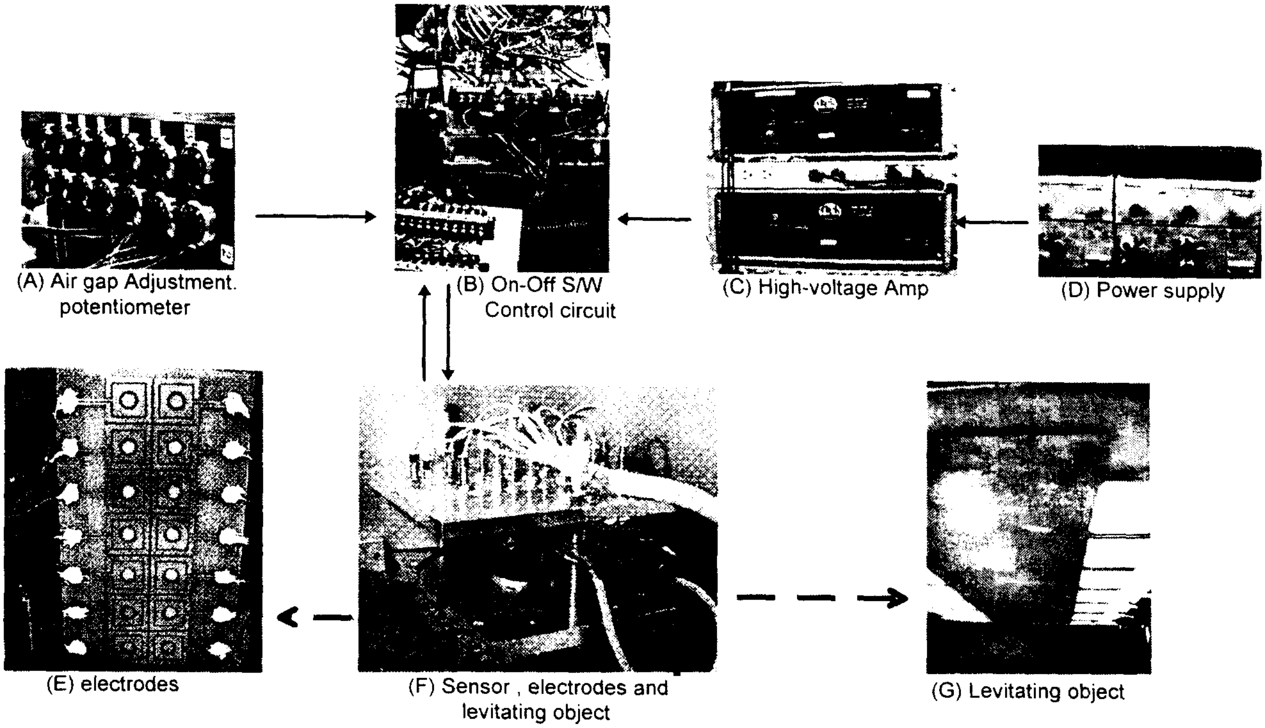

Fig. 3 Configuration of the electrostatic suspension system for flexible objects

Air gaps are set at 750 μm by adjusting the potentiometers shown in Fig.3 (A). High-voltage amplifiers with a gain of 1,000 convert the DC ±1V which are generated from DC power supply shown in Fig.3 (D) to the ±1,000V and these high voltages are applied to each electrodes through the switching control circuits. This system has fourteen channels of electrodes and these electrode channels are numbered as shown in Fig.2. Fig.4 represents the measured air gap and electrode voltage at channel 7 during a stable levitation of the object. Comparing this result with the measured data from adjacent channels, for example ch.5 and 9 as shown in Fig.5 and 6, no relations and no rules of motions between these adjacent air gap and voltage data can be observed. This phenomena of the absence of relation in motion is also revealed with other settings of air gaps from setting potentiometers such as 600μm. In cases of previous papers dealing with the levitation of a rigid body, the final values of air gaps, **Z** used for feed back control are calculated from the relation of the transformation matrix $\{\mathbf{z}\}=[\mathrm{Ts}]\{\mathbf{Z}_i^s\}$ which describes the equation of rigid body motions by yawing ,rolling and pitching with the air gap $\mathbf{Z}^s=\{z_j^S\}$ which are measured from i-th channel sensor. [8][9] On the contrary, in case of the levitation of the flexible body, $[\mathrm{Ts}]$ is an identity matrix, **I** or a matrix whose non-diagonal elements have small value because there is no or small relation between motions of each channels as known from these experiments. $[\mathrm{Ts}]$ depends only on the thickness and material properties of sheet. Such a new $[\mathrm{Ts}]$ for very flexible body means that each channel may be regarded as an independent one-DOF suspension system described in Fig.1 and multi-channel system can be designed just as an array of one-DOF modular suspension systems.

Fig.7 and 8 show the experimental results with the changed air gap reference of 600μm. The experimental results show that the deviation from the reference gap of 750μm commanded from 'air-gap adjustment potentiometer' is larger than that from the reference gap of 600 μm. This is due to the damping effect caused by the squeeze air film between the electrodes and the levitated object.

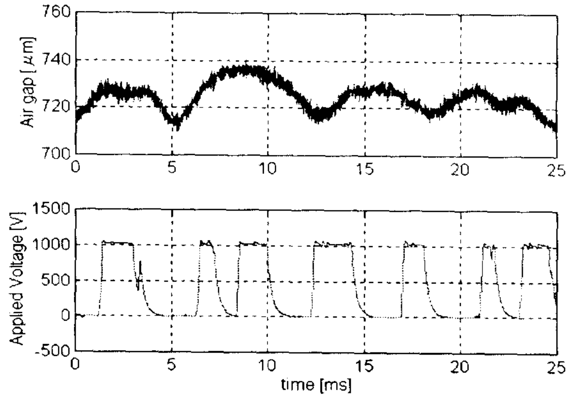

Fig. 4 Air-gap and electrode voltage [Ch7,1000V, 750μm]

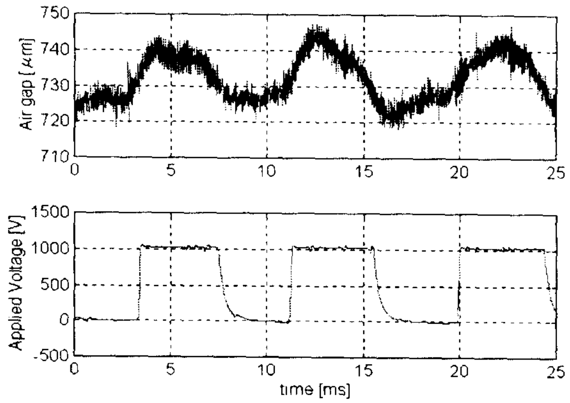

Fig. 5 Air-gap and electrode voltage [Ch5,1000V, 750μm]

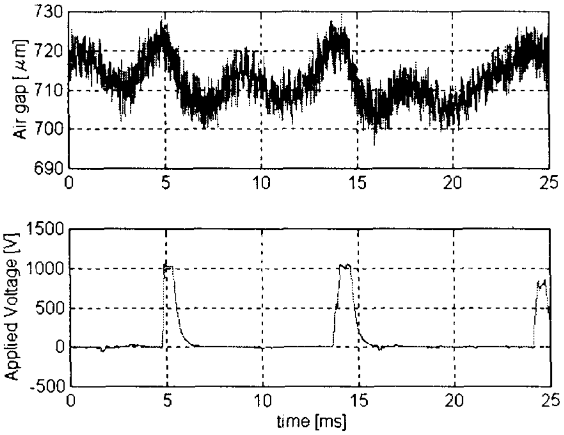

Fig. 6 Air-gap and electrode voltage [Ch9,1000V, 750μm]

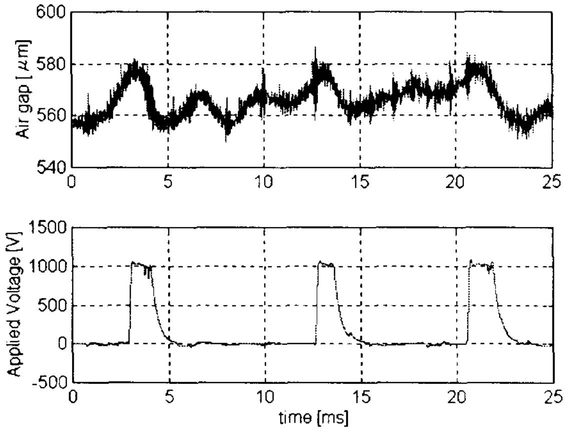

Fig. 7 Air-gap and electrode voltage [Ch10,1000V, 600μm]

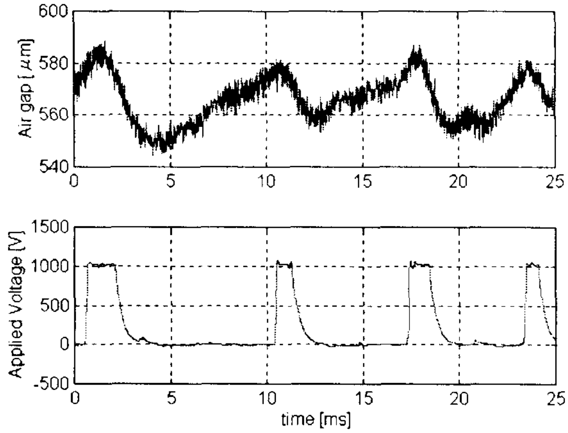

Fig. 8 Air-gap and electrode voltage [Ch12,1000V, 600μm]

Since the original shape of sheet appears in suspension state where the force equilibrium is maintained, a originally deformed edge is attracted toward the electrodes. As a result, more small air gap could not be accomplished in our experiment. The time delay in control circuits results in the offset error existing in the measured air gaps as shown in the experiments.

5. Conclusion

A flexible body consisting of a thin aluminum sheet has been suspended successfully by controlling electrostatic forces acting on it. As a control strategy, on-off switching which is simple and cost effective are utilized.

The experimental results show that in order to implement contactless support of the object, the application of electrostatic levitation to the handling of the flexible bodies like aluminum sheets and other sheet transportation devices is possible. In addition to the advantage of being contactless, the levitation system does not need any complex control circuits or large number of high voltage power amplifiers since on-off control strategy is used to stabilize the object movement. As a consequence, the levitation system become very simple and cost effective. It will be also possible to realize a modular levitation device which simplifies the whole system and give it system-flexibility for modification. This means that it may be easy to implement this kind of electrostatic suspension system in real industrial application for the handling of various objects according to their flexibility.

Using a modified design of our system, it may be possible to transport flexible bodies such as aluminum sheet and film material in more clean and efficient way.

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