Design of Electromagnetic Levitation Linear Bearing for FPD Glass Delivery Applications

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***Abstract* — In flat panel display (FPD) manufacturing, especially in next-generation organic light-emitting diode (OLED) display manufacturing, a high-weighted glass carrying tray is required to be position servo-controlled precisely in long range of vacuum process line without mechanical contact. So special contactless linear bearing, which is called a electromagnetic levitation linear bearing (ELLB) is suggested in this paper. It can expend its operating distance by adding series of electro-magnets and shifting the electromagnets by section switching algorithms suggested in reference [12]. In order to prove the feasibility of the ELLB, a test setup with specially designed ELLB is made-up and the performance of it is observed. With the proposed ELLBs and proper linear propulsion system, the glass-carrier system in vacuum FPD manufacturing process line is expected to be constructed easily in the near future.**

I. INTRODUCTION

The electromagnetic linear bearings (ELB) have been a essential elements in modern industries because of its contactless property. The ELB can be classified by several types based on its operating principles – eddy-current bearing, repulsive linear synchronous motor bearing, electromagnetic suspensions (EMS) and so on. The eddy-current bearings were widely studied in the earlier high speed railways. For example, the Inductrack was a passive, fail-safe electro-dynamic magnetic levitation system, which uses only unpowered loops of wire in the track and permanent magnets on the vehicle to achieve magnetic levitation [1]. The repulsive coreless (air-cored) linear synchronous motor propulsions have been the most popular precision levitation system in semiconductor manufacturing applications where the precision servo-control is most important for the light-weighted tray [2] ~ [6]. The electromagnetic suspension (EMS) can have high load capability and good levitation gap control performance. It is defined as the magnetic levitation of an object achieved by constantly alternating the strength of a magnetic field produced by electromagnets using a feedback loop [7]. With proper design of actuator and controller, the EMS can achieve nanometer position accuracy for high-weighted tray [8], [9].

Meanwhile, in recent manufacturing automation industries, especially in flat panel display (FPD) manufacturing such as organic light-emitting diode (OLED) display in–line fabrication process, precise contactless linear bearings with high load capabilities are required. In conventional semiconductor manufacturing applications, only high precision contactless linear bearings were required, but in upcoming FPD manufacturing applications, heavy-weighted tray is required to move precisely and seamlessly in entire all the process line. So the combination of electromagnetic linear bearing and linear propulsion system is required in the applications [10].

As new type of linear bearing for FPD glass delivery applications, an electromagnetic levitation linear bearing (ELLB) is suggested in this paper. This new bearing is based on the system shown in [9] in structure. The differences are a series of electromagnets fixed on the rail, and these electromagnets can be extended as long as the tray moves. The cut-away view of the suggested transportation system of the FPD glass-carrying tray is shown in Figure 1. In the Figure, 2 ELLBs and one linear active magnetic bearing (LAMB) are used in order to support the tray in five degrees of freedom, and longitudinal position of the tray is controlled by additional linear motor. Because the weight of tray is over hundreds kilograms, the high load capability of the ELLB is essential.

The description of the paper is as follows: In section II, the design strategy of the ELLB is shown and feedback controller design of the ELLB is shown in section III. Experimental setups and results are shown in section IV and V respectively. And final conclusions are shown in section V.

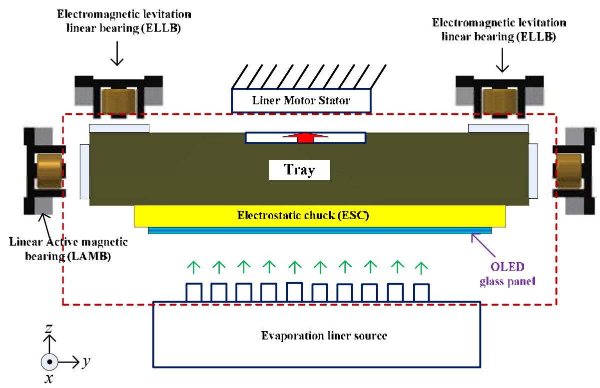

Figure 1. Transportation system of the FPD glass carring tray.

II. DESIGN OF A ELLB

A. *Design of the ELLB*

The ELLB is composed of a series of electromagnets on the rail, which build up attraction forces on the core in the tray against the gravity. A simple transport system of tray with one ELLB is shown in Figure 2, where 5 adjacent electromagnets among a series of electromagnets have a role in attracting the tray against the gravity at the same time. So the number of active electromagnets becomes five. If we can properly define the "Section" as some area among periodic displacement of the electromagnets and the tray can pass through this Section without losing the gap and pitch control performance, it means that long stroke operation of the ELLB is possible. In the Figure, the *k*-th section is defined as the area occupied by most left one among active five electromagnets. Because the length of tray is the same as distance of 5 electromagnets, the center of mass point of the tray exists above the (*k+2*)-th electromagnet. – Figure 2 shows the situation when the Section, $k = 0$. In the Figure, the vertical gap and pitch angle of the tray should be maintained as constant values by the ELLB, while the longitudinal *x* position of the tray is servo-controlled by additional linear motor which is not shown in the figure. Other degrees of freedom such as lateral moment, roll and yaw of the tray are neglected for simplicity. So the ELLB has two degree of freedom. A series of gap sensors can be fixed on the rail to calculate the average air-gap at the center of mass position (CMP) and pitch angle of the tray. The average gap and pitch angle are controlled as constant values by controlling attraction forces between core in the tray and electromagnets on the rail. Figure 2 also shows the attraction forces built by 5 active electromagnets on the rail, when the tray moves.

From the geometry, the resultant force f_{net} and the moment M_{net}, which should be built by the control current of the electromagnets, can be calculated as follows:

$$f_{net} = f_k + f_{k+1} + f_{k+2} + f_{k+3} + f_{k+4} \tag{1}$$

$$\begin{aligned} M_{net} = &(2P + \Delta x) f_k + (P + \Delta x) f_{k+1} + (\Delta x) f_{k+2} \\ &-(P - \Delta x) f_{k+3} - (2P - \Delta x) f_{k+4} \end{aligned} \tag{2}$$

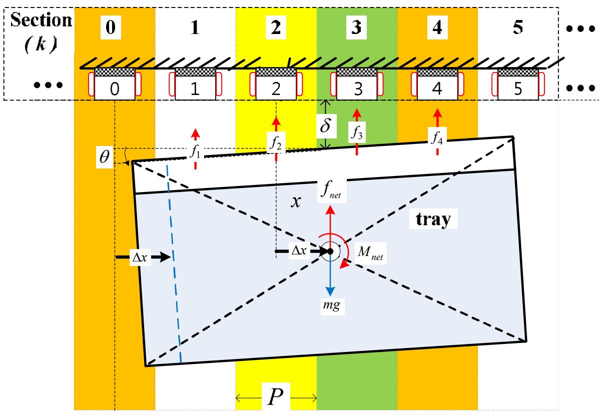

Figure 2. Design of the ELLB.

B. *Dynamic model of the tray supported by the ELLB*

If longitudinal x axis degree of freedom of the tray is neglected, the dynamic equation of the tray levitated by the electromagnets on the rail becomes as follows where *m* is the tray's mass and J_{yy} is moment of inertia of the tray for pitch direction and *P* is interval of electromagnet placement.

$$m\ddot{\delta} = mg - f_{net} \tag{3}$$

$$J_{yy}\ddot{\theta} = M_{net} \tag{4}$$

C. *Design of electromagnet and stiffness of the ELLB*

If the air-gap between *k*-th electromagnet and core in the tray is δ_k, the attraction force exerted by the electromagnet which carries control current i_k is as follows:

$$f_k = K_{mag} \frac{i_k^{\,2}}{\delta_k^{\,2}} \tag{5}$$

If the center of mass point of the levitated tray is exactly under (*k*+2)-th electromagnet and pitch angle of the tray is zero, only three electromagnets among five section magnet, which are (*k+1*)-th, (*k+2*)-th, and (*k+3*)-th electromagnets, levitate the tray with the same control current. At this moment, each electromagnet can be thought as a mechanical spring with open-loop position stiffness of $k_s = 2K_{mag}\, i_k / \delta_k^{\,3}$ as shown in Figure 3. So linearized open loop bearing stiffness of the ELLB becomes follows:

$$k_{eq} = 3k_s = 6K_{mag} \frac{i_k}{\delta_k^{\,3}} \tag{6}$$

Normally the closed loop bearing stiffness can be designed the same order as the open-loop position stiffness in the design of controller for the levitation control system [11].

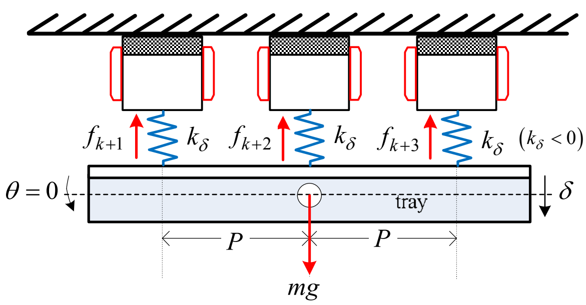

Figure 3. Bearing stiffness model for the ELLB.

III. CLOSED LOOP CONTROL OF THE ELLB

A. *Overall controller design for the ELLB*

The overall control block diagram of the ELLB is shown in Figure 4, and parameters for the ELLB and controllers are shown in Table I and Table II respectively. The reference gap δ is 0.7 millimeter and pitch angle is zero for the 18 kilogram weighted tray. A conventional proportional integral and derivative controller and a special section switching algorithm (SSA) is designed, simulated and tested for control of the tray. The precise description about plant modeling, controller design, and simulation results are shown in reference [12].

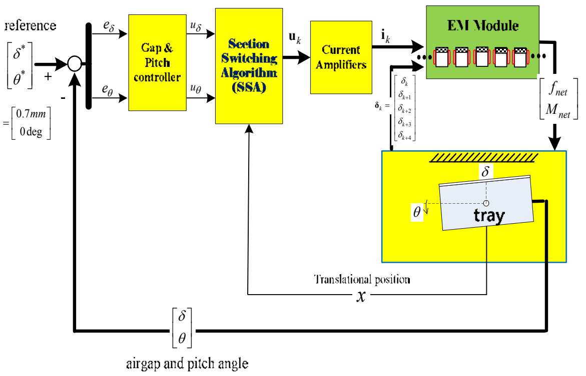

Figure 4. Block diagram of controller for the proposed ELLB.

TABLE I. CONTROL PARAMETERS FOR THE ELLB

Description		Abb.	Value	Unit
Gap control	***Mass***	k_P	23	*kg*
	Moment	ω_D	87	kgm^2
	length	$k_{I\delta}$	15	*m*
Picth control	***Mass***	k_P	18	*kg*
	Moment	ω_D	1.16	kgm^2
	length	$k_{I\delta}$	20	*m*

TABLE II. PARAMETERS OF ELLB AND ELECTROMAGNETS

Description		Abb.	Value	Unit
Pitch of the EMs		P	0.09	*m*
Electromagnet constant		K_{mag}	5.27×10^{-6}	Nm^2/A^2
Nominal gap		δ_0	0.7	*mm*
Tray	***Mass***	m	18	*kg*
	Moment	J_{yy}	0.2225	kgm^2
	length		0.45	*m*
	height		0.25	*m*

IV. EXPERIMENTAL SETUPS

In order to verify the feasibility of the suggested ELLB, a simple test-setup with the closed loop control of the ELLB is made as shown in Figure 5. A ball-screw linear motor is used to control the longitudinal x displacement of the tray. Total 6 numbers of electromagnets are placed with P meter intervals in order to build up levitation forces and two gap-sensors are located between magnets with $2P$ interval on the rail in order to measure gaps and attitude of the tray. For the control of the ELLB, two proportional-integral-derivative (PID) levitation controllers for the pitch and gap control of the tray and a special SSA for successful Section changes are simulated in Matlab/Simulink software package and implemented with the Real-Time Workshop toolbox from MathWorks Inc. The final control algorithms are implemented with a commercial real-time controller, the DS1104 Power-PC control board. Six numbers of current controllers which are composed of liner power OP-Amps are used to apply currents to each electro-magnet as the control commands.

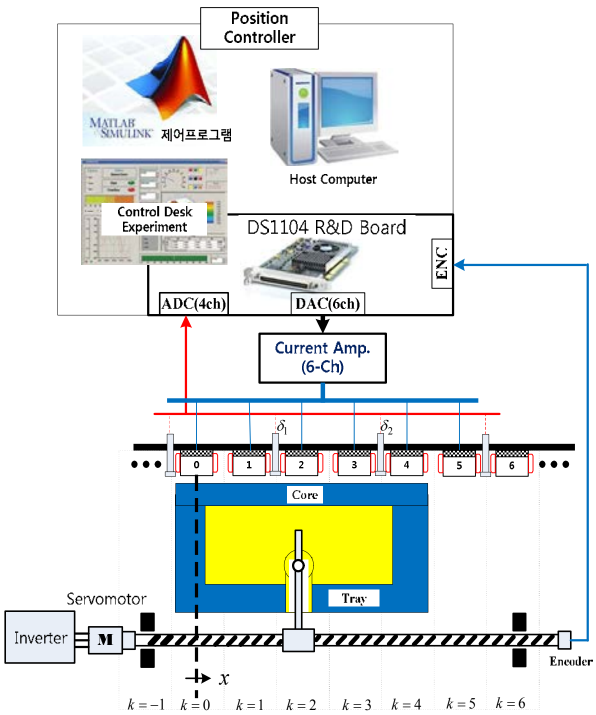

Figure 5. Moving tray model with the proposed ELLB.

The experiments are performed as follows: When the closed loop control of the ELLB is working, the tray' CMP is moved from 2^{nd} magnet position (Section *k= 0*) to the 4^{th} magnet position (Section *k= 2*) with *2P* intervals. This means that the Section is changed twice from 0 to 2. Therefore a long distance operation of the ELLB is possible by extension of Sections and switching control of the Sections. This is implemented by just adding another electromagnets and transition control of the Sections.

V. EXPERIMENTAL RESULTS

The experimental result with the test setup is shown in Figure 6 ~ 8. The center gap δ and pitch angle θ of the tray is calculated from the real gap sensor signals, δ_1 and δ_2. When the levitation and pitch control of the tray is working, the tray is moved forward with constant speed of 5 millimeter per second by the ball-screw linear motor driver.

Figure 6 shows the longitudinal x displacement of the tray, and Section and Section deviations as the tray moves. The control commands of the levitation and pitch controllers also shown in the Figure.

Figure 7 shows the current control commands which is calculated from the SSA. It can be inferred that because the tray's parameters are the same at every moment, the sum of the control current should be the same. But small deviations in control current of the electromagnets was monitored when switching of the electromagnets are occurred.

Figure 8 shows the performance of the closed-loop control of the tray. It is also monitored that the center gap δ and pitch θ of the tray is deviated when switching of the electromagnets are occurred. This can be also monitored from the sensor signals δ_1 and δ_2. These deviations are due to control command changes to each electromagnet when Section changes occur. More observations and precise controls should be done in order to reduce these deviations in near future.

VI. CONCLUSION

New type of magnetic levitation, which can support heavy-weighted moving tray in the long distance rail very precisely with the help of periodic placement of EMs on a rail, is proposed. For the proof of feasibility of the proposed ELLB and SSA, test setup of a moving tray with one ELLB is made up. With the help of a special SSA suggested in reference [12] and proper conventional levitation control techniques, the suggested linear bearing can support a 18 kg weighted, 450 mm long test tray with gap control performance under ±40 μm in the experiment. This new contactless linear bearing could be very useful for next-generation OLED in-line fabrication process, where huge heavy tray is required to move precisely in vacuum environment.

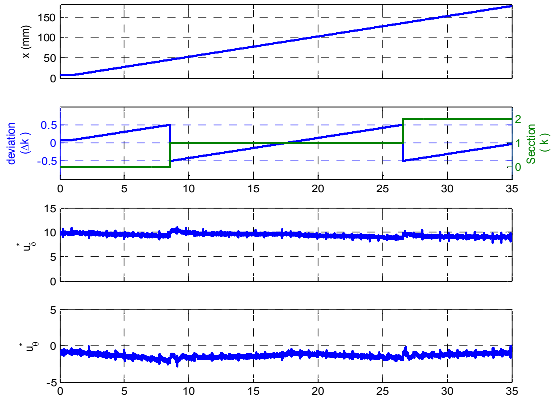

Figure 6. Control commands and Sections.

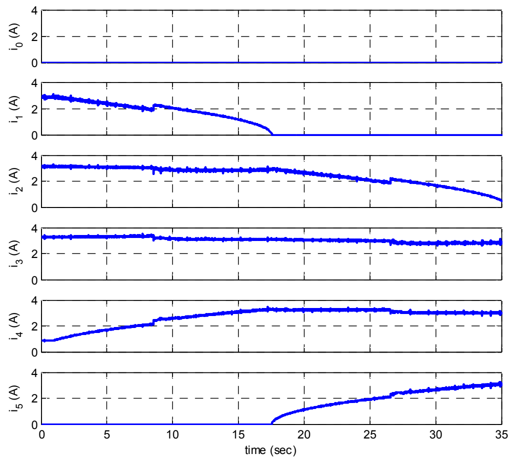

Figure 7. Control currents of the electromagnets.

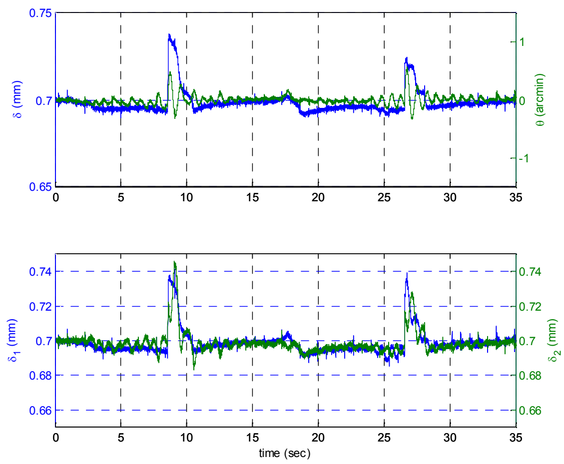

Figure 8. Performance of the ELLB

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