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A Novel High Precision Electromagnetic Suspension for Long-Stroke Movement and Its Performance Evaluation

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Abstract – A new type of high precision electromagnetic suspension (EMS) which can support heavy tray along long stroke rail is proposed in this paper. Compared with the conventional EMS, the suggested moving-core typed EMS has the levitation electromagnets (EMs) on the fixed rail. This scheme has high load capability caused by iron-core and enables simple tray structure. Also it does not have precision degradation caused by heat generation from EMs, which is a drawback of conventional EMS. With these merits, the proposed EMS can be an optimal contactless linear bearing in next generation flat panel display (FPD) manufacturing process if the ability of long stroke movement is proved. So a special Section Switching Algorithm (SSA) is derived from the resultant force and moment equations of the levitated tray which enables long stroke movement of the tray. In order to verify the feasibility of the suggested SSA, a simple test-setup of the EMS with 2 Section-changes is made up and servo-controlled in the simulation and experiment. The simulation shows the perfect changeover the EMs, and the experiment shows overall control performance of under ±40 μm gap deviations. These results reveal that the newly suggested contactless linear bearing can simultaneously achieve high load capability and precision gap control as well as long stroke.

Keywords: Electromagnetic Suspension (EMS), Conventional EMS, Moving core typed EMS, Gap control, Pitch control, Long-stroke contactless linear bearing, Section Switching Algorithms (SSA), Section number, Section deviation, Section Magnets (SMs), Electromagnet (EM)

1. Introduction

Traditionally magnetic levitation (MAGLEV) technology has many merits over the conventional mechanical linear bearing technology because of its contactless property. So it has been widely adapted for new high-edgy industries such as maglev trains, semiconductor manufacturing, factory automation, and so on. As actuators for this technology, permanent magnet linear synchronous motor (PMLSM) and electromagnetic suspension (EMS) are well known. The PMLSM actuator can be divided into two, air-cored and iron-cored one. The air-cored PMSLM can achieve precision levitation gap control of sub micro-meters. With the help of special design like Halbach magnet arrays, it can achieve position servo system of nanometer accuracy [1]. But the load capability of it is very poor because it does not use iron-core for magnetic flux building path. With this type of actuator, position servo systems which can operate in long stroke and wide area have been studied in applications where load capability is not required, such as semiconductor wafer transfer stages [2-7]. Whereas the iron-cored PMLSM is widely used in applications where heavy passenger load and long stroke transportation are required, such as maglev vehicles [8-11]. But its degree of levitation gap performance is not precise enough because of coupling between propulsion and levitation [10]. At the cost of movability give-up, it can also achieve high degree of precision gap performance like [12], which is not the normal case. The conventional EMS, which is composed of just electromagnets and cores, has many merits over the PMLSM typed one - Its rail structure is simple and cost-effective implementation is possible. High gap control performance is also possible because of decoupling from propulsion motors and it is as strong as iron-cored PMLSM. So it has been one of the most popular levitation actuators in transportations and factory automations [13-16].

Recently newly growing FPD manufacturing industries simultaneously requires all the merits of above mentioned technology long stroke movability, simple structure, heavy load capability, useable in vacuum environment, high degree of precision control, and so on. For example, in case of the in-line fabrication process of recent massive organic light emitting diode (OLED) display, a glass carrying tray with hundreds *kg* is required to be levitated with several μm gap on hundreds *m* long process line in vacuum chamber [17, 18]. To fulfill these requirements, a new type of EMS and corresponding SSA is proposed. The proposed

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new linear bearing supports a tray without any contact by precise air gap control along long distance rail in vacuum environment without any actuator and controller on the tray.

The contents of this paper are as follows. In chapter 2, the design concepts of the new EMS and corresponding SSA are proposed. The simulation and experimental tests for the EMS and SSA are shown in chapter 3. The final description and conclusion are followed in chapter 4.

2. Design and Control of the EMS

2.1 Levitation system design

The classification of EMS is shown in Fig. 1. Which is the conventional moving-electromagnet typed one and the proposed moving-core typed one. The former can be useful and cost-effective for factory automations because of its simple rail-structure. But it has complex tray structure and weight reduction of the tray is very difficult as shown in [14-16]. For example, complicated components such as actuators, sensors, controllers and even contactless power supply (CPS) are mixed up in the moving tray. D.K. Hong et al, tried to reduce the weight of electromagnets (EMs) with an optimal design of response surface methodology (RSM) in [19, 20]. But the problems of increased mass and complexity in moving tray could not be solved yet. In the latter, the complexity and problems on the moving tray can be solved by a series of electromagnets (EMs) periodically located on the static rail side. The core on the tray plays a role of building magnetic flux path, which is generated by the EMs on the rail. Heat generated by the ohmic and eddy current losses in the EMs can be easily removed by cooling the EMs in the fixed rail. So heat generation in the EMs does not make degradation of control any more.

So the proposed EMS can be an ideal linear bearing which can simultaneously achieve heavy load capability and high precision gap control performance even in vacuum environment. If proper changeover of active EMs is accomplished successfully, long stroke movement of the tray is also possible for the proposed EMS.

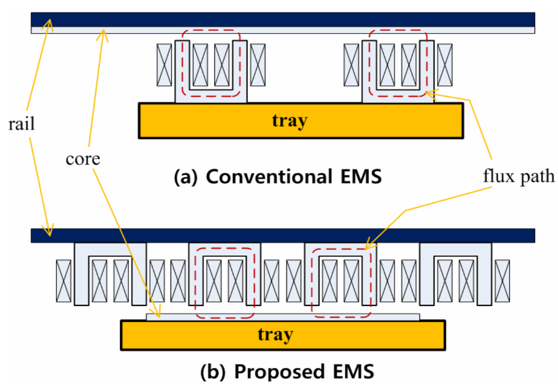


Fig. 1. Classification of EMS

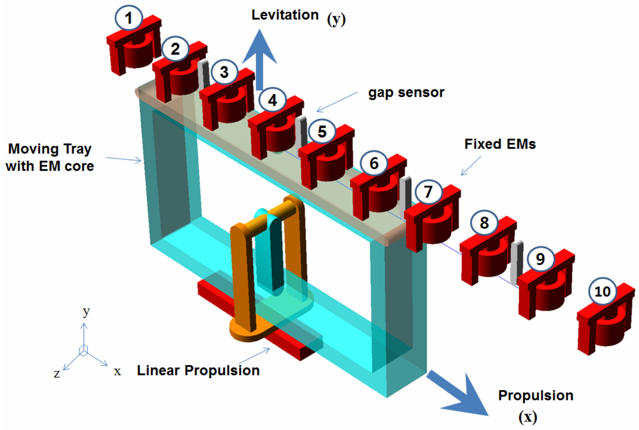


Fig. 2. Moving tray model with the proposed EMS

2.2 Dynamic model for the EMS

A simplified moving-tray model with the proposed EMS is shown in Fig. 2. In the model, the vertical gap and pitch angle of the tray is maintained as constant values by the EMS, while the longitudinal x position of the tray is servo controlled by a linear motor. Other degrees of freedom such as lateral movement, roll and yaw of the tray are neglected for simplicity. A series of gap sensors are fixed on the rail to detect the average air-gap at the center of mass position (CMP) and pitch angle of the tray. This average gap and pitch angle are controlled as constant values by controlling attraction forces between core in the tray and EMs on the rail.

2.3 Overall control block diagram

The overall control block diagram for the proposed EMS is shown in Fig. 3. In order to regulate the pitch angle and the average gap as desired values, two independent controllers, pitch and gap controller, calculate the attitude of the tray and generate each control command u_θ and u_δ respectively. These controllers can be linear or nonlinear controllers such as the proportional, derivative and integral (PID) controllers like [21], sliding mode controllers like [22], lookup table based one like [23], and so on.

The proposed Section Switching Algorithm (SSA) distributes control commands to each current amplifier, which drives each EM on the fixed rail. For the air-cored PMLSM stages, long stroke and wide area movement of the tray are accomplished by a coil current commutation algorithms based on the d-q decomposition or vector control of the PMLSM [2-4, 6, 7]. Whereas the SSA, a method of changing over the active EMs, is proposed in this paper. For the derivation of the SSA, a concept of "Section Magnets (SMs)" is defined as: The EMs which actively make attraction forces jointly with the core in the moving tray at the same time. The derivation of the SSA for the EMS is shown in the following.

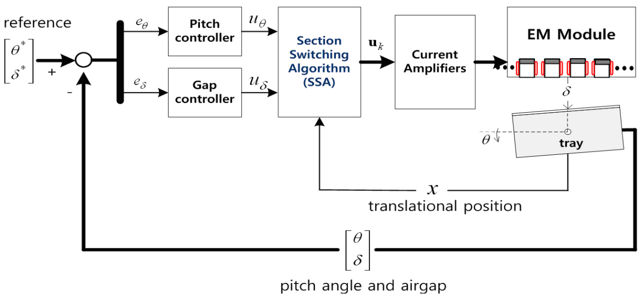


Fig. 3. Overall control block diagram for the proposed EMS

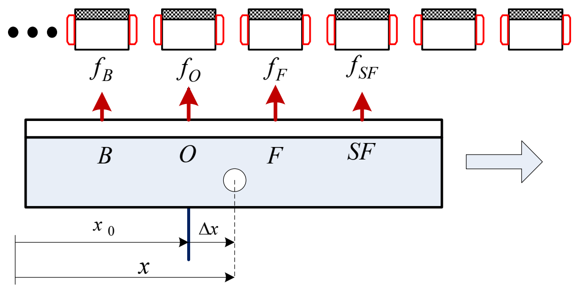


Fig. 4. Moving tray model with the proposed EMS

2.4 Derivation of section switching algorithm (SSA)

The SSA are derived by using the fact that the resultant force and moment in the CMP of the tray should be the tray's mass and zero respectively when attraction force between core and SMs is applied. The longitudinal x position of the CMP of the tray is assumed to be known. More precise explanation is suggested in Fig. 4. Here, the number of SMs are defined as 4, namely only 4 EMs actively support the tray at the same time. The Section Number is defined as the order of EM, which is located on left-side and closest to the CMP of the tray. From Fig. 4, let's assume that at the beginning, the tray is under the 2nd EM, which is the origin of Section 2. If the tray moves forward, small position deviation Δx from the origin of Section 2 is occurred and if this deviation reaches $+P$, next Section (3rd Section) is reached. At this moment, logical switching from Section 2 to Section 3 is occurred. So the Section Deviation Δk, which is defined by $\Delta x/P$, varies from 0 to 1. The attractive forces between SMs and the core are generated on specific points of the tray under SMs - B, O, F and SF points. It is short name of backward, origin, forward and switched forward. These action points vary periodically depending on the Section Deviation Δk as the tray moves.

The bearing force can be defined as forces acting on these points and it becomes:

$$\mathbf{f}_b = [f_B, f_O, f_F, f_{SF}]^T \tag{1}$$

This force is also displayed in Fig. 4. With this bearing force, the resultant force and moment at the CMP of the tray becomes as follows:

$$f_{net}(\Delta k) = f_B + f_O + f_F + f_{SF} \tag{2}$$

$$M_{net}(\Delta k) = P\{(1+\Delta k) f_B + (\Delta k) f_O - (1-\Delta k) f_F - (2-\Delta k) f_{SF}\} \tag{3}$$

Where Section Deviation Δk is defined by $\Delta k = \Delta x/P$ and P is defined as the pitch of the EM position.

In order to derive the SSA, let's start with the problem of the gap control command distribution. If the following levitation force is applied to the tray, from Eq. (2) the resultant force $f_{net}(\Delta k)$ becomes u_δ, where u_δ is the gap control command, which corresponds to the weight of the tray.

$$\begin{aligned} f_B{}^\delta &= \frac{1}{3} u_\delta (1-\Delta k) \\ f_O{}^\delta &= \frac{1}{3} u_\delta \\ f_F{}^\delta &= \frac{1}{3} u_\delta \\ f_{SF}{}^\delta &= \frac{1}{3} u_\delta (\Delta k) \end{aligned} \tag{4}$$

Substituting Eq. (4) to Eq. (3), the resultant moment becomes zero ($M_{net}(\Delta k)=0$). This means that force distribution like (4) can control only the levitation gap without making any moment which can cause disturbance torque to the pitch angle controller.

Now let's consider the distribution of the pitch control command.

$$\begin{aligned} f_B{}^\theta &= +\frac{1}{4P} u_\theta \\ f_O{}^\theta &= +\frac{1}{4P} u_\theta \\ f_F{}^\theta &= -\frac{1}{4P} u_\theta \\ f_{SF}{}^\theta &= -\frac{1}{4P} u_\theta \end{aligned} \tag{5}$$

If the pitch controller output u_θ is distributed just like (5), by substituting the Eq. (5) to Eq. (3), the resultant moment ($M_{net}(\Delta k)$) becomes u_θ, where u_θ is the output of the pitch controller. Also by substituting the Eq. (5) to Eq. (2), the resultant force ($f_{net}(\Delta k)$) becomes zero. So the pitch controller will not make any disturbance force to the gap controller.

By combining Eqs. (4) and (5), the overall Section Switching algorithms are accomplished, which are shown in Fig. 5. In the figure, u_θ and u_δ are control force command from pitch and gap regulator respectively, and $\mathbf{u}_b$ is the bearing current command and $\mathbf{u}_k$ is current command for the k-th SMs. The attraction force between SMs and the core in the tray becomes as follows if constant nominal gap is assumed:

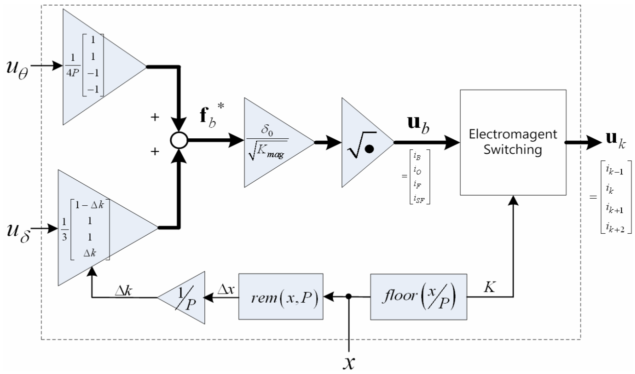


Fig. 5. New SSA for the proposed EMS

$$f_j = K_{mag} \frac{i_j^{\,2}}{\delta_o^{\,2}} \quad where \quad j = B, O, F, SF \tag{6}$$

Where K_{mag} is electromagnet constant which is proportional to electromagnet size, and δ_0 is nominal gap length. From (6), the control currents for the EMs can be easily determined by square rooting each bearing force command component.

Each EM on the rail can be driven on or off by the Section Number *K*. For example if the Section Number is 2, then the components of $\mathbf{u}_k$ become i_1, i_2, i_3 and i_4.

The Section Number *K* and Section Deviation Δk is easily determined by sensing longitudinal displacement of the tray as bellow:

$$\begin{aligned} K &= floor(x/P) \\ \Delta k &= \Delta x/P \\ \Delta x &= rem(x, P) \end{aligned} \tag{7}$$

Where $rem(x,P)$ is a function of remainder after x is divided by P, and $floor(x/P)$ is rounds the elements of x/P to the nearest integers towards minus infinity.

3. Simulation and Experiment

3.1 Parameters for simulation and experiments

To verify the feasibility of the SSA for the proposed EMS, a moving tray model is simulated and tested in the simulation and experiment. Parameters of the tray and the EMS are shown on Table 1, which are commonly used in the simulation and experiment.

3.2 Simulation and discuss

The simulation is carried out by making dynamic model of the tray suspended by the proposed EMS and controllers with the Matlab/Simulink software package. The pitch and gap control of the tray with constant mass and the SSA are activated as simulation starts with given control parameters. During first one seconds, the position of the tray is maintained in the initial position - below the 2nd EM. From time of 1 second, the tray is moved forward with constant speed of *P m/s* by servo-controller. Because the pitch of the EMs on the rail is also *P m*, the Section changes on every one second. The simulation results show good linear bearing performance along the test rail. - The gap is controlled with fixed value of 0.7 *mm* and the pitch angle is maintained as zero degree even when the Section changes. The longitudinal *x* displacement, the levitation gap and pitch angle at the CMP of the tray as the tray moves are shown in Fig. 6. The Section Number and Section Deviation calculated by (7), and control commands from the gap and pitch controller are shown in Fig. 7. The bearing force and currents on SMs of the each Section are shown in Figs. 8 and Fig. 9, respectively. At static load condition like constant tray mass assumption, these currents and forces on SMs have the same pattern, which depends on the Section Deviation, regardless of Section Number. The current in each EM on the rail is shown in Fig. 10, which is the result of distribution of the bearing currents on SMs by the SSA. It has the same pattern as the tray moves in and away from the EM. It can be easily seen that in a specific Section, the bearing current has the same pattern as the currents in SMs.

Table 1. Parameters for the EMS

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

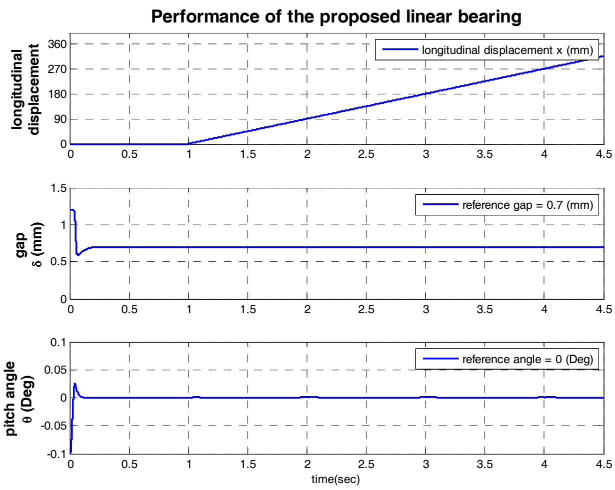


Fig. 6. Performance of the SSA according to tray movement

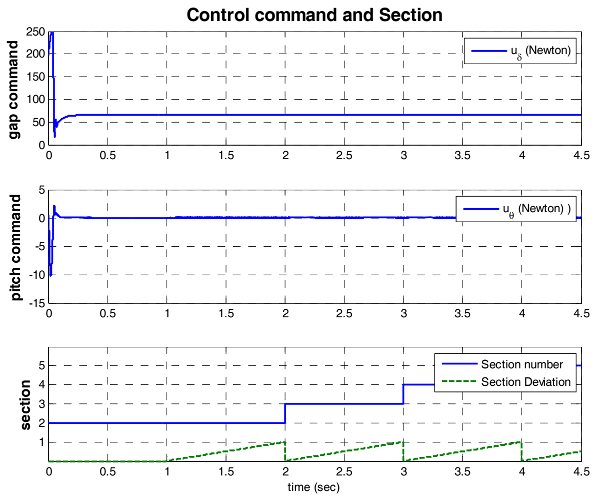


Fig. 7. Pitch and gap control commands and Section

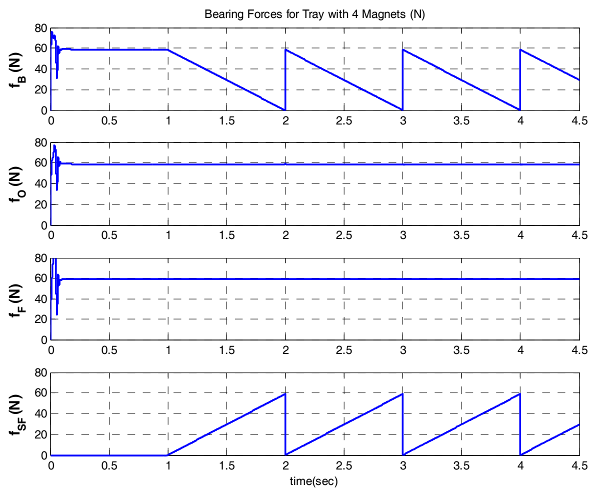


Fig. 8. Bearing forces on SMs

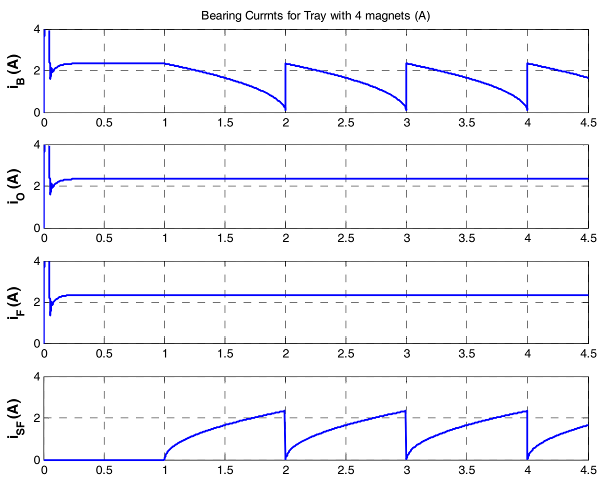


Fig. 9. Bearing currents on SMs

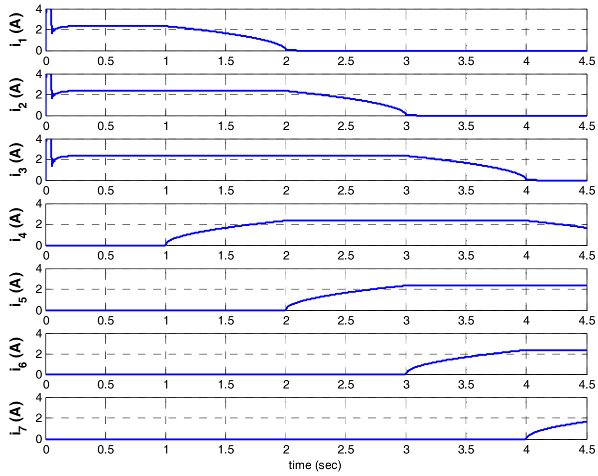
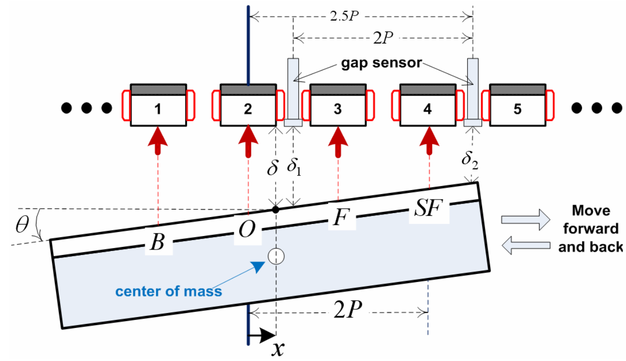
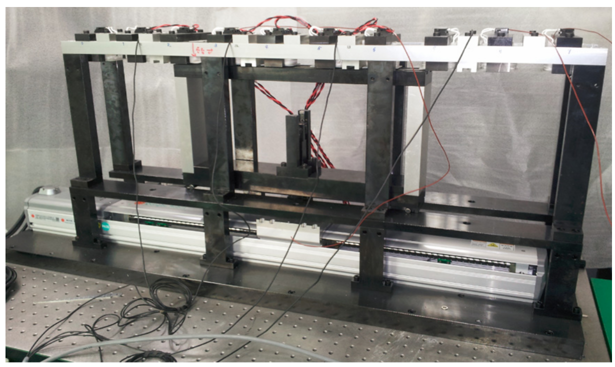


Fig. 10. Control current in each EM on the rail



(a) Experimental setup diagram



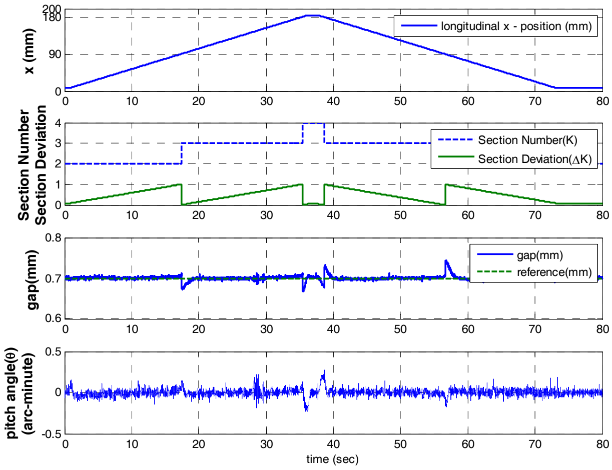
(b) The tray supported by the EMS

Fig. 11. Experimental test setups

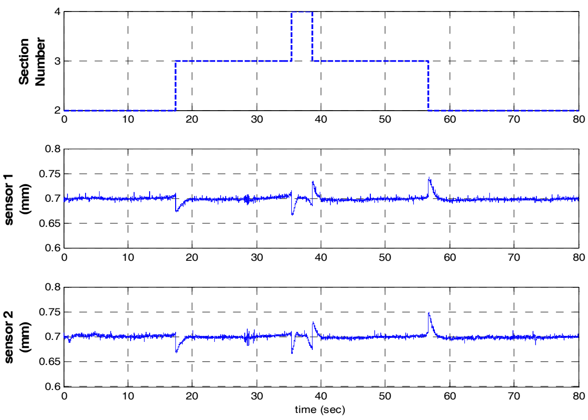
3.3 Experimental setups

To verify the feasibility of the suggested SSA, a simple test-setup of the EMS with two Section-changes is made up, where an 18 *kg* weighted, 0.45 *m* long tray is levitated. A ball-screw linear motor is used to servo control the longitudinal displacement of the tray. The EMs are placed with *P* interval and two gap-sensors are located between magnets with *2P* interval on the rail as shown as Fig. 11. Using the definition of the tangent function in Fig. 11 (a), the pitch angle θ and the average gap above the CMP of the tray δ can easily be calculated as follows:

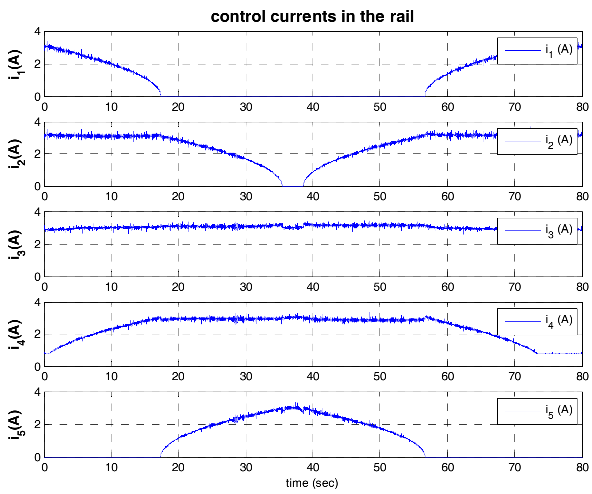
$$\theta = \tan^{-1}\left(\left(\delta_1 - \delta_2\right) \Big/ 2P \right)$$
$$\delta = \delta_2 + \left(2.5P - x\right)\tan\theta \tag{8}$$



(a) The performance of the EMS and SSA w.r.t. longitudinal displacement



(b) Feedback gap sensor value w.r.t. section



(c) Distribution of rail currents by the SSA

Fig. 12. Section Switching results(2→3→4→3→2)

3.4 Experimental results and discuss

Experiments are done with the test setup in the same manner as the simulation. When the levitation controls and SSA are working, the CMP of tray is moved forward and backward from 2^{nd} magnet position to the 4^{th} magnet position with *2P* intervals. This means that the Section Number is changed twice as the tray moves. Therefore a long distance operation of the EMS is possible by extension of the Section.

The experimental results are shown in Fig. 12. Fig. 12 (a) shows the longitudinal displacement of the tray and Section Number and Section Deviation. The controlled gap and pitch angle of the tray at CMP are also shown. Fig. 12 (b) shows the feedback gap sensor signals and Section Number. Fig. 12 (c) shows the controlled currents in EMs on the rail, which is determined by the SSA.

From the experimental results, the gap deviation performance of under ±40 μm at Section Number changing moment can be seen with the *18 kg* test tray. This value is 6 times smaller than the convention EMS shown in [16], where the deviation cannot be decreased because of complex control units and heat generation on the tray. The deviation of ±40μm can be thought because of the differences between simulation model and real plant such as time delay in EM driving amplifier and constant air-gap assumption in Eq. (6), and so on. This can be decreased more if more precise section switching algorithms are applied in near future.

The load capability of the proposed EMS, an 18 *kg* tray is several times higher than the air-cored PMLSM shown in [1, 2, 3]. The EM actuator like proposed EMS can have maximum load capability of 32 N/cm^2 according to [24].

From the experimental results, the proposed EMS has the same load capability as the conventional EMS and higher precision gap control performance over the conventional one and can extend its stroke infinitely by adding and changing Sections according to the SSA.

4. Conclusion

A new contactless linear bearing, which can be useful for recent OLED in-line fabrication process is proposed in this paper. It is new type of the conventional EMS and it can support heavy-weighted moving tray in the long distance rail very precisely with the help of periodic placement of EMs on a rail and newly proposed SSA. For the proof of feasibility of the proposed EMS and SSA, test setup of a moving tray model is constructed in simulation and experiment. To support the tray with gap of 0.7 *mm* and pitch angle of zero degree, the SMs, which can make bearing forces against tray weight at the same time, are defined and analyzed. Also the SSA is derived using the fact that the moment generated by SMs at the CMP of the tray should be zero at any time. With the SSA and proper conventional levitation control algorithm, the suggested linear bearing can support a 18 *kg* weighted, 450 *mm* long test tray with gap control performance under sub μm range in the simulation, and under ±40 μm in the experiment. The gap deviation being occurred whenever Section Number changes in the experiment can be reduced dramatically if more precise section switching control is applied in near future.

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