Dynamic Analysis of a Maglev Conveyor Using an EM-PM Hybrid Magnet

Ki-Jung Kim*, Hyung-Suk Han**, Chang-Hyun Kim† and Seok-Jo Yang*

Abstract – With the emergence of high-integration array and large area panel process, the need to minimize the generation of particles in the field of semiconductor, LCD and OLED has grown. As an alternative to the conventional roller system, a contactless magnetic conveyor has been proposed to reduce the generation of particles. An EM-PM hybrid which is one of magnetic levitation types is already proposed for the conveyor system. One of problems pointed out with this approach is the vibration caused by the dynamic interaction between conveyor and rail. To reduce the vibration, the introduction of a secondary suspension system which aims to decouple the levitation electromagnet from the main body is proposed. The objective of this study is to develop a dynamic model for the magnetically levitated conveyor, and to investigate the effect of the introduced suspension system. An integrated model of levitation system and rail based on 3D multibody dynamic model is proposed. With the proposed model, the dynamic characteristics of maglev conveyor system are analyzed, and the effect of the secondary suspension and the stiffness and damping are investigated.

Keywords: Maglev conveyor, dynamic simulation, EM-PM hybrid magnet, Secondary suspension

1. Introduction

During the last decade, the display industry has made great strides. Significantly, LCD and OLED displays are now widely used in digital devices such as TVs, computer monitors, and many handheld devices. In general, a high level of cleanliness should be maintained in the display manufacturing process. But, it is difficult to accomplish this level cleanliness with the contact-type conveyor system that is currently in use. It is important to decrease the particles generated during the conveyance process, because LCD or OLED panels are more likely to have defects than most semiconductor ICs due to their larger size. As friction between wheels and tracks is the main source of generated particles in conventional conveyor systems, a magnetically levitated suspension may be a good solution to this problem.

An EM-PM hybrid which is one of the magnetically levitated types is already proposed for the conveyor system [1-5]. One of problems with this approach that has been pointed out is the vibration caused by the dynamic interaction between conveyor and rail. To reduce the vibration, the introduction of a secondary suspension system is proposed to decouple the levitation electromagnet from the reference body. The objective of this study is to develop a dynamic model for the magnetically levitated conveyor, and to investigate the effect of the introduced spring as a secondary suspension system. To achieve this, an integrated model of levitation system and rail based on a 3D multibody dynamic model is proposed. With the proposed model, the dynamic characteristics of the maglev conveyor system are analyzed, and the effect of the secondary suspension and their stiffness and damping are investigated.

The remainder of this paper is organized as follows. Section II describes the design of the maglev conveyor system. Also, the design of levitation control and its feasibility are demonstrated. In Section III, dynamic modeling of the integrated system is explained. Section VI provides the dynamic analysis results of the conveyor with secondary suspension. Finally, Section V concludes this paper.

2. Design of the Maglev Conveyor System

2.1 Configuration

Fig. 1 shows a concept of Maglev conveyor system. The configuration is similar to that of a maglev train, in which rail structure is surrounded by the levitation support [6-8]. Attraction forces between electromagnets and rails are used to support the conveyor. To reduce power consumption, we use permanent magnets (PM) as well as electromagnets (EM). The levitation forces are transmitted to the upper plate through a secondary suspension which is composed of linear guides and springs. In the middle of the vehicle, a linear induction motor (LIM) is installed to thrust the
vehicle with the electromagnetic induction force. In addition, guide rollers are employed to prevent collisions between the LIM and the rail. Fig. 2 shows the manufactured LCD glass conveyor system and its various components.

The required performances are listed in the Table 1.

| Table 1. Specifications of the conveyor system |
|----------------|----------------|
| Items          | Value          |
| Weight (Payload) | 250kg (100kg)  |
| Nominal air gap | 3mm            |
| Air gap deviation | ±1mm           |
| Speed           | 4m/s           |
| Acceleration    | 1m/s²          |

2.2 Levitation system

The levitation system consists of four EMs placed at four corners of the vehicle, and is designed to lift a 250kg mass including a 100kg load. Table 2 shows the important specifications of the designed levitation electromagnet. The nominal gap is 3mm, and the computed levitation force without any current at the nominal gap is 285kg.

In order to calculate the basic characteristics of the EM-PM hybrid levitation system in the design step, 3-D FEM is used to analyze its magnetic field distributions and static forces. Due to the relatively large air gap, there exists a large leakage flux which may lead to the error of 2-D FEM. We used a commercial 3-D FEM package named Ansoft’s Maxwell for the analysis.

Fig. 3 shows the estimated levitation force according to the current variation from -5A to +5A at different gaps. For example, assuming that the total weight of the vehicle is 285kg, an attraction force greater than 285kg can be generated by supplying +4A to the coil in order to levitate the vehicle at the landing position (5 mm gap). In addition, the attraction force is less than 285kg by supplying -4A to the coil in order to separate the vehicle from the rail at the stuck position (1 mm gap). Therefore, the levitation control of a 285kg vehicle can be achieved by supplying current within ±5A.

Fig. 4 shows the mathematical model of the electromagnet. In this figure, $c(t)$ denotes the length of the air gap, $f_d(t)$ is the disturbance force, and $i(t)$ is the current of coils. The attraction force $F(i(t),c(t))$, the so-called levitation force, of electromagnet suspension is expressed as (1), and force is the function of the current $i(t)$ and air gap $c(t)$ [9].

$$F = 2A\mu_0N^2\left(\frac{i(t) + i_{pm}}{c(t) + c_{pm}}\right)^2$$

Here,

- $A =$ the area of the pole ($m^2$)
- $\mu_0 =$ electrical coefficient
- $N =$ number of turns
- $i(t) =$ current of electromagnet ($A$)
- $c(t) =$ air gap ($mm$)
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\[ F(\Delta c(t), \Delta i(t)) = k_c \Delta c(t) - k_i \Delta i(t) + F_0 \]  

Here,

\[ k_c = 4 A \mu_0 N^2 \frac{h_b + i_{pm}}{(c_0 + c_{pm})^2} \]
\[ k_i = 4 A \mu_0 N^2 \frac{c_0 + i_{pm}}{(c_0 + c_{pm})^2} \]

Then, the control current signal \( \Delta i_c(t) \) is designed by the PD control theory as:

\[ \Delta i_c(t) = k_p \Delta c(t) + k_D \Delta c(t) \]

The feedback gains, \( k_p \) and \( k_D \), are designed for the linearized equation (5) by using optimal regulator theory. Then, the resulting equation for the control current is

\[ \Delta i(t) = w_c (k_p \Delta c(t) + k_D \Delta c(t) - \Delta i(t)) \]

To verify the characteristics of the designed levitation electromagnets and control systems, a simple levitation experiment was carried out. Because the levitation system is of interest from a design perspective, we disabled the function of secondary suspension by inserting rigid metal blocks into it. The levitation experiment lasted for 10 seconds: levitation starts at 1 second and stops at 7 seconds. In order to take off and land smoothly, ramp input was used as a reference trajectory. The actual weight of the manufactured conveyor is 230kg and we load an additional 50kg weight so that the total weight becomes 280kg. In this study, 4 measurement points are used to measure air gaps, currents and accelerations as shown in Fig. 5.

Fig. 6 shows measured gap trajectories and coil currents. The measured gaps are tracking the reference gap and stay near 3mm after levitation completes. There are small differences in air gaps among the four corners, which mainly results from the unbalanced weight distribution of the conveyor.

Above quantities are either physical constants or determined by the shape of electromagnets. However, the accuracy of a physically derived model is not good enough to be used in simulations. Instead, we used an approximated model of which parameters are obtained from FEM results using least square estimation. The resultant model can be utilized in dynamic analysis and control design.

2.3 Control system

This paper expressed the gap \( c(t) \) and the current \( i(t) \) in terms of the equilibrium state, \( c_0 \) and \( i_0 \), and the displacement and the control current, \( \Delta c(t) \) and \( \Delta i(t) \), around it as:

\[ c(t) = c_0 + \Delta c(t), \quad i(t) = i_0 + \Delta i(t) \]  

Then, the equation of motion around the equilibrium position \( c_0 \) is obtained as:

\[ m \frac{d^2 z(t)}{dt^2} = mg + f_d(t) - F(i(t), c(t)) \]  

The time delay between the commanded current and the actual current is approximated by the simplest first-order time delay model as:

\[ \Delta i(t) = \frac{w_c}{s + w_c} \Delta i_c(t) \]  

where \( \Delta i_c(t) \) is the reference current command and \( w_c \) is the cut-off frequency of electromagnetic current driver. The magnetic force is obtained by using linear approximation around the nominal equilibrium point (\( i_0, c_0 \)) [7]. The resulting linear equations of the system are

![Fig. 4. Simplified model of the levitation system](image_url)
For the coil current, we expect that the required current at the air gap of 3mm is about zero based on the levitation force characteristics in the previous section. From the figure, the coil current has a small positive value of about 0.5A as expected. In addition, it is observed that the required current for takeoff and landing is less than 6A, which is increased slightly because the initial air gap is larger than 5mm.

Based on these observations, the experiment results are consistent with the design results. We can utilize the design results to predict dynamic behaviors of the conveyor system in various simulations for further analysis.

3. Dynamic modeling

To predict dynamic behaviors of the conveyor system in various simulations, an integrated system model considering mechanical components, the designed levitation electromagnets and control systems verified in the experiments is proposed.

3.1 Procedure

Fig. 7 shows the 3-D model of the designed conveyor vehicle for dynamic simulation. A procedure for dynamic simulation is shown in Fig. 8. The paper uses LMS Virtual.Lab Motion as a dynamic analysis tool for generating and solving equations of motion [7-8]. The process is defined in Fig. 8 as follows:

LMS Virtual.Lab Motion performs modeling of bodies and their geometries, joints, suspension, and levitation control systems, and specifies the initial conditions for dynamic simulation. Equations of the magnetically-levitated system that will be given in the next section are defined in the user-defined subroutine of LMS Virtual.Lab Motion. The user-defined subroutine detects the air gap,
which is the distance between an electromagnet and rail and its derivative. Then, the subroutine evaluates the system of differential equations of the levitation system, and calculates the levitation forces. The forces are applied to both the electromagnet and the rail in the subroutine.

### 3.2 Electromagnet

In the determining levitation force using (5) and (7), the \( c(t) \) , \( \dot{c}(t) \) must be calculated from the position and velocity of the pair of bodies. The definition of the vertical air gap is illustrated in Fig. 9 [7-8]. The vector between the electromagnet and the guiderail is first defined in the global reference frame as

\[
\mathbf{r}_{om} = \mathbf{r}_i - \mathbf{r}_m = \mathbf{r}_{oi} + \mathbf{A}_s \dot{s}_{oi} - \mathbf{r}_{om} - \mathbf{A}_m \dot{s}_{om} \quad (8)
\]

where \( \mathbf{A}_s \) is the transformation matrix from guiderail to global reference frame and \( \mathbf{A}_m \) is the transformation matrix from electromagnet to global reference frame.

Transforming the vector in (8) into the guiderail reference frame, the vector in the guiderail reference frame is obtained by

\[
\begin{bmatrix}
\dot{s}_{im}(t) \\

\dot{c}(t)
\end{bmatrix}
= \mathbf{A}_i^T \mathbf{r}_{im} 
\quad (9)
\]

The \( z \) component of the vector in (9) is \( c(t) \) . Differentiating (8) with respect to time and transforming into the guiderail reference frame, the air gap velocity \( \dot{c}(t) \) can be derived as

\[
\dot{\mathbf{r}}_{im} = \dot{\mathbf{r}}_i - \dot{\mathbf{r}}_m = \dot{\mathbf{r}}_{oi} + \mathbf{A}_s \dot{\mathbf{s}}_{oi} - \dot{\mathbf{r}}_{om} - \mathbf{A}_m \dot{\mathbf{s}}_{om} 
\quad (10)
\]

\[
\dot{\mathbf{r}}_{im} = \mathbf{A}_i^T \dot{\mathbf{r}}_{im} 
\quad (11)
\]

To more accurately calculate the levitation force considering the relative position and orientation, the electromagnet’s levitation force is divided into 3 segments along the length of the pole face. After calculating the levitation force of each segment as shown in Fig. 10, they are summed into the total levitation force on one electromagnet, and the force is applied to both the electromagnet and the guiderail [7-8].

### 3.3 Guiderail

Generally, the irregularities in guiderail interacting with the electromagnets have great influence on vehicle vibration. To address this, the surface roughness of the guiderail may be restricted by specifying an allowable deviation. In this paper, the profiles as shown in Fig. 11 are used as the guiderail elevation disturbances in the dynamic behavior predictions [6-8].

### 4. Simulation

#### 4.1 Dynamic behavior

The simulation of air gap, an indicator for stability, is carried out with the model of the maglev conveyor proposed in section 3. Fig. 12 shows the air gap and...
levitation force time histories of each corner of electromagnets measured at gap sensors 1–4 when the maglev conveyor travels over the guiderail with irregularities in Fig. 11 at a constant velocity of 3 m/s. The suspension system is levitated stably, and all results indicate that the air gaps vary from the nominal air gap of 3 mm. Thus, the maglev conveyor with an EM-PM hybrid suspension system yields stable performance with adequate gap response to the disturbance.

### 4.2 Analysis of the effect of secondary suspension

To investigate the effect of using a spring as secondary suspension for maglev conveyor, springs were installed at 4 corners between electromagnets and car body. Fig. 13 and 14 show the air gap time histories of sensor 1 during running with no spring and with springs, having different stiffness. Meantime, damping ratio constant is maintained as $\zeta=0.3$. Except for the spring with stiffness of 22.5 kN/m which fails to levitate, the remaining springs and the case without a spring yielded stable performance with adequate air gap response to the disturbance overall. Namely, all results indicate that air gaps are varied from allowable deviation of ±1 mm.
In the acceleration responses of the car body, the results of each case show better performances than the designed specifications of the manufactured maglev conveyor, 1m/s². The standard deviation of air gaps and accelerations at sensor 1 are presented as shown in Fig. 15, to consider the variability in values. Consequently, all results indicate that the secondary suspension is feasible and effective for use in the maglev conveyor system. In addition, springs with stiffness between 27.5 and 32.5kN/m for air gap and acceleration have relatively strong effects.

5. Conclusion

In this paper, the use of a multibody dynamic model for an EM-PM hybrid-type maglev conveyor was proposed in order to accurately predict dynamic characteristics, and this was carried out using the Virtual Lab. Motion program. Based on the results of the dynamic simulation and experiments, the following conclusions can be drawn.

First, experiments were performed to verify the designed control method. We can see that the designed controller with PD feedback loop can be levitated steadily without contact.

Secondly, using the dynamic model with the defined levitation system, this paper presents a more realistic dynamic simulation of maglev vehicle. Therefore, dynamic simulation could be useful in designing an air gap control system.

Thirdly, we can see that the introduction of a secondary suspension system is considerably effective in the reducing vibration of this suspension system with EM-PM Hybrid.

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References


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