Air Gap Control Simulation of Maglev Vehicles with Feedback Control System

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Abstract

The purpose of this paper is to more realistically predict the air gaps of the maglev vehicles under consideration. For doing so, the much more detailed dynamic modeling techniques, considering all the components are presented. In EMS-type maglev, air gap which is clearance between guideway surface and supporting magnet should be maintained within a limited value for preventing physical contact. The levitation control unit consists of electromagnets, gap sensors, choppers, and a controller. Thus, it would be desirable to include all the mechanical and electrical parts in the air gap simulation model. With the proposed model, air gaps are simulated to evaluate whether the mechanical contact would be occurred at maximum design speed.

Keywords: Air gap, Maglev vehicles, Electromagnetic suspension, Feedback control

1. Introduction

The magnetically levitated trains, as shown in Figure 1, have been proposed as a new passenger transportation mode due to their environmental advantages over conventional wheel-on-rail ones. One of the means of levitation is the use of attractive force of electromagnets being actively controlled for supporting the train without contact. Figure 2 shows the principle of levitation by the attractive of electromagnets. It is the core technology in this kind of train to maintain all the air gaps within a certain range, for instance 8mm, to prevent physical contact between vehicle and guideway surface by control levitation control method. The air gap variations depend heavily on various elements from guideway and vehicle. For example, the guideway’s structural characteristics, such as stiffness, mass, and surface irregularities, as well as vehicle’s mechanical and electrical. Therefore, to optimize the vehicle and guideway, it would be desirable to include all the components in air gap simulations. In the 1970s, some researchers extensively studied the evaluation of dynamic characteristics, like ride quality, of magnetic trains according to guideway construction tolerances and deflections [1-3]. Most dynamics model used was a planar model. To achieve a more realistic air gap, it would be desirable to include all the components in space with less simplification. The paper presents the much more detailed dynamic modeling techniques,
considering all the components, to more accurately predict the air gaps of the magnetic train under consideration. With the proposed model, air gaps are simulated to evaluate whether the mechanical contact would be encountered at maximum design speed.

![Image of urban maglev vehicles](image1)

**Figure 1. Urban maglev vehicles**

![Diagram of magnetic levitation principle](image2)

**Figure 2. Principle of magnetic levitation**

2. **Modeling**

2.1. **System modeling**

The dynamic modeling and analysis procedure are basically based on spatial multibody dynamics. So, the typical creation and execution of system modeling and analysis are not described on the paper while the specific ingredients proposed in the magnetic train are given. The system dynamic model consisting of two vehicles and 8 bogies is shown in Figure 3. The configuration of bogie having suspension and steering functions is shown in Figure 4. The proposed and specific to magnetic train modeling techniques are presented in the following sections. The automatic formulation and solution of the governing equations derived from all
the mechanical and electrical parts are executed following the computational multibody dynamics. [4-5]

Figure 3. Full vehicle multi-body dynamic model

Figure 4. Full vehicle multi-body dynamic model for the bogie

2.2. Electromagnet

Figure 4 illustrates the principle of magnetic suspension. The levitation force \( F_z(t) \), or lift force, and guidance force \( F_y(t) \) are functions of the air gap, \( c(t) \), lateral displacement, \( d(t) \), and current \( i(t) \). To define both the forces, the idle levitation force \( F_{0z}(t) \) is first defined when \( d(t) = 0 \) [2]. A reasonably accurate linear model may be obtained by using linear approximations of the idle levitation force around the nominal equilibrium point \( (i_0, c_0) \):

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\[ F_0(\Delta c(t),\Delta i(t)) = k_c\Delta c(t) - k_i\Delta i(t) + F_{\text{static}} \]  
(1)

\[ \Delta i(t) = \frac{k_c}{k_i} \Delta c(t) - \frac{R}{L_0} \Delta i(t) + \frac{1}{L_0} \Delta v(t) \]  
(2)

Where

\[ L_0 = \frac{\mu_0 N^2 A}{2c_0}, \quad k_i = \frac{\mu_0 N^2 A_i}{2c_0^2}, \quad k_c = \frac{\mu_0 N^2 A_i^2}{2c_0^3} \]

\[ F_{\text{static}} : \text{Static force (N)}, \]
\[ F_0 : \text{Idle levitation force (N)}, \]
\[ A : \text{Section area of magnet (m2)}, \]
\[ \mu_0 : \text{Permeability factor}, \]
\[ N : \text{Number of turn of magnet coil (turn)}, \]
\[ i_0 : \text{Nominal current (A)}, \]
\[ c_0 : \text{Nominal air gap (m)}, \]
\[ c : \text{Air gap (m)}, \]
\[ v : \text{Voltage (V)}, \]
\[ R : \text{Resistance (Ω)}. \]

\[ F_z = F_0 \times \left[ 1 + \frac{2c(t)}{\pi w_m} + \frac{2d(t)}{\pi w_m} \cot^{-1} \left( \frac{c(t)}{d(t)} \right) \right] \]  
(3)

**Figure 5. Principle of electromagnetic suspension**

If the lateral displacement of the electromagnet from the guiderrail \( d(t) \neq 0 \), then the levitation and guidance forces may be expressed as
\[ F_y = F_0 \times \left( -\frac{2c(t)}{\pi w_m} \tan^{-1}\left( \frac{d(t)}{c(t)} \right) \right) \]  \hspace{1cm} (4)

where

- $F_y$: Guidance force,
- $F_z$: Levitation force,
- $d$: Lateral displacement (m),
- $c$: Air gap (m),
- $w_m$: Magnet width (m).

### 2.3. Levitation control

The train employs the 5 states feedback control law to maintain the change in $\Delta c(t)$ within an allowable magnitude [6]. Using the control law, the controlled voltage is determined by

\[ \Delta v(t) = k_1 \Delta \hat{\ddot{z}}(t) + k_2 \Delta \hat{\dot{z}}(t) + k_3 \Delta \hat{\dot{z}}(t) + k_4 \Delta \hat{\dot{z}}(t) + k_5 \Delta \hat{\dot{c}}(t) \]  \hspace{1cm} (5)

where

- $\Delta \hat{\ddot{z}}(t)$: Observed acceleration,
- $\Delta \hat{\dot{z}}(t)$: Observed velocity,
- $\Delta \hat{\dot{z}}(t)$: Observed position,
- $\Delta \hat{\dot{c}}(t)$: Observed air gap velocity,
- $\Delta \hat{\dot{c}}(t)$: Observed air gap,
- $k_1, k_2, k_3, k_4, k_5$: Control gains.

As it is practically difficult to measure all 5 states in the Equation (5), an observer for estimation of the 5 states using only two states, which are the acceleration of the electromagnet $\Delta \hat{\ddot{z}}(t)$ and the air gap $\Delta \hat{\dot{c}}(t)$, is used in the paper. Of course, the observer is designed in consideration of the operating speed and the guideway characteristics. The following equations of states below are employed in this paper as Equations (6) and (7) [7].
\[
\begin{bmatrix}
\dot{x}_1(t) \\
\dot{x}_2(t) \\
\dot{x}_3(t) \\
\dot{x}_4(t) \\
\dot{x}_5(t)
\end{bmatrix} = \begin{bmatrix}
0 & \frac{1}{T_j} & 0 & -\frac{1}{T_j} & 0 \\
-\frac{1}{T_j} & -\frac{V_j}{T_j} & 0 & \frac{V_j}{T_j} & 0 \\
0 & \frac{1}{T_2} & -\frac{V_2}{T_2} & 0 & \frac{V_2}{T_2} \\
0 & 0 & 0 & -\frac{V_3}{T_3} & \frac{1}{T_3} \\
0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x_1(t) \\
x_2(t) \\
x_3(t) \\
x_4(t) \\
x_5(t)
\end{bmatrix} + \begin{bmatrix}
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
\Delta z(t) \\
\Delta \dot{z}(t) \\
\Delta \ddot{z}(t) \\
\Delta \dot{c}(t) \\
\Delta \ddot{c}(t)
\end{bmatrix}
\] (6)

\[
\begin{bmatrix}
\Delta \ddot{z}(t) \\
\Delta \dot{c}(t) \\
\Delta \dot{z}(t) \\
\Delta \ddot{c}(t)
\end{bmatrix} = \begin{bmatrix}
-1 & -V_j & 0 & V_j & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
x_1(t) \\
x_2(t) \\
x_3(t) \\
x_4(t) \\
x_5(t)
\end{bmatrix} + \begin{bmatrix}
1 & 0 \\
0 & 0 \\
0 & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
\Delta \ddot{z}(t) \\
\Delta \dot{c}(t) \\
\Delta \dot{z}(t) \\
\Delta \ddot{c}(t)
\end{bmatrix}
\] (7)

\( T_j - T_j \) and \( V_j - V_j \) are parameters that determine cut-off frequencies, in observing the 5 states, and damping. The parameters are chosen considering levitation control strategy, guideway irregularities, and vehicle speed. The optimum design of the parameters and gains in Equations (5) through (7) is the key technology in this levitation control system.

2.4. Guideway irregularity

The guideway irregularities to be considered are the deflections of girder and rail and randomly formed surface roughness. They are shown in Figures 3 to 5. The surface roughnesses in two plans in Figure 5 are numerically generated by using random function based on measured profiles [5-6]. All the irregularities are combined and then input as disturbance to the vehicle.
Figure 6. Guideway deflection

Figure 7. Guiderail deflection aligned with allowable deflections

Figure 8. Generated guideway surface profiles

(a) Vertical irregularity
(b) Lateral irregularity
3. Analysis

The comparisons of air gaps from simulations and tests are first performed. Figure 10 shows the measured air gaps of one electromagnet on vehicle with varying speed from 20km/h to 44km/h. The impulsive air gaps are encountered at rail joints, which are ignored in control system by switching the measured two gap signals from dual sensor. The peak air gap deviations from nominal one are tabulated in Table 4. For at 44km/h, 1.6mm is the peak air gap deviation. The simulated air gaps at 44km/h are shown in Figure 11. It seems that the peak air gap deviation is about 1.5mm which is very similar to that of test. From the results, even though the rail profile disturbance is somewhat different, the simulation model can represent the actual system. The prediction of air gap at maximum design speed, 110km/h, is carried out to see if those exceed the intentionally limited one of ±3mm. The 8 air gaps on all the bogies are simulated at the speed of 110km/h, as shown in Figure 12. Deviations of all the air gaps from the nominal one of 8mm are within ±3mm. Therefore, it can be expected that the magnetic train can run without mechanical contact between guideway surface and vehicle at 110km/h, maximum design speed.

![Figure 9. Variation air gap according to velocity](image)

Table 1. Peak air gap deviations

<table>
<thead>
<tr>
<th>Speed(km/h)</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>38</th>
<th>44</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak air gap deviation(mm)</td>
<td>0.9</td>
<td>1.1</td>
<td>1.3</td>
<td>1.5</td>
<td>1.6</td>
</tr>
</tbody>
</table>
Figure 10. Vertical air gap at 44km/h
4. Conclusion

It is confirmed that the proposed air gap simulation model including all the mechanical and electrical components well represents the actual magnetic train under consideration. With the model, peak variation of air gaps, at maximum speed of 110km/h, are predicted to see whether exceeds the allowed deviation, ±3mm. It can be noted that the resulting air gap deviations obtained by simulations are within ±3mm, which means the magnetic train could run without physical contact up to 110km/h. The model providing more realistic air gap simulation could be employed to optimize the magnetic train system.

References

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