Controller Design for Commercial Maglev Vehicle

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HongJu Kim, ChoonKyung Kim and SoonMan Kwon
Instrumentation & Control Research Group, P.O. Box 20, Chang Won, 641-600, KOREA
hjkim0429@keri.re.kr, ckkim@keri.re.kr, and smk@keri.re.kr

ABSTRACT: An electromagnetic levitation controller design considering guideway deflection is presented. Even though to design a maglev controller to make a vehicle steady suspension under guideway deflection is a key technology in maglev vehicle system, the vehicle-guideway interaction effects haven't well explored and yet settled. Unlike most approaches based on the linear model, a maglev controller is designed under the nonlinear model.

The nonlinear model for the electromagnetic levitation control system is derived. A guideway is simply modeled to the sinusoidal function, which acts as a disturbance to the maglev control system. Based on the model, a state feedback and a sliding mode control are proposed. The feasibility of the controller is verified through the simulation. All parameters used in the simulation are based on the maglev vehicle which is developed by the commercialization project in Korea.

1 INTRODUCTION

Maglev vehicles are considered as the next generation public transportation system because the lack of physical contact offers superior performance over mechanical bearings from the viewpoint of friction and wear. Compared with ordinary wheeled vehicles, maglev vehicles have advantage such as comfort, lower noise. Several countries have tried to commercialize maglev vehicles as urban transportation means. For successful commercialization, there are many important technologies such as rail construction, maglev vehicle manufacture, and electrical equipment and controller design. Among those technologies, electromagnetic levitation controller design is a key technology because maglev system itself is open loop unstable. The force of attraction between two magnetized bodies is proportional to the inverse square power of their separation, so there is no equilibrium point between two magnetized bodies. The force between an electromagnet and its reaction rail is open-loop unstable. Therefore, it is essential task to design a high performance closed-loop feedback controller to stabilize the force and provide a satisfactory suspension response. When designing a maglev controller, external factors must be considered. When a maglev vehicle runs on an elevated flexible guideway that is mainly made of steel and concrete, elastic deformation takes place in an elevated guideway and can affect the performance of the levitation controller. This elastic deformation dynamically interacts with the maglev vehicle, which even makes the maglev vehicle unstable. In this sense, the interaction between the maglev vehicle and guideway should be included at controller design stage. Controller design problem were addressed in many papers [1-4] but papers which present the controller design problem under vehicle-guideway interaction are few and most of the papers used the linear model and linear controller but this paper is based on the nonlinear model and nonlinear controller. It is well known that the sliding mode control provides a systematic approach to controller design in presence of external disturbances. Using the sliding mode control technique, the interaction affected by the guideway deflection is reduced. The fundamental nonlinear equation for the levitation is derived in model of the magnetic levitation system Section. Nonlinear levitation controller design Section describes the nonlinear levitation control without the guideway defection. Sliding mode controller design Section presents the sliding mode control with the guideway deflection. Simulation results Section shows the feasibility of the controller. The parameters used in simulation are specified. Conclusion Section concludes the paper and proposes the future work.

2 MODEL OF THE MAGNETIC LEVITATION SYSTEM

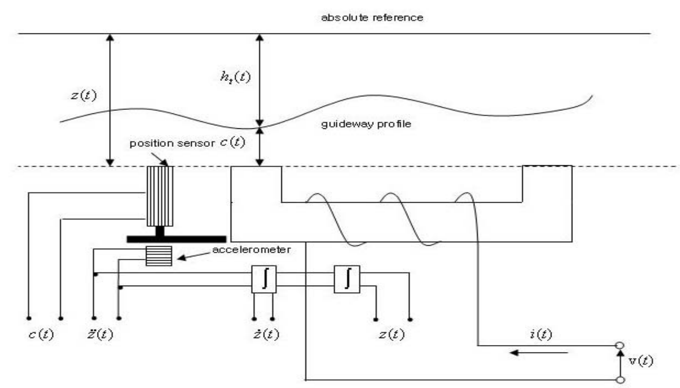

Figure 1. System configuration with an absolute reference.

For the electromagnet shown in Figure 1, the attraction force is

$$F(i,c) = \frac{\mu_0 N^2 A}{4}[\frac{i(t)}{c(t)}]^2, \tag{1}$$

where μ_0 is permeability of air, N is the number of turns, A is the cross sectional area, $i(t)$ is the excitation current and $c(t)$ is air gap. The force in (1) will affect the vertical dynamics of the system which is described by

$$m\ddot{z}(t) = -F(i,c) + mg, \tag{2}$$

where $z(t)$ represents the position of the magnet in space. The relation between $c(t)$ and $z(t)$ is given by

$$c(t) = z(t) - h_t(t), \tag{3}$$

where $h_t(t)$ is the guideway height. The excitation current is controlled by

$$v(t) = Ri(t) + \frac{\mu_0 N^2 A}{2c(t)}\frac{di(t)}{dt} - \frac{\mu_0 N^2 A i(t)}{2[c(t)]^2}\frac{dc(t)}{dt}, \tag{4}$$

where R is the total resistance of the circuit. The following variables are defined to simplify (1), (2) and (4).

$$x_1 = c$$

$$x_2 = \frac{di}{dt}$$

$$k = \frac{2}{\mu_0 A}$$

Using the above notations, (2) and (4) can be rewritten as

$$m\ddot{x}_1 + \frac{N^2}{2kx_1^2}\dot{x}_2^{\,2} + m\ddot{h}_t - mg = 0 \tag{5}$$

and

$$R\dot{x}_2 + \frac{N^2}{kx_1}\ddot{x}_2 - \frac{N^2\dot{x}_2}{kx_1^2}\dot{x}_1 = v \tag{6}$$

Gap error is defined as

$$e = m(x_1 - x_{1d}), x_{1d} = 0.008[m] \tag{7}$$

3 NONLINEAR CONTROLLER WITHOUT GUIDEWAY DEFLECTION

In case without the guideway defection, the guideway height is zero, that is, $h_t(t) = 0$. Differentiating (7) with respect to time, it gives

$$\dddot{e} = \frac{\dot{x}_2}{x_1}\left(\frac{N^2}{k}\frac{\dot{x}_1\dot{x}_2}{x_1^2} - \frac{N^2}{k}\frac{\ddot{x}_2}{x_1}\right) \tag{8}$$

$\dddot{e}$ can be expressed as follows after inserting (6) into (8).

$$\dddot{e} = \frac{\dot{x}_2}{x_1}\left(R\dot{x}_2 - v\right) \tag{9}$$

The controlled voltage is selected to stabilize the gap error to zero as follows

$$v = R\dot{x}_2 + \frac{x_1}{\dot{x}_2}(c_2\ddot{e} + c_1\dot{e} + c_0 e) \tag{10}$$

Then (9) becomes $\dddot{e} + c_2\ddot{e} + c_1\dot{e} + c_0 e = 0$. If c_0, c_1, c_2 are positive values, then $e \to 0$ as $t \to \infty$. $\dot{x}_2$, $\ddot{e} = m\ddot{z}$, x_1 can be acquired by using the CT sensor, acceleration sensor, gap sensor, respectively. $\dot{e}$ is estimated by using the following derivative filter.

$$\dot{e}(s) = m\frac{10^6 s}{s^2 + 10^3 s + 10^6}c(s) \tag{11}$$

4 SLIDING MODE CONTROLLER WITH GUIDEWAY DEFLECTION

Differentiating (3) with respect to time and inserting (6) into the result equation, $\dddot{e}$ can be expressed as

$$\ddot{e} = \frac{\dot{x}_2}{x_1}\left(R\dot{x}_2 - v\right) - m\dddot{h}_t \tag{12}$$

The first step in designing a sliding mode control is to design a switching surface. Let the switching surface s be

$$s = \ddot{e} + c_2\dot{e} + c_1 e, \tag{13}$$

where c_1 and c_2 are positive scalars.
Differentiating (13) with respect to time and using (12), $\dot{s}$ is as follows

$$\begin{aligned} \dot{s} &= \dddot{e} + c_2\ddot{e} + c_1\dot{e} \\ &= \frac{\dot{x}_2}{x_1}\left(R\dot{x}_2 - v\right) + c_2\ddot{e} + c_1\dot{e} - m\dddot{h}_t \end{aligned} \tag{14}$$

The controlled voltage v is proposed as

$$v = R\dot{x}_2 + \frac{x_1}{\dot{x}_2}\left(c_2\ddot{e} + c_1\dot{e} + v_s\right), \tag{15}$$

where v_s is a switching controller.
Substituting v in (15), $\dot{s}$ can be written as

$$\dot{s} = -v_s - m\dddot{h}_t \tag{16}$$

v_s is designed to make $\dot{s}$ in (16) be negative as follows

$$v_s = k\,\mathrm{sgn}(s), k > \left|m\dddot{h}_t\right|_{\max} \tag{17}$$

The above v_s satisfies the sliding condition as follows

$$\begin{aligned} V(s) &= \frac{1}{2}s^2 \\ \dot{V}(s) &= s\dot{s} = s(-m\dddot{h}_t - k\,\mathrm{sgn}(s)) \\ &= -k|s| - m\dddot{h}_t s \\ &= -(D+\eta)|s| - m\dddot{h}_t s \\ &\le -\eta|s|, D = \left|m\dddot{h}_t\right|_{\max}, k > D \end{aligned} \tag{18}$$

Chattering is undesirable because it involves high control activity and may excite high-frequency dynamics. Therefore v_s is redesigned to avoid chattering as follows

$$\begin{aligned} v_s &= ksat(s/\Phi), k > \left|m\dddot{h}_t\right|_{\max} \\ sat(s/\Phi) &= \begin{cases} -1 & \text{if} \quad s/\Phi \le -1 \\ s/\Phi & \text{if} \quad -1 < s/\Phi \le 1 \\ 1 & \text{if} \quad s/\Phi > 1 \end{cases} \end{aligned} \tag{19}$$

5 SIMULATION RESUTS

Parameters used in simulation are as follows

- $m_0 = 1250[kg], A = 0.01888[\mathrm{m}^2]$
- $L = 0.07[H], R = 1.2[\Omega]$
- $z_0 = 0.008[m], i_0 = 28.6[A]$
- $c_0 = 77408, c_1 = 8972, \mathrm{c}_2 = 133$

The guideway height is simplified as follows

$$\begin{aligned} h_t(t) &= \frac{1}{2}\frac{L}{a}\sin(\omega t + \phi) + \frac{1}{2}\frac{L}{a} \\ L &= 25[m], a = 2000, \omega = 2\pi\frac{\mathrm{v}}{\mathrm{L}}, \phi = 2\pi\frac{3}{4} \end{aligned} \tag{20}$$

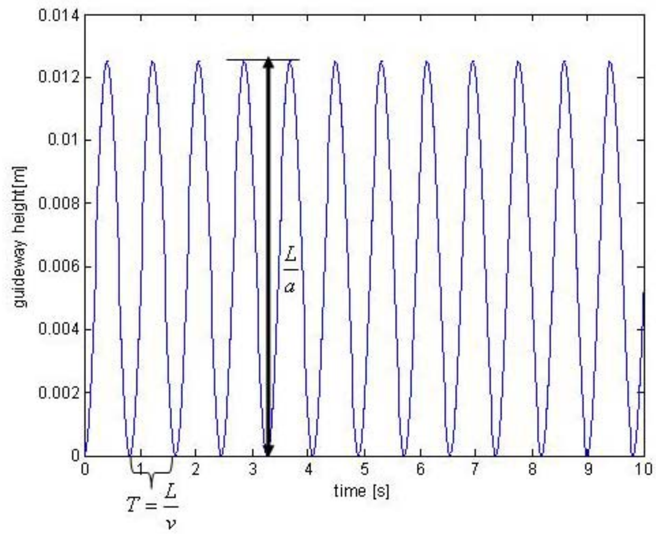

Figure 2. Profile of the guideway height.

Figure 2 shows the profile of the guideway height expressed as (20).
Three control algorithms are compared in simulation. First, the state feedback type linear controller is used as follows

$$v = k_{pr}c^* + k_{vr}\dot{c}^* + k_{pa}z_1^* + k_{va}\dot{z}_1^* + k_{aa}\ddot{z}_1^*$$

The unmeasured states are estimated by using the observer which outputs five states inputting two sensors, gap and accelerometer. As shown in Figure 3, the gap deviation is about ± 3mm which is acceptable but has room to improve.

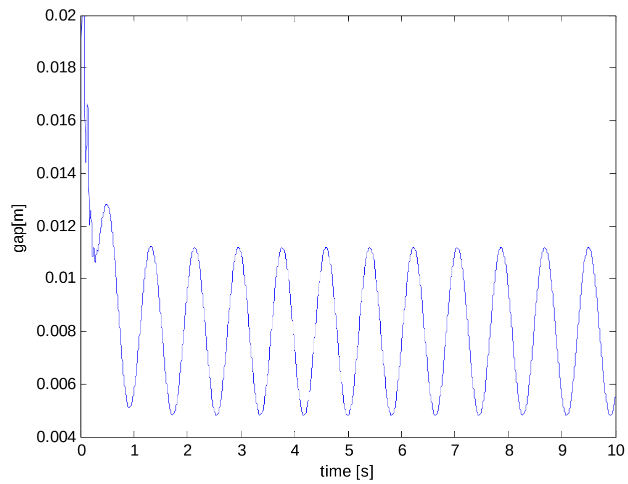

Figure 3. Gap profile of the state feedback controller.

Second, the nonlinear controller as (10) is used in simulation. As shown in Figure 4. The gap deviation is ± 0.7mm. This result is better than the state feedback type controller.

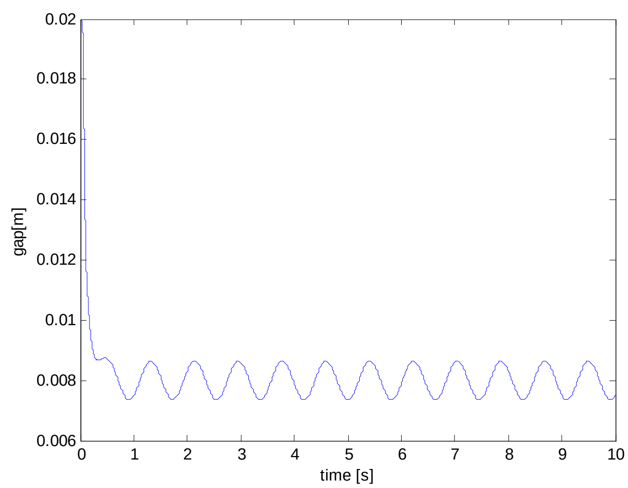

Figure 4. gap profile of the nonlinear controller.

Finally, the sliding mode controller as (15) is used. As shown in Figure 5, the gap deviation is ± 0.1mm which is the best result of the three algorithms.

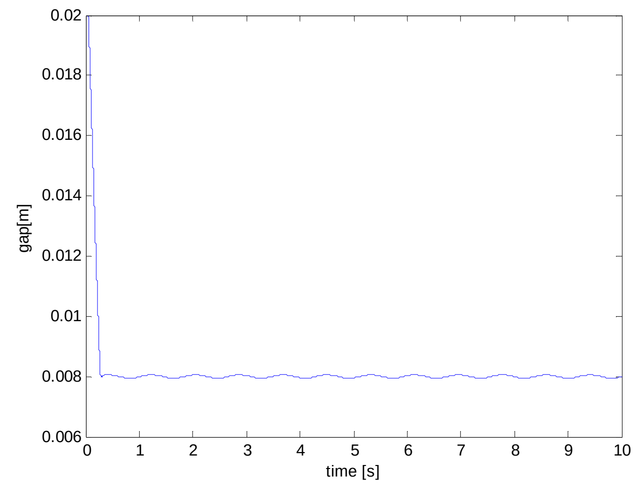

Figure 5. Gap profile of the sliding mode controller

6 CONCLUSIONS

In this paper, the nonlinear controller and the sliding controller are proposed and three control designs are compared. The sliding controller shows the best performance. In future, we will apply the proposed controllers to the commercial maglev vehicle and after that, will feedback the results for improvement.

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