Maglev System with Hybrid-excited Magnets And an Air-gap Length Control

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Keywords— state controller, hybrid magnet, linear synchronous motor, magnetic levitation.

Abstract—This paper describes the levitation control to a new maglev model vehicle with four hybrid-excited magnets for high-speed transportation. Four hybrid magnets are mounted at the bottom of the levitation frame that brings advantage of larger air gap length and less power loss compared with traditional electromagnetic suspension system. The air gap lengths are accurately controlled by only one chip of DSP and the maximum working air gap length may come up to 15mm. The Experiment results show satisfactorily stable levitation and robust performance to this model vehicle in our Lab, which verified the excellent characters and the rationality of the control strategy.

1. INTRODUCTION

Shanghai Maglev transportation system, which is based on Transrapid08 technology, has started its commercial operation with the maximum speed 430Km/h [1]. Transrapid is a typical electromagnetic suspension (EMS) system with the levitation air-gap of only about 10mm, which requires very high precision of the track and causes the high cost to the long distance Maglev line. Another disadvantage of this kind of EMS system is that the magnets consume too much energy. So auxiliary power rail must be constructed along the track. Also batteries of large capacity are needed onboard. Both the structures of the vehicle and the guide way become more complex. In this paper, levitation control to a new maglev model vehicle with four hybrid-excited magnets [2] is described. The levitation clearance is elongated and the energy consumed by levitation subsystem is significantly reduced due to permanent magnets. Figure 1 shows the prototype of the carrier with four hybrid-excited magnets that are mounted at the four corners on one surface. Figure 2 shows a picture of the

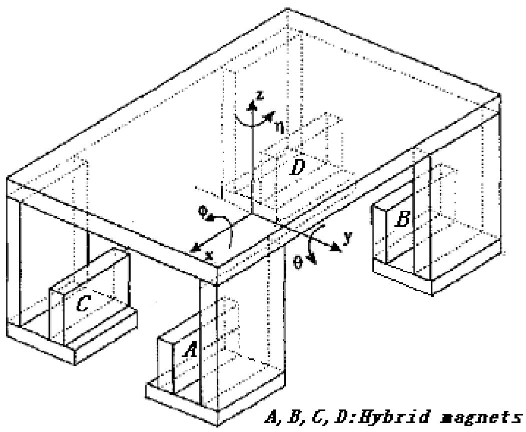


Figure 1.The carrier of the maglev

Figure 2. A picture of the maglev system

maglev system including the carrier and the guide way in our Lab.

2. DESIGN OF THE CONTROLLERS

Four motion modes of the carrier are considered in this paper [2].

Equations could be described as follows [6].

$$\mathbf{M}\ddot{\mathbf{Z}}_{\mathbf{g}} = -\mathbf{f}_{\mathbf{mg}} + \mathbf{f}_{\mathbf{exg}} \tag{1}$$

$$\mathbf{M}_\theta \ddot{\mathbf{Z}}_\theta = -\mathbf{f}_{\mathbf{m}\theta} + \mathbf{f}_{\mathbf{ex}\theta} \tag{2}$$

$$\mathbf{M}_\varphi \ddot{\mathbf{Z}}_\varphi = -\mathbf{f}_{\mathbf{m}\varphi} + \mathbf{f}_{\mathbf{ex}\varphi} \tag{3}$$

$$\mathbf{M}_\delta \ddot{\mathbf{Z}}_\delta + \mathbf{C}_\delta \dot{\mathbf{Z}}_\delta + \mathbf{K}_\delta \mathbf{Z}_\delta = -\mathbf{f}_{\mathbf{m}\delta} + \mathbf{f}_{\mathbf{ex}\delta} \tag{4}$$

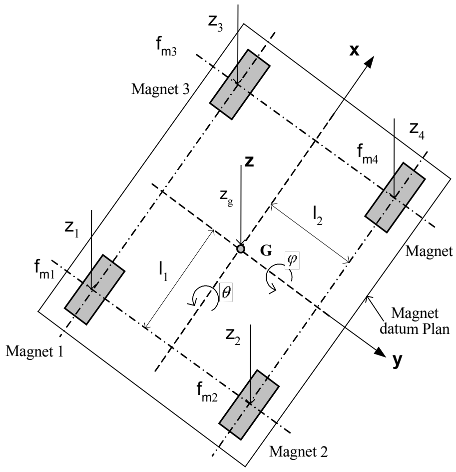


Figure 3. Model of bogie truck in

Where, $\mathbf{J}_\theta$ is the inertia moment of rolling axis, $\mathbf{J}_\varphi$ the inertia moment of pitching axis; $\mathbf{f}_{\mathbf{mg}}, \mathbf{f}_{\mathbf{m}\theta}$, $\mathbf{f}_{\mathbf{m}\varphi}$ and $\mathbf{f}_{\mathbf{m}\delta}$ are the equilibrium forces exerted on the carrier by the guide way respectively. $\mathbf{f}_{\mathbf{exg}}$, $\mathbf{f}_{\mathbf{ex}\theta}$, $\mathbf{f}_{\mathbf{ex}\varphi}$. and $\mathbf{f}_{\mathbf{ex}\delta}$ are the disturbances inertia moment. In addition, $\mathbf{M}_\theta = \mathbf{J}_\theta / \mathbf{l}_1^2$ is the effective mass in rolling, $\mathbf{M}_\varphi = \mathbf{J}_\varphi / \mathbf{l}_2^2$ the effective mass in pitching, $\mathbf{M}_\delta$ torsion inertia mass, $\mathbf{C}_\delta$ brake coefficient, $\mathbf{K}_\delta$ torsion coefficient, and $\mathbf{Z}_\theta = \mathbf{l}_1\theta$, $\mathbf{Z}_\varphi = \mathbf{l}_2\varphi$. We also have the following relation equation:

$$\begin{bmatrix} \mathbf{Z}_1 \\ \mathbf{Z}_2 \\ \mathbf{Z}_3 \\ \mathbf{Z}_4 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{Z}_{\mathbf{g}} \\ \mathbf{Z}_\theta \\ \mathbf{Z}_\varphi \\ \mathbf{Z}_\delta \end{bmatrix} = \mathbf{T} \begin{bmatrix} \mathbf{Z}_{\mathbf{g}} \\ \mathbf{Z}_\theta \\ \mathbf{Z}_\varphi \\ \mathbf{Z}_\delta \end{bmatrix} \tag{5}$$

Further study shows that the coupling of the four hybrid magnets is weak under the condition that the length $(2\mathbf{l}_1)$ is relatively bigger than the width $(2\mathbf{l}_2)$ of the carrier, and the four hybrid magnets can be controlled independently. Because the four hybrid magnets have exactly the same structure, we just consider only one of them.

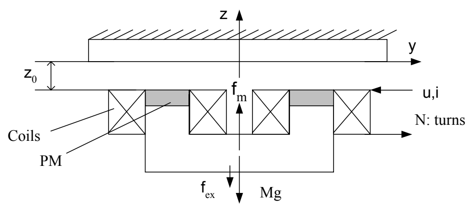


Figure 4. Analysis model of hybrid magnet

Neglecting the influence from armature current, the analysis model of a single hybrid magnet is shown in Fig.6. It is well known the magnetic flux density of hybrid magnet $\mathbf{B}$ is,

$$\mathbf{B} = \mu_0 \frac{\mathbf{N}\mathbf{i}_{\mathbf{e}}}{2\mathbf{Z}_{\mathbf{e}}} \tag{6}$$

$$\mathbf{Z}_{\mathbf{e}} = \mathbf{Z} + \mu_0 \mathbf{l} / \mu + \mu_0 \mathbf{H}_{\mathbf{c}} \mathbf{h}_{\mathbf{m}} \mathbf{B}_{\mathbf{r}} \tag{7}$$

$$\mathbf{i}_{\mathbf{e}} = \mathbf{i} + \frac{2\mathbf{h}_{\mathbf{m}}\mathbf{H}_{\mathbf{c}}}{\mathbf{N}} \tag{8}$$

where i_e is the effective current and Z_e is the effective gap length ; i is the real coil current and Z is the length of the mechanic air gap. μ_0 is free space permeability, N is the number of turns per control coil, H_c is the PM coercive force, B_r remanence, H_m the height of PM. Because there is linear generator on the magnet surface to supply levitation power when vehicle is running, the effective gap length become very large. The magnetic force is expressed as:

$$\mathbf{f_m} = \frac{\mathbf{B}^2\mathbf{S}}{\mu_0} = \frac{\mu_0\mathbf{N}^2\mathbf{S}}{4}\left[\frac{\mathbf{i_e}}{\mathbf{Z_e}}\right] \tag{9}$$

Where S is the cross section area of a single hybrid magnet. We can get the linearized, model of (8) around nominal operating point $(\mathbf{Z_{e0}}, \mathbf{i_0})$ as:

$$\mathbf{f_m} = \mathbf{K_i i} - \mathbf{K_z Z} \tag{10}$$

Neglecting leak inductance, circuit equation is linearized as,

$$\mathbf{u} = \mathbf{Ri} + \mathbf{L_0 i} - \mathbf{K_i} \dot{\mathbf{Z}}_\mathbf{k} \tag{11}$$

Where u is the control voltage of a specified hybrid magnet, R the resistance of the control coil, L_0 the inductance. K_i and K_z are linearized constants of current coefficient and gap coefficient respectively.

Linearized system in state equations is described in the following state equation:

$$\begin{aligned} \dot{\mathbf{X}} &= \mathbf{AX} + \mathbf{BU} \\ \mathbf{Y} &= \mathbf{CX} \end{aligned} \tag{12}$$

where : $\mathbf{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \frac{4\mathbf{K_z R}}{\mathbf{mL_0}} & 0 & -\frac{\mathbf{R}}{\mathbf{L_0}} \end{bmatrix}, \mathbf{X} = \begin{bmatrix} \int \mathbf{Z} \\ \mathbf{Z} \\ \dot{\mathbf{Z}} \\ \ddot{\mathbf{Z}} \end{bmatrix}, \mathbf{B} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ -\frac{4\mathbf{K_i}}{\mathbf{ML_0}} \end{bmatrix}, \mathbf{C} = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}^\mathbf{T}$ and $\mathbf{U} = \mathbf{u}$.

The state controller is designed based on the above state equation. According to the state feedback control theory and minimum error control method, command input is derived as:

$$\mathbf{u} = \mathbf{K_i}\int \mathbf{Zdt} + \mathbf{K_e Z} + \mathbf{K_v}\dot{\mathbf{Z}} + \mathbf{K_a}\ddot{\mathbf{Z}} = \mathbf{KX} \tag{13}$$

where: $\mathbf{K} = [\mathbf{K_i} \quad \mathbf{K_e} \quad \mathbf{K_v} \quad \mathbf{K_a}]$

This closed loop control system has four poles which decides the gains $\mathbf{K_i}, \mathbf{K_e}, \mathbf{K_v}$ and $\mathbf{K_a}$. To realize a steady and robust control of the closed loop control system, the feedback gains for state variable are deduced as follows by using the robust pole assignment.

$$\mathbf{K} = [-125302 \quad -14991 \quad -345 \quad -1.2]$$

3. EXPERIMENT RESULTS

The mass of the model vehicle device is 78Kg in total and the rated levitation gap length is 12.5mm. Part of the parameters of one magnet is given in table I. The four magnets are controlled by only one chip of DSP (TMS320F2407).

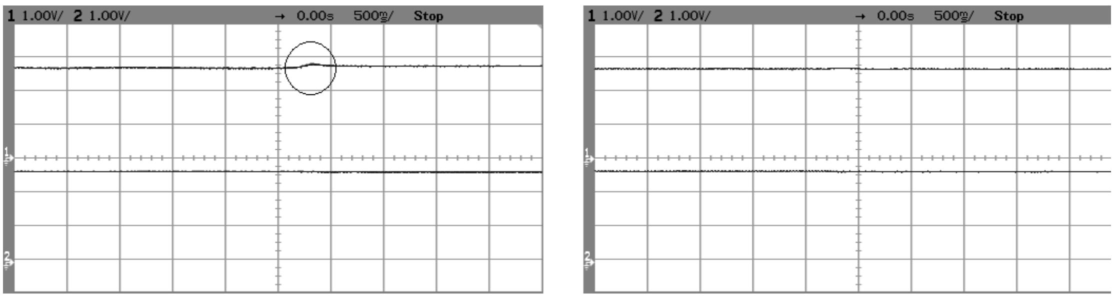
L_0	1.83×10^{-3}	H	M	23	Kg
R	1.75	Ω	K_Z	75540	N/m
I_0	1	A	K_I	11.8	N/A
Z_0	12.5	cm	U_{dc}	75	V

TableⅠ. The parameters of one magnet

Figure 9 shows the gap length of the vehicle during adding an 8Kg iron block at the position of the first hybrid magnet.

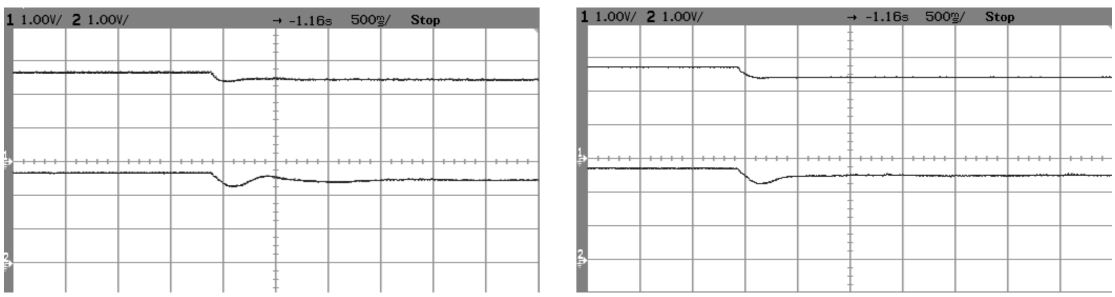
A circle in figure 9(a) marks the time when the iron block was added. It can be easily found that only the air gap of magnet 1 has a visible transient response procedure while the other 3 gaps almost keep constant at the same time. This proves the ideal levitation rigidity of the vehicle and also proves the feasibility of the assumption of the weak coupling of the four magnets.

Figure 10 shows the transient responses of the four gaps when a step of reference of 1mm occurs.



a. air gap of magnet 1 and magnet 2 b. air gap of magnet 3 and magnet 4

Figure 5.four gap of the vehicle when adding a mass of 8Kg at the position of magnet 1 (X: 0.5s/div, Y: 5mm/div)



a. gap of magnet 1 and magnet 2 b. gap of magnet 3 and magnet 4

Figure 6. Step of reference gap (X: 0.5s/div, Y: 5mm/div)

It shows that the transient procedures of the four gaps all finish within 0.5s. Test results show the ideal robust ability and rapidity of the system.

4. CONCLUSIONES

In this paper the mathematical model of the vehicle with four hybrid-excited magnets was analyzed. A controller was also developed to meet the high safety standard of high-speed vehicles based on the analysis of the mathematical model of the vehicle, and a relatively simple but feasible algorithm was also described for the controller. Test results show the satisfactory transient and stable performance of the vehicle. The energy-saving characteristic of the system proves its good perspective of appliance on high-speed maglev systems.

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