Design of a Magnetic Levitation System for Commercial Maglev Vehicle

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ABSTRACT: This paper discusses the design of a magnetic levitation system for a commercial MAGLEV vehicle. The magnetic levitation system for electromagnetic-suspension-type MAGLEV vehicle typically consists of a power supply such as DC/DC converter, electromagnets, magnet drivers including choppers and levitation controllers, and sensors. The bogie on which the magnets are attached can also be considered as a component of the levitation system. In this paper, how to design the hardware and software of the levitation controller is explained. The effect of the electrical characteristics of the electromagnet to levitation stability is investigated to derive a levitation control algorithm in which the interaction between the vehicle and the guideway is counted. In order to achieve a certain level of software quality for the control software, which is required for the software used in safety-related system, we follow a standard software development process based on the software life cycle. A reliability evaluation result to measure the hardware quality of the levitation controller is also included

1 INTRODUCTION

Electromagnetic-suspension-type maglev vehicles are being commercialized as urban and inter-city transportation systems in several countries [1-3]. In Korea, a realization program to build a new urban maglev vehicle in the area of Incheon international airport was initiated in November 2006, with the target of commercial operation by 2012. The vehicle will be running at 110[km/h] with 8[mm] nominal airgap.

The magnetic levitation system for electromagnetic-suspension-type MAGLEV vehicle usually consists of a power supply, electromagnets, magnet drivers including choppers and levitation controllers, and some sensors. The bogie where the magnets are installed may be included in the components of the levitation system.

One of the most important consideration factors in the levitation system design for commercial mid-low-speed maglev vehicle may be the satisfaction of the stability performance and reliability under the constraints on the rail, vehicle, and running speed.

In this paper, the design of the hardware and software of the levitation controller is explained in detail. Also, the effect on the levitation stability of the electrical characteristics of the electromagnet is analyzed. The analysis includes the consideration for the interaction between the vehicle and the guideway.

In order to fulfil the quality requirement of the software of the levitation controller for commercial use, we follow a software development process based on the software life cycle described in IEEE 1074. The reliability evaluation for the controller hardware is done in compliance with MIL-HDBK-217 F2.

Table 1 shows the whole system specifications that should be considered in the levitation system design.

Table 1. System specifications

Weight	Empty load :20ton Full load :26.5ton
Max. Speed	110km/h
Levitation	4bogies/car, 32magnets/car Nominal air gap:8mm
Propulsion	LIM Nominal air gap:11mm
Magnet Driver	Input voltage:DC300V Nominal current:27A Chopping freq.:5kHz
Guideway	Max. grade:7% Min. Radius:50mR Sag:L/2000

2 DESIGN OF MAGNETIC LEVITATION SYSTEM

2.1 Design of Electromagnet

Mass of the electromagnets is designed to be less than 3 ton per bogie to reduce mass of the whole vehicle and the response time is reduced as possible to guarantee the stable control. Table 2 shows the load conditions for single magnet design.

Table 2. The load conditions for single magnet design

Load	Units	Values	Remarks
Full Weight	N	8,124	26,500kg/32magnet
LIM Vertical Force	N	620	(2,480N/LIM)/4magnet
Load due to side wind	N	1,000	32,000N/32magnet, for side wind 26m/s
Over Payload	N	1,933	for 200% Payload(6,500kg/32magnet)
Displacement center of gravity	N	300	for 5%
One Magnet Failure	N	812	for 10% Full weight(8,124N*10%)
Total	N	12,789	

Table 3 shows the input parameters for designing the electromagnet.

Table 3. Input parameters for designing electromagnet

Item	Unit	Spec.	Remark
Empty car mass	ton	20.0	
Full loaded car mass	ton	26.5	
Max dynamic mass at max speed	ton	41.7	
Max speed	km/h	110	
# of bogie	ea	4	
Nominal gap	mm	8	
Max lateral displacement	mm	15	
Max dynamic force per magnet at max speed	N	12,789	41.7ton/32magnet
Length of the magnet	mm	589	

Table 4 shows the design results of electromagnet for commercial maglev vehicle. Also figure 1 shows the levitation and guidance force at nominal air gap to lateral deviation(0-15mm), and figure 2 shows the time constant variation to current density and temperature.

Table 4. the design results of electromagnet

Item	Unit	Analysis Result	Remark
rated attraction force	N	8,124	in case of single magnet
max. guidance force	KN	100(at 15mm lateral deviation)	in case of 1 vehicle
pole width	mm	216	-
pole height	mm	128	-
weight/magnet	kg	94	-
time constant	sec	0.5	-
LTWR	ton/ton	8.8	-

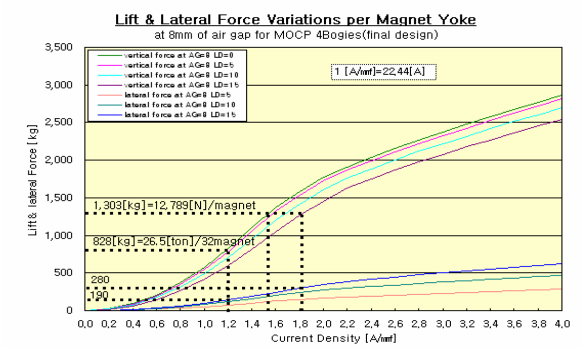

Figure 1. Levitation & guidance force at nominal air gap(8mm)

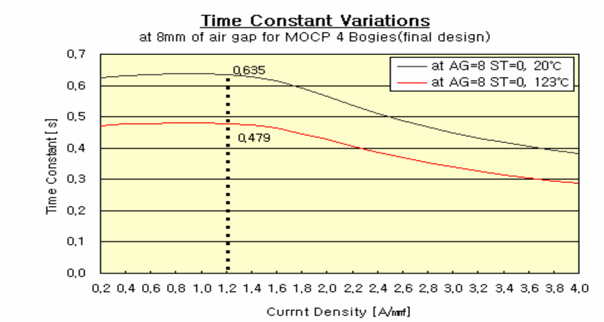

Figure 2. time constant to current density and temperature

2.2 Design of Magnet Driver

As shown in Figure 3, the magnet drive includes analog preprocessing circuit for sensors, DSP(Digital Signal Processor) micro controller and memory management circuit, IGBT driving circuit, and electro magnetic current driving circuit. By making dual controllers and dual power supply units, stability and reliability are greatly increased.

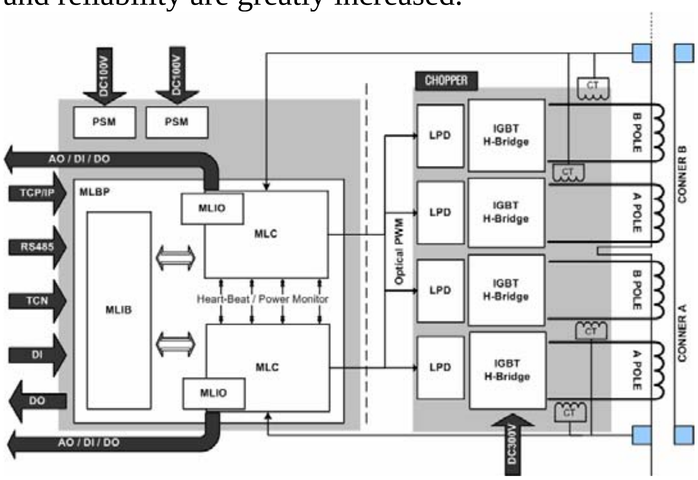

Figure 3. Structure of the magnet driver

The magnet drive is mainly divided into two units: one is the controller unit and the other is the chopper unit.

2.2.1 *The controller unit*

As shown in Figure 4, the controller unit is composed of the dual MLC(Magnetic Levitation Controller), MLO(Magnetic Levitation I/O) which is added on each MLC, the dual PSM(Power Supply Module), MLIB(Magnetic Levitation Interface Board), and MLBP(Magnetic Levitation Back Plane) on which each module is inserted.

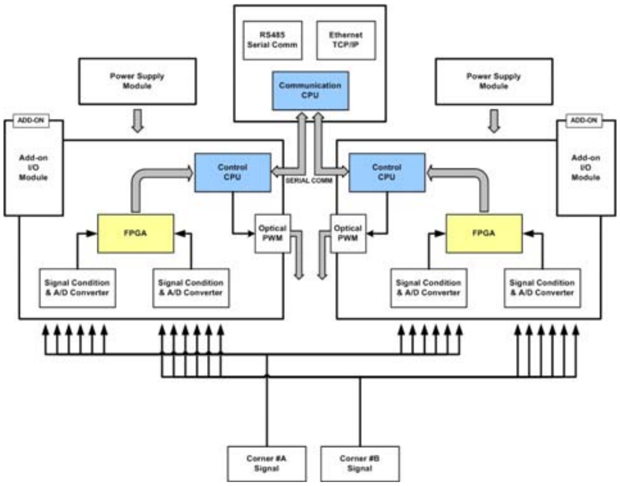

Figure 4. Structure of the controller unit.

2.2.2 *The chopper unit*

The dual chopper design is developed to increase reliability. Figure 5 shows the topology of the dual chopper. As shown in Figure 5, the chopper unit consists of four LPDs(Levitation Power Drive), eight IGBT modules for 1200V/160V, capacitor charging circuit including magnetic contacts and resistors for limiting current, two ultra capacitor for 5000uF/500V, and the hall effect PT and CT.

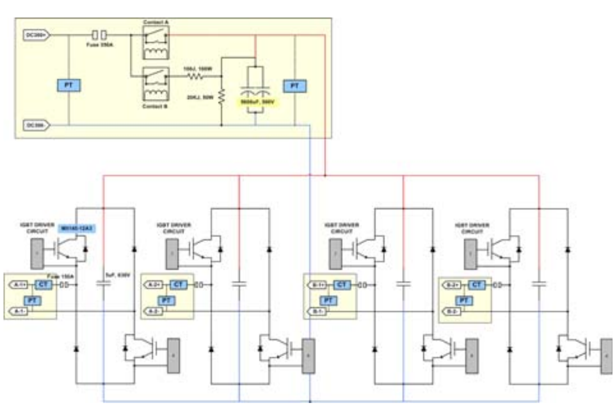

Figure 5. Structure of the chopper unit.

Figure 6 is the simulation result to verify the proper operation of it. At time 1 sec a fault happens at one half choppers, and then at time 2 sec the other half choppers takes care of driving current.

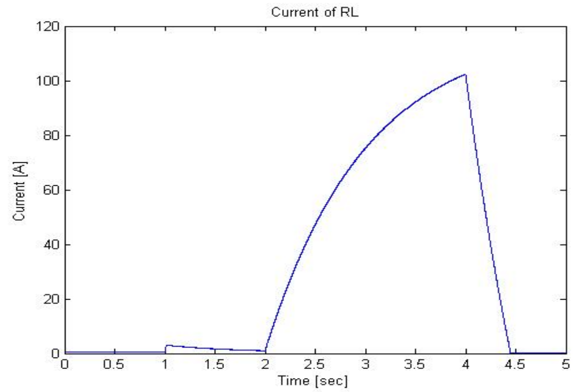

Figure 6. Load current profile by using dual chopper

2.2.3 *Reliability Analysis for Levitation Controller*

The reliability prediction of the controller is essential to verifying the applicability of the system for commercial use. A widely-used failure rate calculation for mission-oriented systems is in compliance with MIL-HDBK-217 which was published by the United States Department of Defense. Although there were several revisions made, MIL-HDBK-217 F2 is used in our analysis. The Reliability Workbench V9.1 was used for the calculation.

Table 5 shows the results of the prediction of the failure rates of four modules. The failure rate of MLC is relatively higher than others because it contains a digital signal processor with some peripherals. Although the requirement for the permitted failure rates of the electronic modules has not given yet, the values are acceptable in view of the other mission-critical system, for example, nuclear power plant system where the failure rate of 10^{-6} order is accepted. The failure rate of the controller for simplex case is 10.26×10^{-6}/hour since the modules are connected in series. The failure rate of the dual-type controller becomes smaller than that of the simplex case. Furthermore, if the software-based backup operation of the dual system is included in the analysis, a very high system reliability of maintaining normal operation may be evaluated.

Table 5. Results of the failure rate prediction

Module name	Failure rate (@25℃)
Magnetic Levitation Controller (MLC)	5.61×10^{-6}/hour
Magnetic Levitation I/O (MLO)	2.48×10^{-6}/hour
Power Supply Module	0.43×10^{-6}/hour

(PSM)	
Magnetic Levitation Interface Board (MLIB)	1.74×10^{-6}/hour

2.3 Design of Dual-Redundant Levitation Controller

The main design objective of dual redundant levitation controller is to make a duplex magnetic levitation controller lest one controller's failure of the duplex controller should fail to control magnetic levitation.

There are two magnet levitation controllers in the duplex magnetic levitation controller. Initially one magnetic levitation controller of the two magnetic levitation controllers as master takes charge of control while the other controller waits for switching signal as slave. It is the master controller in master mode that takes care of current control and the slave controller in slave mode is following control signal of the master controller. The slave controller is switched from slave mode to master mode as soon as some faults in the master controller happen.

Figure 7 is the flowchart that determines normalcy or abnormality of the master and slave controller using the heart beat transmitted from each other controller. The master controller operates periodically at scheduled period, and transmits the heart beat to the slave controller which checks the transmitted the heart beat signal using logic circuit and determines the normalcy or abnormality of the master controller. The output of HeartBeat_Rd() function is zero in case the heart beat signal from the master controller is not transmitted for scheduled time or transmitted earlier than expected. After setting HB_Flag to 1, continuously check the heart beat by the HeartBeat_Rd() function. If the HB_Chk_Count goes over the defined heart beat threshold count, then the slave controller declares that a fault happens in the master controller and is switched to master mode. Doing this, frequent switch resulted from loss of the heart beat signal for short time or noise can be avoided.

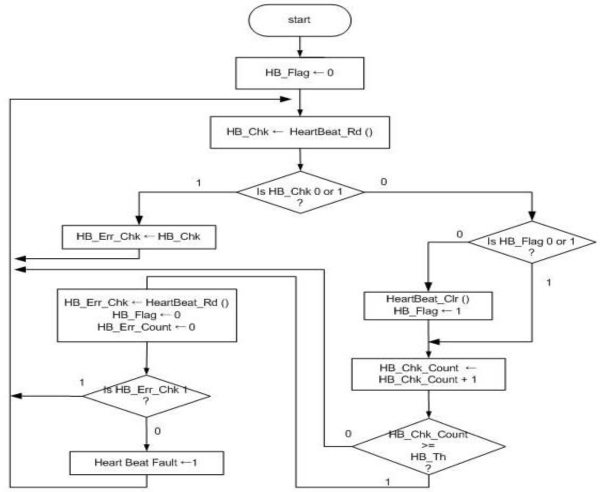

Figure 7. Flowchart for the heart beat check

Figure 8 is the flowchart of switch from master mode to slave mode. The switch between two modes occurs automatically or manually. The automatic switch takes place when the controller in slave mode declares fault occurrence in the controller of master mode or when the faults occur in the controller components such as A/D and D/A converter, memory, DI and DO. The manual switch can happen when an operator presses a push button which is set up outside the FTLC because of maintenance. As shown in Figure 8, when the controller in master mode becomes abnormal, the controller in slave mode takes over master authority only when it is normal after self checking whether it is normal or not. The moment the switch between two modes happens, bumper in levitation control can rise for short time and this bumper influences the stability of the Maglev vehicle. Therefore to minimize the bumper during mode switch is very important considering item.

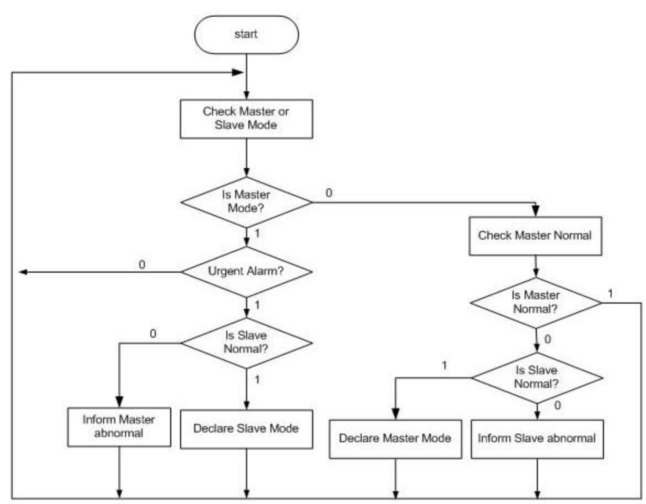

Figure 8. Flowchart of switch from master mode to slave mode

2.4 Consideration for Bogie Structure

The secondary suspension affects the levitation system. For simulating these effects, the secondary suspension is modeled as two degree of freedom mass spring damper under rail irregularity shown in Figure 9.

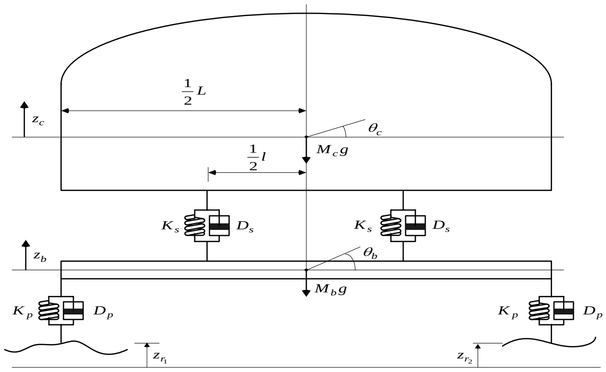

Figure 9. Simplified maglev vehicle and second suspension

Figure 10 compares the effects in case of installing the secondary suspension at the end of both sides of the bogie and in case of the center of the bogie. Figure 10 shows that the fluctuation increases for the last case. If the secondary suspension is installed at the center of the bogie, the riding comfort increases but it affects the levitation controller as a disturbance.

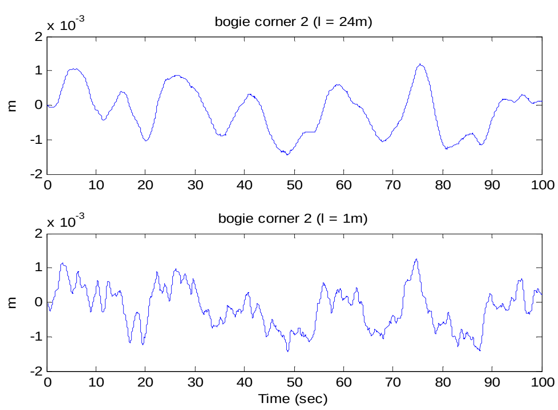

Figure 10. Profiles of bogie corner according to second suspension position.

2.5 Design of Control Algorithm

Using the results of the designed electromagnet in Section 2.1, dynamic analysis for the single magnet system is performed after the attraction force equation depending on the gap and current is derived. The attraction force can be expressed as follows

$$F(i,c) = \frac{(n_1 c^2 + n_2 c + n_0) i^2}{1 + (n_4 c^2 + n_5 c + n_6) i^2} \qquad (1)$$

By using linear interpolation method, the unknown coefficients can be acquired.

(3) is the equation which outputs five states inputting two sensors, gap and accelerometer. Using the observer, the state feedback controller is designed as

$$v = k_{pr} c^* + k_{vr} \dot{c}^* + k_{pa} z_1^* + k_{va} \dot{z}_1^* + k_{aa} \ddot{z}_1^* \qquad (2)$$

In (1), $\ddot{z}_1^*, \dot{z}_1^*, z_1^*, \dot{c}^*$ and c^* are observed as follows

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \end{bmatrix} = \begin{bmatrix} a_{11} & 0 & 0 & 0 & a_{15} \\ a_{21} & a_{22} & 0 & a_{24} & 0 \\ 0 & a_{32} & a_{33} & 0 & 0 \\ a_{41} & a_{42} & 0 & 0 & 0 \\ a_{51} & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} + \begin{bmatrix} 0 & b_{12} \\ b_{21} & 0 \\ 0 & b_{32} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \ddot{z}_1 \\ c \end{bmatrix}$$

$$\begin{bmatrix} \ddot{z}_1^* \\ z_1^* \\ c^* \\ \dot{z}_1^* \\ \dot{c}^* \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & 0 & c_{14} & 0 \\ 0 & 0 & c_{23} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{35} \\ 0 & c_{42} & 0 & 0 & 0 \\ c_{51} & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} + \begin{bmatrix} d_{11} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \ddot{z}_1 \\ c \end{bmatrix} \qquad (3)$$

where

$$a_{11} = -1000, a_{15} = -10000, a_{21} = 10, a_{22} = -10, a_{24} = -10$$
$$a_{32} = 1000, a_{33} = -100, a_{41} = -10, a_{42} = 10, a_{51} = 10$$
$$b_{12} = 2.5\times10^6, b_{21} = 1.5, b_{32} = 2.5\times10^6, c_{11} = 2, c_{12} = -2,$$
$$c_{14} = -2, c_{23} = 1.5, c_{35} = 1.5, c_{42} = 20, c_{51} = 20, d_{11} = 0.5$$

3 ANALYSIS RESULTS IN SINGLE MAGNET SYSTEM

Using the attraction force (1), simplified rail model, single magnet system and levitation controller, dynamic characteristics analysis for the designed levitation system is performed. In Figure 11, the rail is modeled to have flexibility[4].

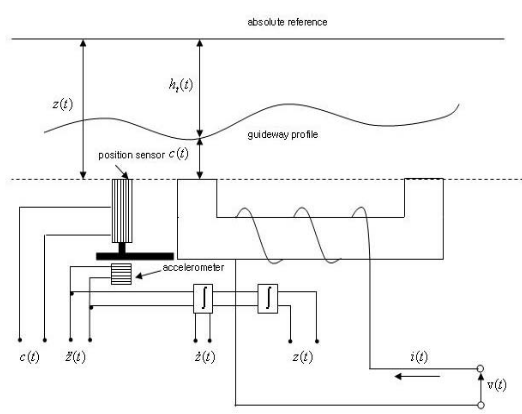

Figure 11. System configuration with an absolute reference

Figure 12 shows the block diagram for simulation which is composed of the controller, observer, rail and levitation system.

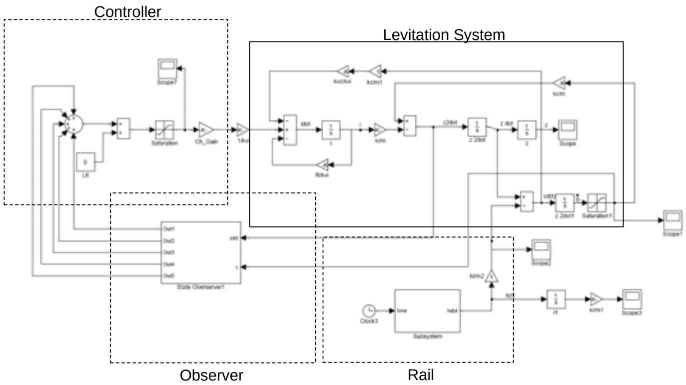

Figure 12. Block diagram for the single magnet control system.

Figure 13 is the gap profile according to vehicle speed, which shows that gap fluctuation increases if the vehicle run faster and in case of 25 meter/200 0 rail deflection and 110 km/h speed, +1.5 mm and -2.9 mm gap fluctuation happens.

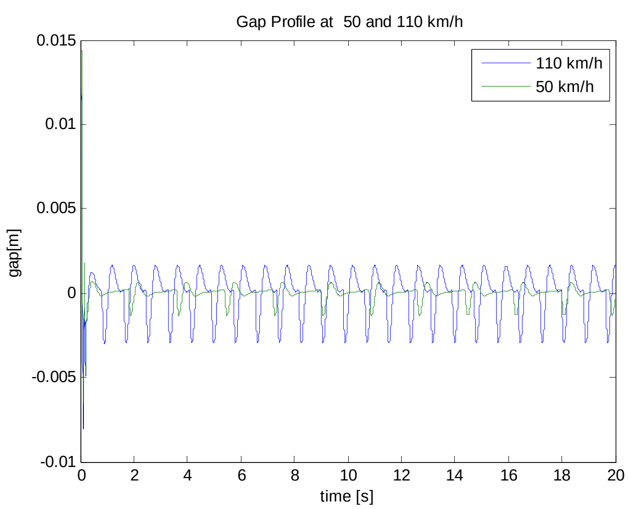

Figure 13. Gap profile according to vehicle speed.

Tow parallel rails are connected by cross arms installed at 1.25 meter span. When the vehicle runs, the rail is deflected depending on the span which affects as disturbance to the levitation control system. Figure 14 shows that when the cross arm disturbance is modeled as a sin wave of 1 mm amplitude and 24.44 Hz period, about 0.5 mm gap fluctuation is added.

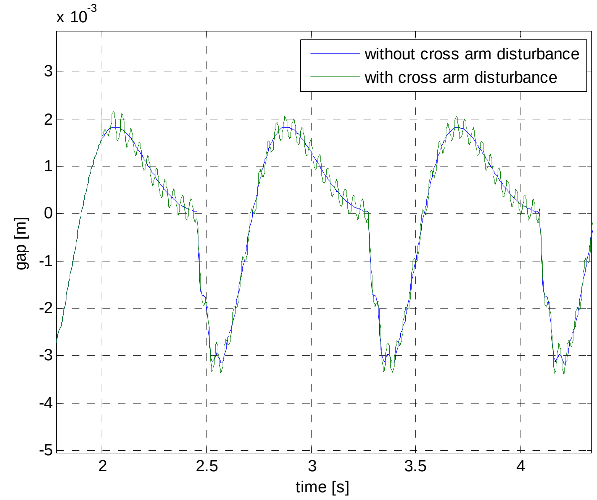

Figure 14. Gap profile according to vehicle speed.

4 CONCLUSIONS

In this paper, we have discussed the design of levitation system for a commercial maglev vehicle. Electromagnet and magnet driver are designed, and two types of bogie structure have been compared in view of suspension stability and ride quality. Also the reliability analysis of the levitation controller is performed, and we have designed the redundant magnet driver to improve the reliability of levitation controller. Through the computer simulation, we have proved the feasibility of a designed levitation system.

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