

Design and Control of Levitation and Guidance Systems for a Semi-High-Speed Maglev Train

Min Kim*, Jae-Hoon Jeong**, Jaewon Lim[†], Chang-Hyun Kim***
and Mooncheol Won*

Abstract – Research on Maglev (Magnetic Levitation) train is currently being conducted in Korea, concerning Urban Transit (110 km/h of maximum speed), semi-high-speed (200 km/h of maximum speed), and high-speed (550 km/h of maximum speed) trains. This paper presents a research study on the levitation and guidance systems for the Korean semi-high-speed maglev train. A levitation electromagnet was designed, and the need for a separate guidance system was analyzed. A guidance electromagnet to control the lateral displacement of the train and ensure its stable operation was then also designed, and its characteristics were analyzed. The dynamic performance of the designed levitation and guidance electromagnets was modeled and analyzed, using a linearized modeling of the system equations of motion. Lastly, a test setup was prepared, including manufactured prototypes of the designed system, and the validity of the design was verified and examined with performance evaluation tests.

Keywords: Maglev, Levitation, Guidance, Semi-high-speed train

1. Introduction

Next-generation transport systems must satisfy several requirements concerning speed, reliability, stability, and environmental friendliness. Maglev (Magnetic Levitation) trains are suitable candidates to satisfy the requirements for next-generation transport systems, because they operate without friction, unlike previous train systems, based on wheels and rails. Maglev trains have various advantages when compared to the previous wheel/rail systems. First of all, there are no consumable parts (owing to the absence of friction), which is crucial for maintenance cost reduction; the absence of wheels also eliminates noise and vibration. Secondly, maglev trains exhibit superior hill-climbing performance and requires, smaller radius for curved lane. This leads to greater flexibility in route selection criteria, which reduces construction costs. Thirdly, it is less sensitive to weather conditions [1, 2]. Fourthly, maglev trains do not have the risk of derailment, as a result of their structure, and exhibit excellent stability even under levitation system malfunctions, as emergency wheels can be activated [3].

Maglev trains can be generically classified, in terms of the used levitation method, into those based on EDS

(Electro Dynamic suspension), and those based on EMS (Electro Magnetic Suspension). EDS technology is based on the principle of exploiting the force created by a superconductive magnet to maintain a levitation gap of more than 10 mm. Coils can be installed on the track bottom or the sidewalls, to generate mutually repulsive forces that repel the superconductive magnet of the train throughout the entire track surface. Coils are currently installed mostly on sidewalls. This levitation method is suitable for high-speed maglev trains, because it can achieve high speeds without requiring precise track and levitation control [1]. EMS technology, on the other hand, exploits the force created by electromagnets installed at the bottom side of the train, which attract the rail (attractive force), maintaining the levitation gap within 8 mm; it requires precise air gap control. This technology can be used to implement economical levitation systems, owing to its relatively simple structure. However, if the levitation gap is increased, excessive current flows through the electromagnets, because of the levitation force limitations, which degrades the energy efficiency of the overall levitation system. Moreover, high precision track installation is hard to achieve. Most of the maglev trains being developed in Korea are based on EMS technology [1, 3].

This paper discusses levitation and guidance systems for 200 km/h semi-high-speed maglev trains based on EMS technology. We derive the levitation and guidance forces in accordance with the specifications for regionally operated maglev trains, and an appropriate electromagnet is designed, using a finite element model (FEM). A linearized model of the designed levitation and guidance system was created, to analyze its characteristics and validate the

[†] Corresponding Author: Dept. Magnetic Levitation and Linear Drive, Korea Institute of Machinery & Materials (KIMM), Korea. (einses@gmail.com)

* Dept. of Mechatronics Engineering, Chungnam National University, Korea. ({kimmin, mcwon}@cnu.ac.kr)

** Dept. of Electrical Engineering, Chungnam National University, Korea. (tpts@cnu.ac.kr)

*** Dept. Magnetic Levitation and Linear Drive, Korea Institute of Machinery & Materials (KIMM), Korea. (chkim78@kimm.re.kr)

Received: February 19, 2016; Accepted: June 8, 2016

design. The designed levitation/guidance system was also examined through a test-bench model, and its operating characteristics were analyzed.

2. Research Trends about Maglev Train

2.1 Research trends

Research on maglev trains is being conducted in various nations around the world; the resulting train systems can be classified in terms of the used levitation principle. These include superconducting maglev trains models MLX and L0 of Japan and the Inductrack technology of the United States, based on permanent magnetic repulsion. Trains based on EMS technology include the high-speed maglev train, Transrapid (TR), of Germany, and the Mid-Low-Speed maglev train, Birmingham People Mover, of the United Kingdom, M-Bahn of Germany, High-Speed Surface Transport (HSST) of Japan, and Urban Transit Maglev (UTM) of Korea [4, 5].

The research on maglev train development in Germany is well represented by the TR train model. TR, based on EMS levitation and linear synchronous motor (LSM) propulsion technologies, was opened to the public in Shanghai, China, in 2003 [6]. Japan is developing a High-Speed maglev train based on EDS levitation and LSM propulsion technologies. Based on the superconductive null-flux method, the world's fastest speed of 603 km/h was achieved in the operational test. The Japanese government is planning to introduce a maglev train service between Tokyo and Nagoya by 2027, and it aims to open a maglev train service to connect Tokyo and Osaka in 2045 [5, 6]. China is more actively promoting the public application of maglev trains, with successful construction and operational tests in Beijing and Changsha; maglev train services are therefore expected to be made widely available in China [7, 8].

Fig. 1 shows the maglev trains developed in Korea. Ecobee, shown on the top half, is an urban transit, while the SUMA550 (bottom half) is a high-speed maglev train. The development of Ecobee started in 2006, followed by successful practical implementation, with a maximum speed of 110 km/h. The SUMA550, with a maximum speed of 550 km/h, is currently under development [9].

This paper concerns the levitation and guidance system of a 200 km/h semi-high-speed maglev train, which is currently being developed. Semi-high-speed trains are intended for intercity travelling between small and medium-sized cities, and they can therefore provide alternative maglev train solutions with excellent environmental characteristics for urban sections. It is therefore desirable for their technological solutions and design to be more closely based on the concept of urban maglev trains rather than on that of high-speed maglev trains; however, in the development of the semi-high-speed maglev train, the



Fig. 1. Maglev Train in Korea. ECOBEE (110 km/h urban class); SUMA550 (550 km/h high-speed class)

concept of passive displacement guidance system of the urban maglev train should be augmented, with active control of lateral disturbances and displacement.

2.2 Development specifications for the korean semi-high-speed maglev train

The levitation system of the semi-high-speed maglev train is based on the EMS of a lightweight metal structure. The propulsion system is consisted with linear induction motor (LIM). LIM propulsion system has price competitiveness in low to semi-high speed transfer system, and linear synchronous motor (LSM) has superior performances in high to super high speed system.

The railway has a gauge of 1850 mm, a maximum gradient of 35%, and a minimum curve radius of 2000 mR. The loading conditions are 35 ton and 41.5 ton when empty and full, respectively; the passenger load is 6.5 ton. The maximum design speed is 200 km/h, and the maximum operating speed is 180 km/h. The maximum acceleration is 3.0 km/h/s, and the maximum deceleration is 4.0 km/h/s during ordinary operation and 4.5 km/h/s in emergencies. The hill-climbing ability is greater than 35%. The air gap is set at 10 mm for levitation, and 11 mm for propulsion, and speed control is based on acceleration and deceleration control by a VVVF inverter. In terms of ride comfort, the International Union of Railways ride comfort index must be lower than 2.0, during empty-carriage operation in a straight flat route at maximum speed.

The train can be separated into car body and bogie. The length of the car body is 20000 mm for a single car, with six bogies per car. The width of the bogie is 2700 mm, and the car is 41000 mm high. Air spring-based steering bogies are used, with mechanical clamp brakes as the fundamental braking system.

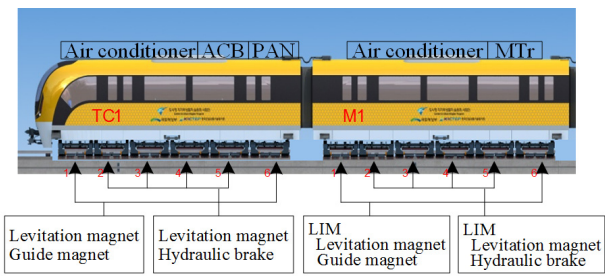


Fig. 2. Configuration diagram of the semi-high-speed maglev train.

The levitation device is supplied with the electrical power required to obtain the amount of force (current) calculated from the loading conditions of the train, the configured gap, and the actual gap between the electromagnet and rail track. It consists of a calculation and levitation control device (magnet driver), a levitation sensor (gap sensor, acceleration sensor), and an electromagnet. An overall view of the semi-high-speed maglev train addressed in this paper can be seen in fig. 2.

3. Design of Levitation and Guidance System for the Semi-high-speed Maglev Train

In the current urban maglev train developed in Korea, lateral displacement is controlled using the restoring force generated by the levitation electromagnet. In other words, lateral displacement is passively controlled using the guidance force generated by the levitation system. While the lateral displacement generates the guidance force, this simultaneously decreases the levitation force. Moreover, the guidance force generated by the levitation electromagnet often causes low-frequency noise and malfunctions of the levitation system. Even though additional current is supplied to compensate for such effects during actual operations, this is a passive control method and causes degradation of the ride comfort in curved track operation. As such, if the train is to be operated at high speed, an active control of lateral disturbance and displacement is required. The guidance system of a semi-high-speed train must be designed with careful consideration of its interference with the levitation system. In particular, the levitation and guidance characteristics under mechanical and electromagnetic interference must be thoroughly examined, considering its correlation with the maglev track [10].

3.1 Design of the levitation electromagnet

EMS levitation technology is adopted for the semi-high-speed maglev train, and four electromagnets are installed on each side of a single bogie, for a total of 48 levitation electromagnets per car. Considering the weight of the train with full loadings, 41.5 ton, the required force of a single

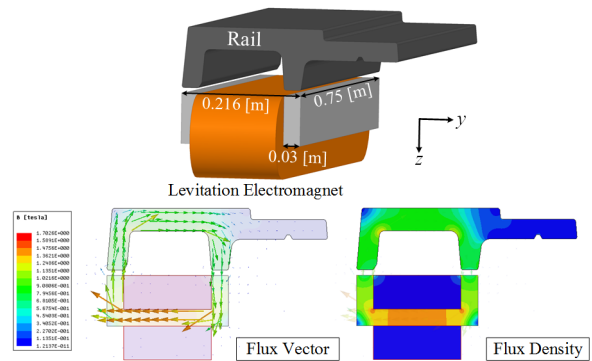


Fig. 3. Levitation electromagnet for the Semi-high-speed maglev train and FEM analysis results.

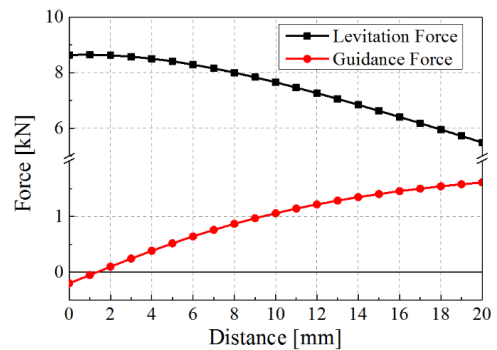


Fig. 4. Levitation and guidance forces versus levitation electromagnet alignment displacement.

electromagnet can be shown to be 8500 N.

The semi-high-speed maglev rails are identical to those of the urban maglev trains. This choice was made to maximize the utility of the semi-high-speed train during operation within urban city environments, even though its main objective is inter-city connection. Fig. 3 shows the levitation electromagnet and the corresponding FEM analysis results. The levitation electromagnet has 187 turns, and an input current of 56 A. In these conditions, the levitation force in the z-direction is 8635 N, and the guidance force in the y-direction is 201 N when aligned. In an ideal structure, there would be no force in the y-direction with aligned electromagnet. However, such a guidance force is generated, because actual rails have additional ferro magnetic materials for assembling with a girder.

Fig. 4 shows the analysis results for the levitation and guidance forces, with varying lateral displacement of the levitation electromagnet. For this analysis, the levitation electromagnet was displaced from alignment with right shifts of 10 mm up to 20 mm. The results show that the levitation force decreases and the guidance force increases as the lateral displacement increases. The guidance force from the levitation electromagnet is sufficient to counteract the lateral displacement of urban maglev trains; however, for semi-high-speed maglev trains with twice the operating speed, it is likely that the guidance force from the levitation

electromagnet will not be sufficient to avoid lateral contact. Moreover, even if it were possible to counteract the lateral displacement, this approach decreases the levitation force, which negatively impacts on stable operations. It can therefore be concluded that, to ensure stable high-speed operation, guidance electromagnets are necessary, for active lateral displacement control.

3.2 Analysis of the guidance force in semi-high-speed maglev trains

Once the train enters a curved track segment, a centrifugal force is generated, which is a lateral force acting perpendicularly to the direction of travel, and can cause contact between the bogie and the guide rail. Centrifugal forces act towards the outside of the radius of curvature of the track, and they can degrade the ride comfort. Unlike ordinary trains, maglev trains in particular run on guideways with small curve radii, and research is hence required on the reduction of the centrifugal force, to improve stable curve driving performance [10].

In this section, the lateral forces originating from curves are analyzed, to examine the need for a guidance electromagnet and guidance control in semi-high-speed maglev trains with a maximum speed of 200 km/h. The lateral disturbance for a curving maglev train is given by the centrifugal force F_C shown in fig. 5. This force acts perpendicularly to the train's direction of travel, and is equal to the compensating guidance force F_L , created by the guidance magnet, as given by Eq. (1).

$$F_L = F_C = \frac{mv^2}{R} \tag{1}$$

Railway construction standards impose a minimum radius of curvature of 2000 mR for a semi-high-speed maglev train operating at 200 km/h. Fig. 6 shows the lateral force analysis results, for increasing speed and curve radius. According to the analysis results, the lateral force is 64000 N per carriage when the train drives through a curve radius of 2000 mR at 200 km/h. There are eight electromagnets (per carriage) active during the curve, resulting in a required guidance force of around 8000 N for each

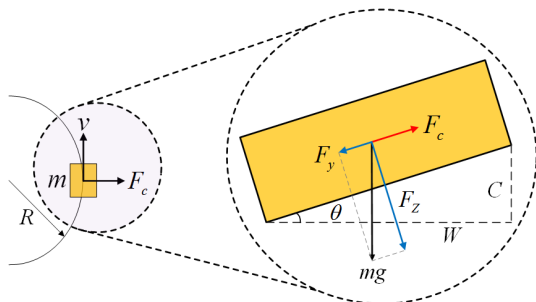


Fig. 5. Cant and lateral force model for curving maglev train.

guidance electromagnet.

Train systems are designed to prevent derailment in curves by slightly tilting the track. This is referred to as cant, and such a system can be adopted in semi-high-speed maglev trains for a more efficient opposition to lateral displacement. The concept behind the cant can be seen in fig. 5, where C is the cant amount, and W is the rail width set as 1850mm which is identical to that of urban maglev train. Considering the cant, the lateral force is given by Eq. (2). The cant amount, C, is given by Eq. (3), and the cant angle (θ) can be obtained using Eq. (4).

$$F_L = F_C - F_y = \frac{mv^2}{R} - mg \sin \theta \tag{2}$$

$$C = 11.8 \times \frac{v^2}{R} \tag{3}$$

$$\sin \theta \cong \tan \theta = \frac{C}{W} \tag{4}$$

The analysis results considering cant are shown in fig. 7, for a radius of curvature ranging from 1000 mR to 5000 mR. According to these results, a lateral force (and, hence, a required guidance force) of approximately 12200 N per car is generated in curves with a radius of 2000 mR at 200 km/h. As a result, a guidance force of around 1525 N is

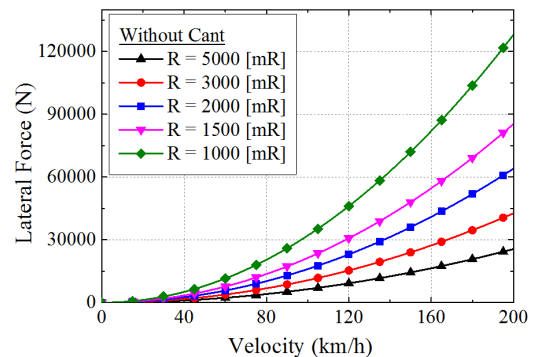


Fig. 6. Lateral force versus operating speed for various radii of curvature.

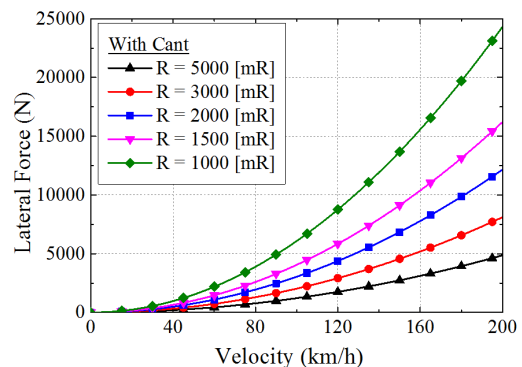


Fig. 7. Lateral force versus operating speed for various radii of curvature, considering the effect of cant.

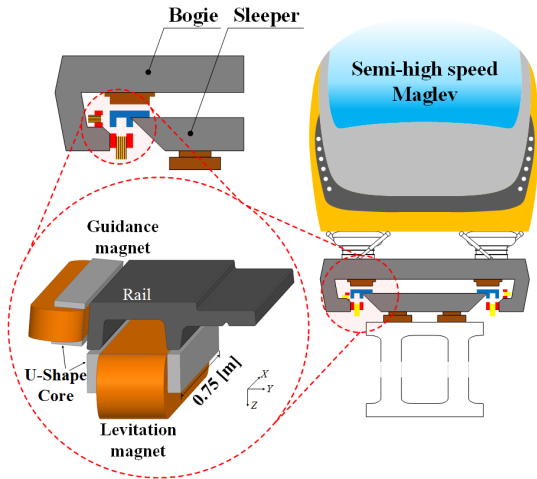


Fig. 8. Levitation and guidance system for the Semi-high-speed maglev train

required from a single guidance electromagnet. Using a safety factor of 50%, the guidance force required from a single guidance electromagnet at maximum operating speed was determined to be 2300 N.

As shown in fig. 4, for a horizontal displacement of 15 mm (equivalent to half the levitation electromagnet pole width), the levitation force will have dropped to 6600 N, and a guidance force is 1400 N will be produced. Comparing these values to the requirements, we can see that the levitation and guidance forces are insufficient by 22% and 44%, respectively. It is likely that the use of the guidance force from the levitation electromagnets may lead to difficulties in ensuring the maglev train driving stability at high speeds. Therefore, it can be concluded that guidance electromagnets are necessary for stable control of the levitation and centrifugal forces in high-speed operation.

3.3 Design of the guidance electromagnet

Based on the cant analysis results, a guidance electromagnet was designed using a FEM. Fig. 8 shows a conceptual diagram of the levitation/guidance system of semi-high-speed maglev trains used in urban transit maglev train rails. The configuration of both the levitation and guidance electromagnets installed on the bogie of the train can be observed; as can be seen, these two electromagnets are installed on a single rail. As such, levitation and guidance forces can mutually affect each other, depending on the geometry of the rail and the position of each electromagnet. Therefore, two electro-magnets were modeled simultaneously, and the forces from each one were calculated by FEM analysis.

Fig. 9 shows the FEM analysis results for the magnetic flux density vector fields of the levitation and guidance electromagnets. The levitation and guidance electromagnets were designed so that the magnetic flux of each electro-

Table 1. Specifications and analysis results for the levitation and guidance electromagnets

Parameter	Levitation Magnet	Guidance Magnet
Air Gap	10 mm	12 mm
Turn	187 turns	78 turns
Input Current	55 A	96 A
Force	8531 N	2638 N
Current Density	1.83 A/mm ²	3.22 A/mm ²

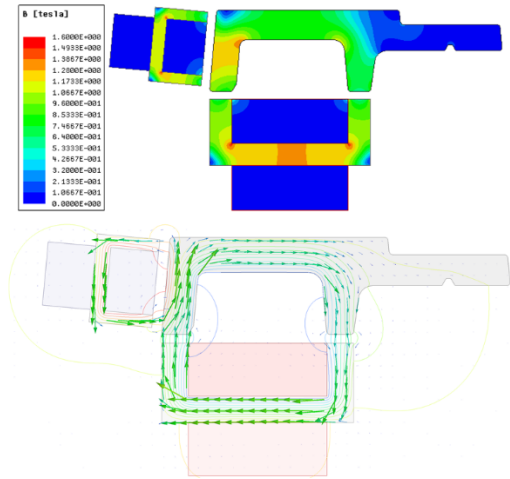


Fig. 9. FEM analysis results for the levitation and guidance electromagnets.

magnet can act independently. The cores of the levitation and guidance electromagnets were designed to reach magnetic flux saturation at less than 1.5 T. The previously calculated required forces for the levitation and guidance electromagnets are 8500 N and 2300 N, respectively. The detailed FEM analysis parameters and results are shown in Table 1. The levitation and guidance forces both satisfied the requirements, and the current density was also stable in the design.

4. Control and Experiment

4.1 Electro mechanical system modeling and simulation

Before system control design, the model and equations of motion of the target system must be obtained. Fig. 10 shows the geometric model of the used levitation system. A coil surrounds a U-shaped electromagnet, which produces the levitation force (F_{Lev}) and the guidance force (F_{Gud}). In the fig. 10, V_G and V_L are the input voltage to the guidance and levitation electromagnets, respectively. The guidance and levitation gaps are g_g and g_l , respectively. The lateral displacement of the levitation magnet is denoted by d . Based on this physical model, both the equations of motion and the electromagnet equivalent circuit can be obtained. Even though the force from the guidance electromagnets

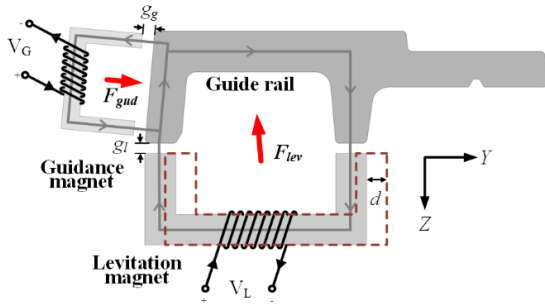


Fig. 10. Model of the maglev system.

also acts on the system, the force from the levitation electromagnet was considered firstly in obtaining the equation of motion [11].

The magnetic levitation force can be represented as a function of air gap and current, as follows:

$$F_{Lev}(i, z) = \frac{B^2 A}{\mu_0} = -\frac{\mu_0 N^2 A}{4} \left[\frac{i(t)}{z(t)} \right]^2 \quad (5)$$

In this equation, $i(t)$ is the Levitation current, $z(t)$ is the Levitation air gap, μ_0 is the magnetic permeability of air, N is the number of coil turns, A is the pole cross-section area, R is the resistance of the coil, and L is the coil inductance. The voltage-current equation of the system is:

$$\begin{aligned} v(t) &= Ri(t) + \frac{d}{dt} [L(z, i)i(t)] \\ &= Ri(t) + \frac{\mu_0 N^2 A}{2} \frac{d}{dt} \left[\frac{i(t)}{z(t)} \right] \\ &= Ri(t) + \frac{\mu_0 N^2 A}{2z(t)} \frac{di(t)}{dt} - \frac{\mu_0 N^2 A i(t)}{2[z(t)]^2} \frac{dz(t)}{dt} \end{aligned} \quad (6)$$

The physical equation of motion can be deduced by referring to fig. 10. Here, m is the mass of the magnet, and g is the gravitational acceleration.

$$m\ddot{z} = -F_{Lev}(i, z) + f_d(t) + mg \quad (7)$$

Zero-power control is used to derive the state equation; letting the current, air gap, and voltage at steady state be i_0 , z_0 , v_0 the corresponding components can be described as

$$i = i_0 + \Delta i, z = z_0 + \Delta z, v = v_0 + \Delta v \quad (8)$$

Linearizing Eqs. (6) and (7) at nominal operating point, the following state equations can be obtained

$$\begin{bmatrix} \Delta \ddot{z} \\ \Delta \dot{z} \\ \Delta \dot{i} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ k_z/m & 0 & -k_i/m \\ 0 & i_0/z_0 & -R/L_0 \end{bmatrix} \begin{bmatrix} \Delta z \\ \Delta v \\ \Delta i \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 1/m \\ 1/L_0 & 0 \end{bmatrix} \begin{bmatrix} \Delta v \\ f_d \end{bmatrix} \quad (9)$$

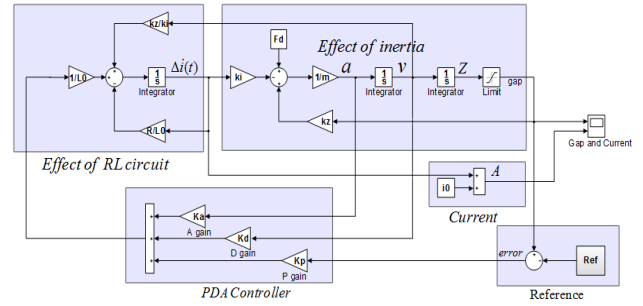


Fig. 11. Block diagram of the maglev system.

Table 2. Parameters of the levitation/Guidance test setup

Parameter	Levitation	Guidance
R	0.192Ω	0.077Ω
N	197 turns	78 turns
A	0.0225 m^2	0.0105 m^2
μ_0	$4\pi \times 10^{-7}$	$4\pi \times 10^{-7}$
i_0	29.02 A	56.33 A
z_0	7 mm	7 mm
v_0	5.57 V	4.33 V
L_0	0.1035	0.0167
m	850 kg	250 kg
g	9.8 m/s^2	9.8 m/s^2

where,

$$k_z = \frac{\mu_0 N^2 A i_0^2}{2z_0^3}, k_i = \frac{\mu_0 N^2 A i_0^2}{2z_0^2}, L_0 = \frac{\mu_0 N^2 A}{2z_0} \quad (10)$$

The dynamic system was modeled with these linearized equations. Fig. 11 shows the block diagram based on Eqs. (5)-(7). The block implementing Eqs. (5)-(7) was controlled with a PDA controller (Proportional-Derivative-Acceleration). The acceleration value is integrated to velocity, the velocity integrated to air gap, and the difference between the reference input and the air gap (the error) is multiplied by the proportional gain. The integration of the velocity and acceleration values helps stabilize the error. Control gains were mathematically tuned to their appropriate values. Fig. 12 shows the simulation results for levitation and guidance. In both cases, the simulation was configured in such a way that the air gap varied from the initial value of 12 mm to 7 mm, in accordance with the reference air gap. While the actual levitation gap shows a small steady-state error compared to the reference air gap, it can be observed that stability is maintained without difficulties. This figure also shows that the current exhibits a large variation upon levitation and landing, but is maintained at a constant value when levitation reaches its steady-state value.

The initial current is considered in the simulated system; hence, as can be observed, the current graphs start from that initial value. In a real, non-simulated experiment, the initial value for current at switch-on would naturally be

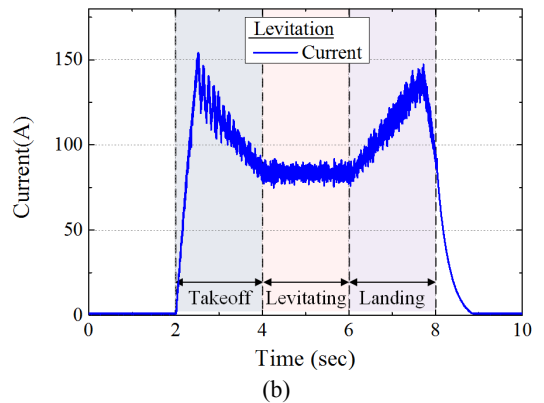
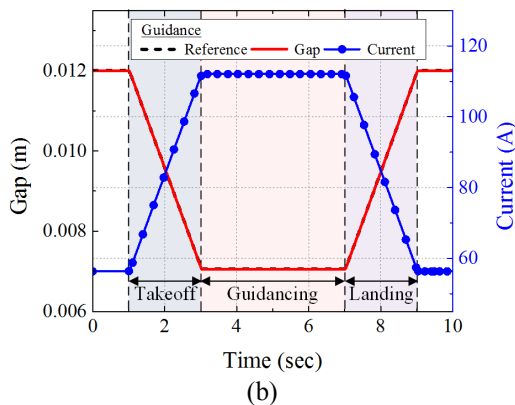
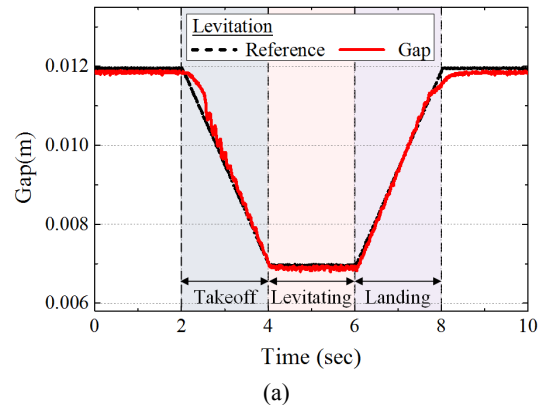
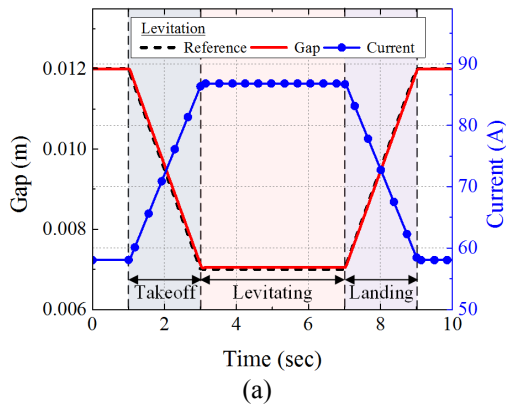


Fig. 12. Maglev system simulation : (a) simulated levitation; (b) simulated guidance

Fig. 14. Experimental results of levitation for maglev system : (a) levitation air gap; (b) levitation input current

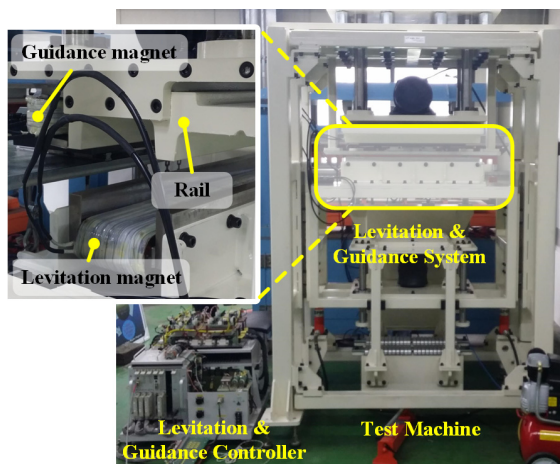


Fig. 13. Levitation and guidance test-bench.

zero, and this upward translation of the current graphs would not be observed. As in the figure, this translation has no influence on levitation stability.

4.2 Levitation/guidance electromagnets performance evaluation

Fig. 13 shows a test device that includes the previously designed levitation/guidance electromagnets. It can be

generically divided into a levitation electromagnet, a guidance electromagnet, and the rail; a loading mass was installed on the lower section of the guidance and levitation electromagnets to simulate various loading conditions of the train. In this paper, both simulation and experiments were conducted only for certain loading conditions. The system was levitated and guided from 12 mm to 7 mm, as was done in the simulation, and both the change in air gap with levitation, and the levitation and guidance stability with varying current values were observed.

Fig. 14 shows the experimental results for the levitation gap and reference current, obtained from the test device shown in fig. 13. The reference air gap was varied from an initial value of 12 mm to 7 mm, as had previously been done in the simulation; this can be compared to the actual obtained air gap. Even though steady-state errors are observed in the levitation result, they do not appear to have significant impacts on levitation stability. The current graph shows variations upon levitation and landing, as happened in the simulation, and a constant current must be applied to maintain a constant air gap, as seen in this figure. Moreover, as shown, the experimental results show the current starting from zero, which did not happen in the simulation, for reasons already discussed.

Fig. 15 shows the equivalent experimental results for the

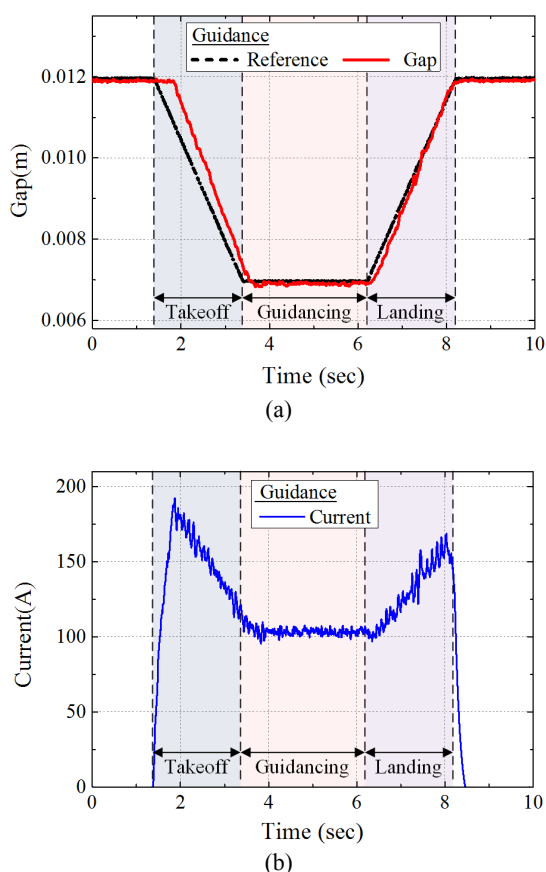


Fig. 15. Experimental results of guidance for maglev system: (a) guidance air gap; (b) guidance input current

guidance air gap, reference and current, obtained from the test device shown in fig. 13. The reference air gap was varied from an initial value of 12 mm to 7 mm, as had been previously done in the simulation; this can be compared to the actual obtained air gap. Even though errors at initializing state and steady-state errors are observed in the guidance result (integral and acceleration controllers were not used here), it can be observed that they have no impact on guidance stability. Guidance gaps are rapidly controlled around the rated gap in vehicle running state. Initial errors only occurred in start-up process because the controller gains are selected with rated airgap operation. Initial state errors can be ignored in vehicle running state. The current graph shows the largest variations upon onset and retreat, and also that a constant value of current must be applied to maintain a constant air gap. The experimental results show the current starting from zero, which did not happen in the simulation, for the same already discussed reasons.

5. Conclusion

This paper presented the design of a levitation and guidance system for a semi-high-speed (220 km/h maximum

speed) maglev trains, and analyzed its characteristics. Both levitation and guidance electromagnets were designed using a FEM, complying with the specifications for semi-high-speed maglev trains. The guidance force for lateral displacement control was analyzed through consideration of the centrifugal force at maximum speed, and the need for dedicated guidance electromagnets was established. A linearized model of the designed levitation and guidance electromagnets was developed, to analyze their dynamic characteristics. Lastly, a test setup was prepared, including manufactured prototypes of the designed system, and the operation and validity of the design was verified by performance evaluation tests.

Acknowledgements

This research was supported by a grant (15RTRP-B070556-03) from railroad technology research program funded by Korean ministry of land, infrastructure and transport of Korean government

References

- [1] H. W. Lee, K. C. Kim, and J. Lee, "Review of maglev train technologies," *IEEE Trans. Magn*, vol. 45, no. 7, pp. 1917-1925, July. 2007.
- [2] S. M. Jang, B. S. Kim, M. W. Yoo, and I. K. Kim, "MAGLEV," *KIEE*, Vol. 49, no. 5, pp. 19-27, May. 2002.
- [3] D. Y. Park, B. C. Shin, and H. S. Han, "Korea's Urban Maglev Program," *IEEE Trans. Magn*, vol. 97, no. 11, pp. 1886-1891, Nov. 2009.
- [4] J. Meins, L. Miller, and W. J. Mayer, "The High Speed Maglev Transportation System TRANSPAID," *IEEE Trans. Magn*, vol. 24, no. 2, pp. 808-811, Mar. 1988.
- [5] H. S. Han, "High-Speed Maglev Train Development Trends and Implications," *Journal of the Korea Society for Railway*, vol. 17, no. 5, pp. 36-40, Oct. 2014.
- [6] M. Ono, S. Koga, and H. Ohtsuki, "Japan's superconducting Maglav train," *IEEE Trans. Magn*, vol. 5, no. 1, pp. 9-15, Mar. 2002.
- [7] Y. Luguang, "Progress of High-Speed Maglev in China," *IEEE Transactions on applied superconductivity*, vol. 12, no. 1, pp. 944-947, Mar. 2002.
- [8] G. Lin, and H. S. Han, "China's Urban Maglev Train Development and Commercialization Status," *Journal of the Korea Society for Railway*, vol. 17, no. 6, pp. 18-21, Dec. 2014.
- [9] J. Lim, C. H. Kim, J. B. Han, and H. S. Han, "Design of an Electromagnet with Low Detent Force and its Control for a Maglev Super-Speed Vehicle," *JEET*, vol. 10, no. 4, pp. 1668-1674, Oct. 2015.

- [10] B. H. Yim, H. S. Han, J. K. Lee, and S. S. Kim, "Curving performance simulation of an EMS-type Maglev vehicle," *Veh. Syst. Dyn.*, vol. 47, no. 10, pp. 1287-1304, Oct. 2009.
- [11] P. K. Sinha, "Electromagnetic Suspension : Dynamics & Control," *IEE Contr. Eng. Series*, vol. 30, 1987.

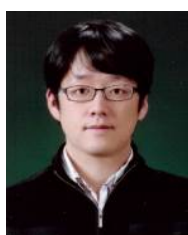


Min Kim She received the B.S. degree in mechatronics engineering from Chungnam National University, Daejeon, Korea, in 2015. She is currently working toward the M.S. degree in mechatronics engineering in Chungnam National University, Daejeon, Korea. Her research interest is the control of mechatronics

systems.



Jae-Hoon Jeong received the B.S. degree in electric, electronic, and communication engineering education and M.S. degree in electrical engineering from Chungnam National University, Daejeon, Korea, in 2011 and 2013 respectively. He is currently working for the Ph.D. degree in electrical engineering from Chungnam National University. His current research interests include design and analysis of motor/generator.



Jaewon Lim He received the B.S., M.S., and Ph.D. degrees in electrical and computer engineering from Seoul National University in 2004, 2006 and 2011, respectively. Since 2011, he has been a senior researcher in KIMM (Korea Institute of Machinery and Materials). His research interest is the design of magnetic actuator and linear propulsion systems.



Chang-Hyun Kim He received the B.S., M.S., and Ph.D. degrees in electrical and electronic engineering from Korea Advanced Institute of Science and Technology in 2000, 2002 and 2009, respectively. Since 2009, he has been a senior researcher in KIMM (Korea Institute of Machinery and Materials). His research interest is the control of magnetic levitation and linear propulsion systems.



Mooncheol Won He received a B.Sc. and M.Sc. degree from Seoul National University, Korea, in the Department of Naval Architecture and Ocean Engineering. He also received a Ph.D. degree in mechanical engineering from the University of California at Berkeley, USA. Currently, he is a professor in the Department of Mechatronics Engineering at Chungnam National University, Korea. His research interests include control of mechatronics systems, and machine learning applications of vehicle and robotic systems.