Simulation modelling in design of a city transit vehicle with electromagnetic suspension

M V Yaroslavtsev¹, R N Latyshev¹, E A Zemlyakov¹

¹ Novosibirsk State Technical University, 20, Karla Markx ave., Novosibirsk, 630073, Russia
E-mail: yaroslavev@corp.nstu.ru

Abstract. Intensive development of city transit vehicles with electromagnetic suspension of the last decade raises the significance of their optimal design problems. In this paper, the simulation model of an electromagnetic suspension system of the city transit vehicle created in Simulink is presented. The model is featuring feedback applied to determine the magnitude of the magnetic flux. The main parameters of the electromagnet were evaluated while creating the model. The presented model was used to obtain the air gap regulator settings. An adaptive control system ensuring low energy consumption at low speed and high gap control accuracy at high speed could lead to the realization of the stable and efficient suspension system.

1. Introduction
The intensive development of high-speed urban public transport systems tightens their performance requirements and leads to the reduction of their life cycle cost. In the conditions of intensive city growth, raising the operational speed becomes necessary to reduce transport fatigue of passengers as well as to downsize the noise and vibration. These problems can be solved by a transition from traditional rail urban transport to magnetic suspended transit systems. Elimination of moving parts in the running gear of such vehicles improves their durability, reduces the noise level and maintenance costs of the rolling stock.

In recent years, the active construction of the urban transit lines using electromagnetic suspension systems takes place in the world [2]. Despite the high energy costs of the suspension, this technology provides lower network construction cost and ensures the ease of operation. The passenger service on the line connecting Seoul with Incheon airport was introduced in 2016. This line operates two-car trains using EMS. A large amount of research work was carried out by Hyundai Corporation to create the system, including manufacturing of 2 prototype vehicles. The last one was taken as the basis for the production of serial trains [2–4]. Their main technical parameters are provided in [3].

The transit line using EMS operates in Changsha (China) since 2016. A metro line with the similar vehicle design was opened in Beijing in 2018 [5].

A number of contradictory requirements should be fulfilled by the electromagnetic suspension system [1, 6–9]. The electromagnet should have possibly smaller weight, which requires reduction of the magnetic circuit cross section. At the same time it should have low power consumption, which requires a reduction in the specific magnetic induction. The air gap must be large enough to ensure safety motion and sufficiently long response time of the control system, but simultaneously as short as possible to reduce the energy consumption. Suspension electromagnet should create a constant lifting
force in a wide range of gaps. The electromagnet should have sufficiently small inductance to simplify
the gap control. At the same time, it is desirable to increase the number of turns in its coil to reduce the
power consumption of the magnet.

In order to solve the problem of determining the most effective geometric and electromagnetic
properties of the suspension system, as well as to develop a control algorithm, the application of
mathematical modelling is required. The authors performed a scoping calculation of a single hanging
magnet for a vehicle with the properties similar to Hyundai cars. According to its results, a model of a
magnet and its control system was created in Simulink, using which the characteristics of the
suspension system had been studied.

2. Electric Magnet Design Calculation
The main properties of the suspension electromagnet were found using the standard technique given in
[9,10]. Calculation was performed for a one magnet, considering that the carriage is being supported
by four bogies. A sketch showing the main dimensions of magnet is given in Fig. 1.

The total mass of the rolling stock per each magnet M is

\[ M = \frac{M_L}{n} = 3.38 \times 10^3 \text{ kg} \tag{1} \]

where \( M_L = 27,000 \text{ kg} \) is the vehicle laden weight;
\( n = 8 \) is the number of magnets installed on the car.

To calculate the active surface \( S \) of the electromagnet, the equation of Maxwell electromagnetic
force (2) was used:

\[ S = \frac{2\mu_0 \cdot M \cdot g}{B^2} = 0.089 \text{ m}^2 \tag{2} \]

where \( g = 9.8 \text{ m/s}^2 \) is the gravity acceleration;
\( \mu_0 = 4\pi \times 10^{-7} \text{ G/m} \) is air magnetic permeability;
\( B = 1 \text{T} \) is the calculated magnetic induction in the gap.

The magnetizing force \( \theta \) of the coil of electromagnet with two gaps was found as

\[ \theta = \frac{1.2 \cdot 2 \cdot B \cdot \delta}{\mu_0} = 1.53 \times 10^3 \text{ A} \tag{3} \]

where 1.2 is a factor considering field leakage;
\( \delta = 8 \times 10^{-3} \text{ m} \) is the nominal air gap.

The average length of a coil winding for this magnet is about 2 m. For a projected magnet, the
number of winding turns \( w \) was taken as 350, and the average feeding voltage for maintaining the
nominal gap was taken equal to 300 V.

Thus the inductance of the winding \( L \) was calculated using the expression (4)

\[ L = w^2 \cdot \frac{\mu_0 \cdot S}{\delta} = 1.3 \text{ H} \tag{4} \]

where \( w \) is the number of turns of the electromagnet coil.

To reduce the reaction time of the electromagnet, the resistance of its circuit was artificially
increased to 13 Ohm. The average power consumed by designed winding was 6.9 kW, which
corresponded to a specific power of 2 kW/t.

3. Modeling of the Electromagnetic Suspension System
To investigate the dynamic characteristics of the electromagnetic suspension system, a model in
MatLab Simulink was developed. The general view of the model is shown in Fig. 2.

The developed model consists of several subsystems that implement expressions describing the
electromagnetic suspension. To ensure the suspension of the vehicle, an electromagnetic force \( F \)
overcoming the gravity force at given air gap was calculated as

\[ F = -\frac{1}{2} \cdot \frac{\Phi_0^2}{G^2} \left( \mu_0 \cdot \frac{S}{\delta} \right), \tag{5} \]
where $\Phi_\delta$, Wb is the magnetic flux in the air gap; $G_\delta$, H is the magnetic conductivity of the air gap.

An U-shaped magnetic core was chosen for the magnetic suspension system. It provides the smallest magnet weight and volume. The magnetic conductivity of the working gap between the end of a flat rectangular magnetic core and the parallel armature was calculated.

To calculate the magnetic field in the magnetic circuit, magnetization curves of the electrotechnical steel [10] were used. The reverse magnetization curve was implemented in Simulink using the piecewise linear approximation realized in the Lookup Table block. A feature of the implemented model of the magnetic suspension was the application of feedback loop to find the magnetic flux. The value of the magnetic flow required to equalize the fall of the magnetizing force at a given magnet current was found using an integral regulator.

![Figure 1](image1.png) **Figure 1.** Main geometrical properties of the suspension magnet.

In the air gap block shown in Fig. 3, the actual value of the air gap was calculated by integrating the equations of motion. In this subsystem were implemented the constraints caused by the contact of the vehicle with the rail when the minimum or maximum allowable values of the air gap are reached. This requires resetting the velocity value under the command of the logical equation circuit.

To find the current supplied to the coil, the electric circuit shown in Fig. 4 was created. In the model, the suspension electromagnet and additional resistor were represented by the equivalent RL-circuit. The high-value resistor R connected in parallel to the switch was needed to model the leakage currents of the closed switch which was required by Simulink environment peculiarities.

![Figure 2](image2.png) **Figure 2.** Simulation model of electromagnetic suspension system.

![Figure 3](image3.png) **Figure 3.** Air gap calculation block.

![Figure 4](image4.png) **Figure 4.** Electric circuit model.

A step-down voltage regulator with PWM control was implemented in the model to control the current of the electromagnet. The duty factor of the current converter was determined by the PID controller maintaining the air gap constancy. The current in the coil was measured to calculate the suspension force. The carrier frequency of the pulse width modulation in the model was taken as 1
kHz to simplify the calculation, though the actual current oscillations frequency could be higher. However, the reaction time of the electric magnet exceeds the PWM period approximately $10^2$ times.

A model of the electromagnet was also created in FEMM to verify the magnet levitation forces. As this model provided detailed calculation of forces and magnetic flux in the cross section, it was also used for evaluation of the lateral forces. These forces provide lateral stabilization of the vehicle on straight track, but may be insufficient to counteract centrifugal forces while passing the curved track sections.

As gravity is frequently used to counteract centrifugal forces, the track should be made inclined. To find the incline and the maximum speed of the vehicle, it was assumed that the gravity force should be equal to the lateral electromagnetic force of a standing vehicle, as shown in (6)

$$k \cdot M \cdot g \cdot \sin \alpha = F_{x, \text{max}}$$

where $k=1.4$ is the safety coefficient;
$\alpha$, ° is the angle of track incline;
$F_{x, \text{max}}$, N is the lateral force of the electromagnet.

The maximum allowed speed was found by equation (7)

$$M \cdot g \cdot \sin \alpha + F_{x, \text{max}} = \frac{M \cdot \upsilon^2}{R}$$

where $\upsilon$, km per hour is the speed of the train;
$R$, m is the turning radius.

4. Modeling Results
The proposed model of the magnetic suspension system was implemented in Simulink. The verifying calculation performed on the model confirmed the preliminary calculated main parameters of the magnet. The average coil current at stationary 8-mm gap was 25.1A, and its average power consumption was 8.2 kW. Thus, the achieved specific power of the suspension is 2.43kW/t. Its excess over the preliminary calculation results may be explained by taking into the account losses in the steel core of a magnet having a stretched shape.

In Figure 5 the dependences of the air gap and coil current on time in the absence of (a) and the presence of disturbances (b) with amplitude of 1 mm [3, 11] and a circular frequency of 35 rad/s are shown. These disturbances simulate the track irregularities impact on the vehicle motion. The amplitude of the gap oscillations was 0.4 mm, and the amplitude of the current oscillations 5 A at the frequency of 14 Hz. Under the implemented gap regulator settings the vehicle position at higher disturbance frequencies was unstable.

![Figure 5](image5.png)

**Figure 5.** Dependences of air gap and coil current on time in the electromagnetic suspension model without (a) and with (b) external disturbance.

Modelling in FEMM had proved the preliminary calculations of levitation forces. It was also shown that changing the ratio of width and length of the winding could provide an additional increase
in the lifting force of a single magnet from 35.7 kN to 37.3 kN. According to the modelling results, the maximum speed at curves with incline of 3.5° should be limited by 60 km per hour on curves with the radius of 80 m and by 120 km per hour on curves with the radius of 800 m.

5. Conclusion
In the article, the main parameters of the electromagnetic suspension system of the city transit vehicle were determined. A model of EMS system was developed and implemented in the Simulink. The model is featuring a feedback applied to determine the magnitude of the magnetic flux. The parameters of the current proportional-integral-derivative regulator providing a constant air gap were evaluated using the model. Finite-element simulation in FEMM was used to verify the results, optimize magnetic core dimensions and found speed limitation on curved track sections.

Further design problems, which may be solved using the proposed model are the increase of the control accuracy for achieving greater vehicle motion speeds, as well as optimizing system parameters in order to maintain low specific energy consumption and electromagnet cost. An adaptive control system, ensuring low energy consumption at low speed and high gap control accuracy at high speed could lead to realization of stable and efficient magnetic suspension. The presented simulation model of a suspended vehicle can be used in its development.

References
[1] Liu Z, Long Z, Li X 2015 Maglev Trains: Key Underlying Technologies (London: Springer)
[2] Cassat A, Bourquin V 2011 MAGLEV – Worldwide Status and Technical Review Electro technique de Future 12 14
[3] Shin B, Kim W, Park D, Beak J, Kang H 2011 Progress of Urban Maglev Program in Korea Proc. of WCRR 2011 (9th World Congress on Railway Research, Lille, France)
[4] Yim B H et al., 2009 Curving Performance Simulation of an EMS-type Maglev Vehicle Vehicle System Dynamics 47(10) 1287
[5] Briginshaw D 2018 Beijing opens First Maglev International Railway Journal 4 Jan 16
[6] Amoskov V et al. 2018 Modelling EMS maglev systems to develop control algorithms Cybernetics and Physics 7(1) 11
[7] Sun Y, Li W, Qiang H 2016 The design and realization of magnetic suspension controller of low-speed Maglev train Proc. of 2016 IEEE/SICE International Symposium on System Integration (Sapporo, Japan: IEEE RAS) 7843966
[8] Li G, Jia Z, He G, Li J 2017 Analysis of eddy current induced in track on medium-low speed maglev train Proc. of 2016 IEEE Conference Series: Earth and Environmental Science 69 012184
[9] Ding J, Yang X, Long Z, Dang N 2018 Three-Dimensional Numerical Analysis and Optimization of Electromagnetic Suspension System for 200 km/h Maglev Train Considering Eddy Current Effect IEEE Access 6 61547-61555
[10] Sakharov P V 1971 Electric Apparatus Design (In Rus.) [Proektirovanie elektricheskich apparatov] (Moscow: Energiya)
[11] Han Jong-Boo et al. 2016 Design and Validation of a Slender Guideway for Maglev Vehicle by Simulation and Experiment Vehicle System Dynamics 54(3) 370