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Electromagnetic Suspension used for High-Speed Vacuum Transport

Nikolay Grebennikov[1] and Alexander Kireev[2]

Closed joint-stock company «Scientific-Technical Center «PRIVOD-N»
Krivoshlykova Street 4a, 346428, Novocherkassk, Russia.

[1]ORCID ID: 0000-0001-5959-2547, Scopus Author ID: 56584746500
[2]ORCID ID: 0000-0003-1157-2402, Scopus Author ID: 56583946900

Abstract

The given article presents electromagnetic suspension used for the high-speed vacuum transport. The mathematic description is given to determine the basic dimensions of the electromagnetic suspension. 3-D suspension model has been developed as well as the computer model, needed for investigation of the suspension dynamic operation modes. The simulation results show that the joint application of both electromagnet and permanent magnets for levitation allows us to reduce significantly the energy costs needed to ensure the high-speed vehicle levitation.

Keywords: high-speed vacuum transport, magnetic levitation, electromagnetic levitation, computer model, Matlab/Simulink

INTRODUCTION

At the present time, there is an interest in non-contact technologies for moving the objects by means of magnetic suspension [1], the most topical issue is the high-speed transport equipped with magnetic suspension. The overcrossing conception «Evacuated tube transport technology» [2] is an example of the energy-efficient convergence of vacuum and especially magnetic- levitation and superconducting technologies for the land transport. Such technologies allow vehicles to reach the running speed more than 1000 km/h in potential and about 6000 km/h in prospect.

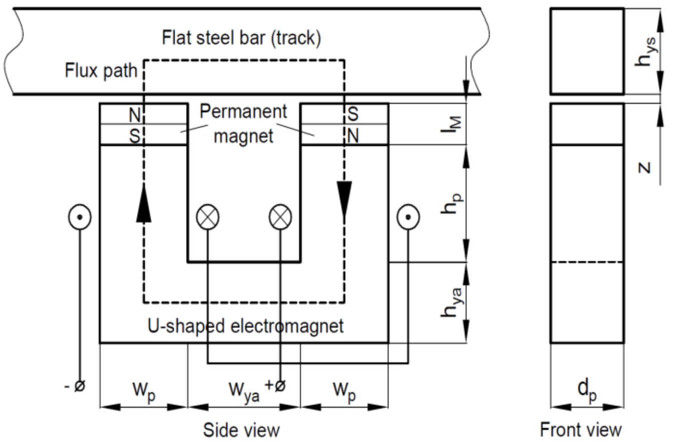
The theoretical estimation of the energy costs, required for the development of discharged environment to ensure the transport unit movement, has shown that the energy costs are assumed to be much less in comparison with the equivalent energy costs needed to achieve the same speed in natural air environment.

The basic elements of «Evacuated tube transport technology» are the guide track structure, levitation system, lateral stabilization system and traction system. The vehicle moves in non-contact way without mechanical parts worn; there is no mechanical component in travel resistance, which allows reducing dramatically the maintenance and energy consumption costs and increasing the service life of the system.

Currently, different ways of levitation for a high-speed vehicle are proposed: the air gap [3] and electrodynamic levitation [4]. In the vacuum environment, the actual task is to minimize the losses related to the movement as well as to levitation system. Therefore, the aim of the article is to study electromagnetic suspension used for levitation of the high-speed vacuum transport.

DESIGN PROCEDURE

The vehicle suspension considering in the article is realized by four electromagnets having permanent magnets fixed on them. The conceptual design is shown in figure 1..



w_p, h_p, d_p – width, height and thickness of the electromagnet pole; w_{ya}, h_{ya} – width and height of the electromagnet core; h_{ys} – height of the flat steel bar (track); l_M – permanent magnet thickness; z – air gap.

Figure 1. The conceptual design of the electromagnet suspension

The calculation of the electromagnet dimensions is based on the assumption that the levitation and traction systems are independent. This allows us to simplify the calculation procedure and increase the system reliability. Figure 1 presents the electromagnet configuration of the lateral DC flow, which consists of the flat steel bar (track) and U-shaped electromagnet and permanent magnets. The geometrical dimensions calculation of the electromagnet should be performed based on the magnetic flow value in the air gap.

Regardless of the magnetic flux generation method, the operating point position determines the energy margin in the air gap, since the specific magnetic energy is $w_M = B_g H_g/2\ [J/m^3]$. For the gap having the following dimensions :A_g, l_g ,the field energy is:

$$W_g = \frac{B_g H_g}{2} A_g l_g$$

where A_g – cross sectional area of the air gap; l_g – the air gap length; B_g – magnetic flux density in the air gap; H_g – magnetic field intensity in the air gap.

In this case, the change of the gap length l_g causes the change of the magnetic field energy and requires the force application equaled to:

$$F = \frac{dW_g}{dl_g} = \frac{B_g H_g}{2} A_g = \frac{B_g^2 A_g}{2\mu_0}$$

where μ_0 – magnetic inductivity of the air.

The force F is the gravity force generated by the electromagnet. The force value depends on the magnetic flux density value in the air gap. Changing the magnetic density value, it is possible to control the gravity force.

U-shaped magnet, used for the vehicle suspension, has two poles generating the electromagnetic force and in this case, the electromagnet gravity force is the following:

$$F_Z = 2F = \frac{B_g^2 A_p}{\mu_0} = \frac{B_g^2}{\mu_0} w_p d_p$$

where w_p – electromagnet pole width; d_p – electromagnet thickness.

In the equation above, dispersion fluxes and iron magnetic resistance are not taken into account; the constant flux density over the cross sectional area of the air gap is also assumed.

If the allowable value of magnetic flux density in the air gap is set, then it is possible to calculate the required cross sectional area of the electromagnet according to the formula:

$$A_p = w_p d_p = \frac{\mu_0 F_Z}{B_g^2}$$

With electromagnetic suspension of the vehicle, each electromagnet must have a force that is one-fourth of the vehicle weight :

$$F_Z = \frac{M_V \cdot g}{4}$$

where g – gravity acceleration; M_V –vehicle weight.

Having the reference dimension of one side of the U-shaped electromagnet core, it is possible to calculate the size of the other side.

To develop the electromagnetic suspension having the minimal power consumption, the permanent magnets, which should generate the nominal magnetic flux under the specified operating air gap, are fixed at the U-shaped electromagnet core. In this case, the electromagnet is used to keep the specified value of the air gap. The air gap needs to be dynamically changed in order to minimize the current flow going through the electromagnet windings.

The electromagnet thickness can be calculated based on the Ampere law for the magnetic circuit:

$$\oint H dl = I \cdot T_W$$

where H – magnetic field intensity at the magnetic circuit section; dl – the length of the magnetic circuit section; I – current in the electromagnet winding; T_W – turning number in the electromagnet winding.

Thus, for the given electromagnet, the Ampere law for the magnetic circuit at levitation due to permanent magnets will be the following:

$$2 \cdot H_M \cdot l_M - 2 \cdot H_{ya} \cdot \left(w_p + w_{ya} + h_p + \frac{h_{ya}}{2} + \frac{h_{ys}}{2} \right) - 2 \cdot H_g \cdot z = 0$$

$$l_M = \frac{H_{ya} \cdot \left(w_p + w_{ya} + h_p + \frac{h_{ya}}{2} + \frac{h_{ys}}{2} \right) + H_g \cdot z}{H_M}$$

$$H_M = Hc \cdot \frac{Br - Bg}{Br}$$

where Bg – magnetic flux density in the air gap; Br – residual flux density of the permanent magnet; Hc – coercive force.

To create the zero magnetic flux, it is required to let the current go through the windings of the U-shaped electromagnet core; the value of the current can be calculated by the formula:

$$\mathrm{I} = \frac{2 \cdot H_M \cdot l_M - H_{ya} \cdot \left(w_p + w_{ya} + 2h_p + \frac{h_{ya}}{2} + \frac{h_{ys}}{2} \right)}{T_W}$$

T_W – turning number in the electromagnet winding.

Therefore, it is possible to generate the virtually zero flux going through the U-shaped electromagnet core, but at the same time the dispersion fields should be taken into account, which gravity force can exceed the vehicle weight; for this reason, the gap separator between permanent magnets and track structure should be foreseen.

The electromagnet design is performed for the vehicle with maximum weight of 600 kg. The magnetic flux density in the air gap is assumed as 0.7 T. The nominal air gap is 10 mm. In this case, the required levitation force is the following:

$$F_z = \frac{M_V \cdot g}{4} = \frac{600 \cdot 9.81}{4} = 1471.5 \text{ H}$$

If w_p = 50 mm, then the thickness of the U-shaped core d_p , is:

$$d_p = \frac{\mu_0 \cdot F_z}{w_p B_g^2} = \frac{4\pi \cdot 10^{-7} \cdot 1471.5}{0{,}05 \cdot 0{,}7^2} = 0.075 \text{ м}$$

For the high-speed vehicle we take the margin equaled to not less than 25% and then, we take the core thickness equaled to 100 mm.

Magnets NdFeB 52 MGOe have been selected as permanent magnets (**Coercitive force is** $Hc = 875kA/m$, $Br = 1.45\ T$). Then, it is possible to calculate the dependency of the permanent magnet thickness on the air gap value. It is shown in figure 2.

$$l_M = \frac{H_{ya} \cdot (w_p + w_{ya} + h_p + h_{ya}) + H_g \cdot z}{H_M}$$

$$H_M = Hc \cdot \frac{Br - Bg}{Br}$$

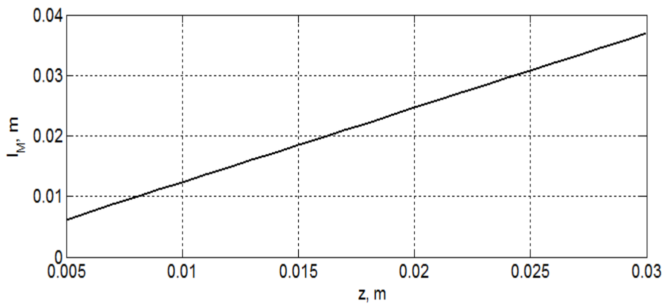


Figure 2. The dependency of the permanent magnet thickness on the operating gap nominal value

3-D MODEL OF ELECTROMAGNETIC SUSPENSION

In order to develop 3-D model of electromagnetic suspension, it is necessary to use the special software designed for magnetic fields calculation in 3-D area. The designed 3-D model of electromagnetic suspension is shown in figure 3.

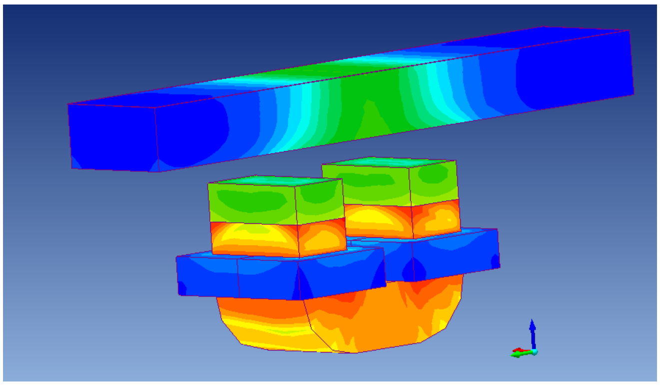


Figure 3. 3-D model of electromagnetic suspension

As the calculation result, based on 3-D model of electromagnetic suspension and shown in figure 1, we obtained the distribution of magnetic flux density in the air gap above electromagnetic suspension poles at current zero value. The distribution of magnetic flux density is demonstrated in figure 4.

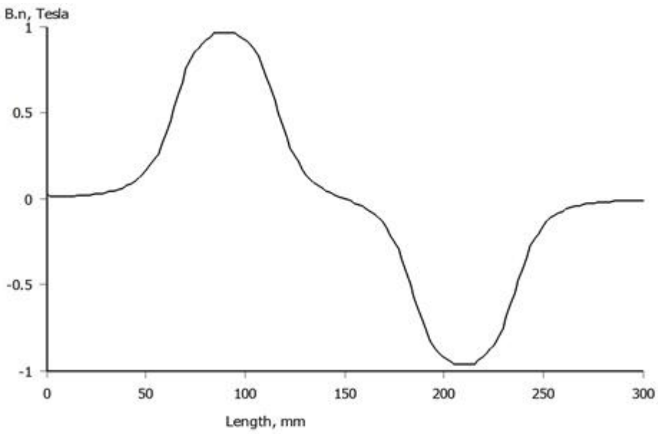


Figure 4. The distribution of magnetic flux density above electromagnetic suspension poles

Figure 4 proves that the wavelength of magnetic induction is about 250 mm. The flux reversal frequency of the track structure core under the speed of 1000 km/h is 1100 Hz, that is allowable for electrical steel.

As the result of the electromagnetic calculation, performed by means of 3-D model, the dependency of the lifting force on the current, flowing in the electromagnet and air gap coils, was obtained and presented in figure 5.

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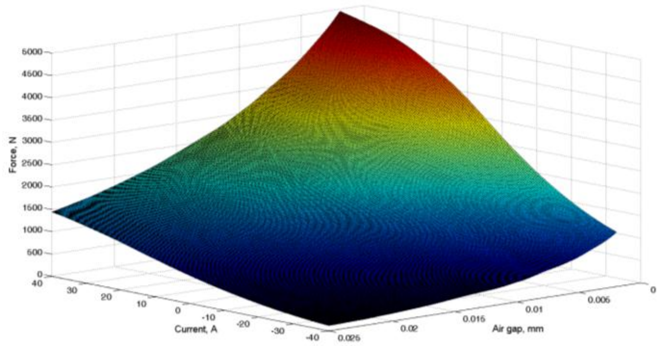

Figure 5. The dependency of the lifting force on the current flowing in the electromagnet and air gap coils

DYNAMIC MODES SIMULATION

To simulate the dynamic modes in magnetic suspension, it is advisable to use computer models [5]. The model being developed is based on the electrical circuit equation and shown in figure 6.

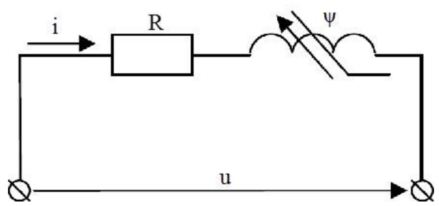

Figure 6. Substitution scheme of electromagnetic suspension

The equation, describing the electromagnetic processes occurring in the electromagnetic module, is given below:

$$u = R \cdot i + \frac{d\psi(i,z)}{dt} \quad ,$$

where u – phase voltage (applied to a phase); i – current in the electromagnet coil; $\psi(i,z)$ – dependency of the electromagnetic module flux linkages on current and air gap.

The equation of motion under levitation (in Z line direction) is given below:

$$m \cdot \frac{d^2 z}{dt^2} = F_z - m \cdot g - f_z$$

where m – vehicle mass per one electromagnetic module; Fz – vertical force generated by the electromagnetic module; fz – disturbance effect.

The computer model has been designed by means of MATLAB/Simulink software (figure 7); the initial data is the calculation results based on 3-D model of electromagnetic suspension.

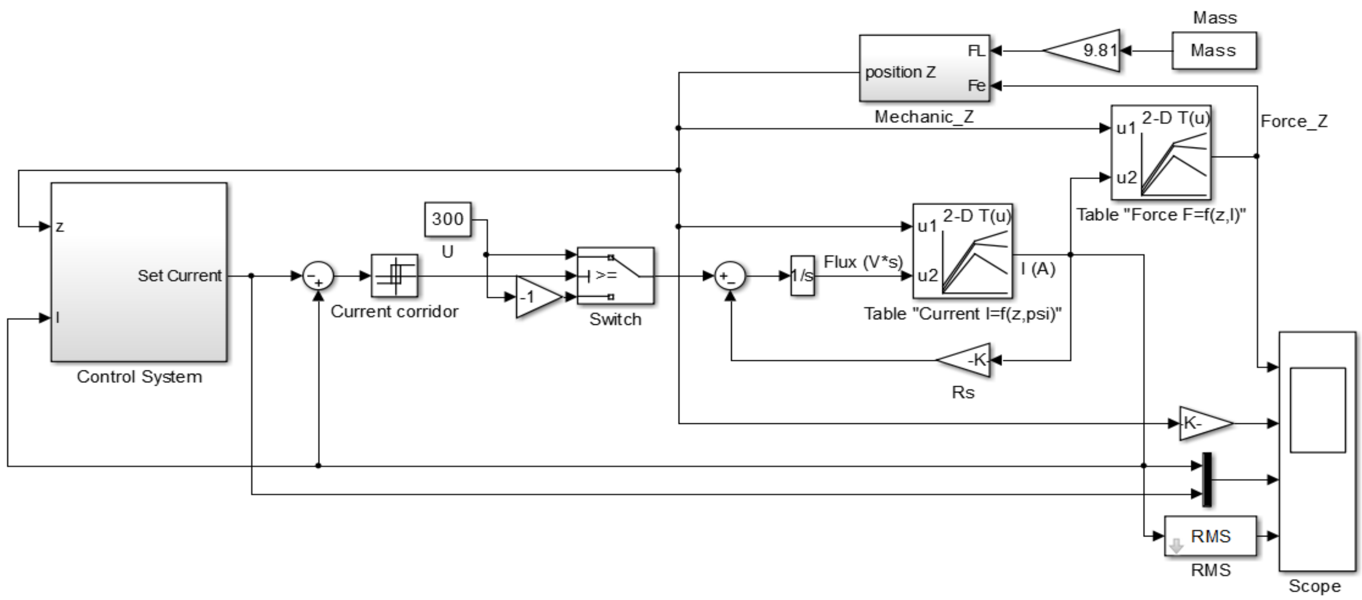

Figure 7. The computer model of the electromagnetic module

In block **Table "Current I=f(z,psi)",** the current dependency is set in the gap and flux linkage function. This function is obtained by recalculating the flux linkage dependency in the gap and current function, that is the 3-D model calculation results. In block **Table "Force F=f(z,psi)",** the dependency of the lifting force in the electromagnetic module is set in the gap and flux linkage function. Due to the permanent magnets application, it is possible to reduce the current in the electromagnet coils to practically zero value.

The key switching is simulated by **Switch unit**, the voltage supply is 300V, the value of the current corridor is regulated by the **Current corridor** unit.

The control system, consisting of the **Control System** unit**,** is designed to regulate the current specified value in accordance with the air gap value. Besides, the regulator, minimizing the current consumption, is foreseen in the control system. The detailed analysis of the control system will be given in the further article.

RESULTS

The vehicle of 600 kg (i.e. 150 kg per one traction module) has been chosen as a simulation object. The initial air gap is 22 mm, the vehicle is at rest.

Both direct and reverse polarity current can be fed to the electromagnetic coil. With the direct polarity, the magnetic flux, going from the permanent magnets, coincides with the magnetic flux of the winding and, as a result, the lifting force increases. With the reverse polarity, the magnetic flux of the permanent magnets weakens and the lifting force decreases. The air gap is possible to be controlled by regulating the current force in the electromagnet coil. In this case, the air gap should be changed in the way that the current, flowing through the electromagnet windings, tends to zero. Figure 8 shows the process of the vehicle lifting and its further levitation.

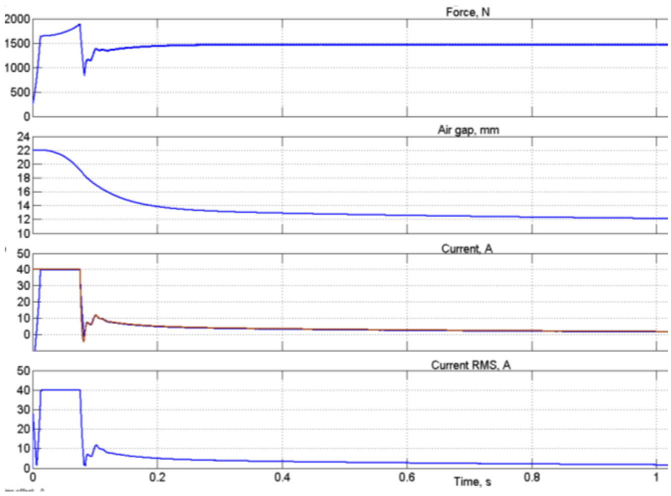

Figure 8. Simulation results

At the idle position, the air gap is 22 mm. The current is supplied to the direct polarity winding. Then, the current value reaches the maximum specified value of 40 A. The vehicle is lifted, the gap is reduced and the lifting force increases up to 1850 N. At time 0,085-0,1 s, the control system reduces the current to 10 A, thereby stabilizing the air gap. Further, there is a smooth current decrease to virtually zero and at the same time the air gap is changed. In steady state (time is 3 sec), the actual current is 0,15 A. The total power required for levitation of the vehicle of 600 kg is 180 W.

CONCLUSION

The present article reviews the design and simulation of electromagnetic suspension for the high-speed vehicle. The joint application of electromagnet and permanent magnets for levitation allows us to achieve a significant reduction of the energy costs to ensure the vehicle levitation. The levitation force is generated by permanent magnets while the electromagnet controls the air gap.

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