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Hybrid electromagnetic suspension for high-speed vacuum transport

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ABSTRACT

The given paper presents a hybrid electromagnetic suspension designed for high-speed vacuum transport, where the main levitation force is generated by permanent magnets, while the electromagnet controls the air gap. The computer model is designed by means of MATLAB/Simulink software package, which allows us to simulate the dynamic operational modes of the system. The calculated studies are carried out when the vehicle accelerating to 1000 km/h with account of track irregularities. Permanent magnets incorporated in the system of electromagnetic suspension make it possible to reduce the energy consumption needed for levitation force generation.

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1. INTRODUCTION

The concept of high-speed land transport development provides for the absence of “wheel-rail” contact system. Instead, various vehicle levitation systems are proposed: air bearing suspension [1], electromagnetic levitation [2]-[4] or electrodynamic levitation [5]. The present paper shows the hybrid electromagnetic suspension [6], where the levitation force is generated by permanent magnets, whereas the electromagnet is used to regulate the air gap [7]. At least four hybrid levitation modules are installed at the vehicle. They consist of U-shaped electromagnets equipped with permanent magnets at the end of each. The block diagram of the hybrid electromagnetic suspension are shown in Figure 1. The windings of U-shaped electromagnet are powered by UZ converter.

One of the problems for high-speed vacuum transport (HSVT) moving in vacuum conditions (discharged environment) is the removal of heat energy losses. The hybrid electromagnetic suspension allows allows us to reduce the energy consumption needed for levitation force generation and, as a result, to reduce the heat losses amount. Another problem is that the hybrid electromagnetic suspension is an unstable system and so, a quick response control system is required to regulate it.

To test the control modes, a computer model of a hybrid electromagnetic suspension [8] with a control system is built, which operates according to the data coming from current sensors TA and air gap sensors BZ. If deviation from the set air gap value, the corrective action should be immediately effected by applying voltage to windings of the U-shaped electromagnet. The larger the deviation, the greater the corrective effect has to be. The most high-quality control has been proved by the system having an intermediate link forming a quadratic dependence [9] of the air gap variation, which is the input signal for the PID controller of the current value in the windings of a U-shaped electromagnet. The air gap control system is based on the “zero power” principle [10] in the nominate operation mode [11]. The air gap value varies depending on the external load in the way that the average current value of the control electromagnet tends to zero. This approach allows minimizing the energy consumption for the levitation force generation.

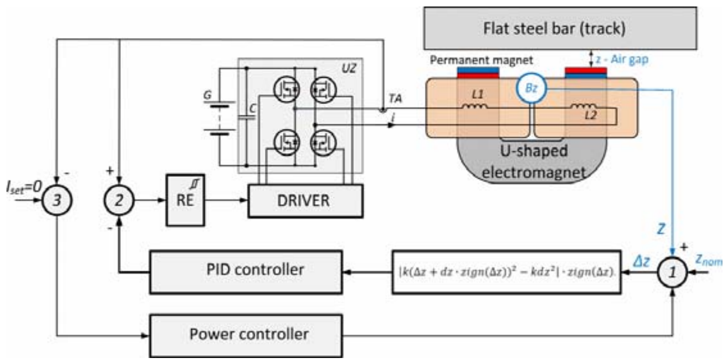


Figure 1. Block diagram of a hybrid electromagnetic suspension

2. DYNAMIC MODES SIMULATION

In order to simulate the dynamic conditions occurring in the hybrid electromagnetic suspension, it is worthwhile applying the principles of the computer modeling design described in [12], [13]. The model is based on the differential equations system describing the electrical and mechanical processes within the system.

$$\begin{cases} v = R \cdot i + \dfrac{d\psi_{EM}(i,z)}{dt} + \dfrac{d\Phi_{PM}(z)}{dt} \cdot w, \\ m \cdot \dfrac{d^2 z}{dt^2} = F_{EM}(i,z) + F_{PM}(z) - m \cdot g - f_z. \end{cases} \tag{1}$$

where i is the current in the winding, z is the air gap, w is the number of winding turns, ψ_{EM} is the flux linkage of the winding, Φ_{PM} is the magnetic flux of the permanent magnet, g is the gravity acceleration, m is the levitation object mass, R is the copper resistance, v is the winding power supply voltage, F_{EM} is the electromagnetic force, F_{PM} is the permanent magnet force, f_z is the perturbing force.

The necessary information for the computer modeling is the results of electromagnetic calculation (dependency of flux linkage $\psi_{EM}(i,z)$, electromagnetic force $F_{EM}(i,z)$ as the function of current and air gap, gravitation force of the permanent magnet as the air gap function $F_{PM}(z)$) performed by means of the finite elements method (FEMM). The calculation by FEMM is run for the module of the hybrid electromagnetic suspension, that is we consider together the assembly of a U-shaped electromagnet and permanent magnets. As a calculation result, we instantly obtain the levitation force dependence of the hybrid electropermanent magnet module $F_{EPM}(i,z)$ as the function of current and air gap. This approach makes it possible to simplify the system (1) and describe it in the following way:

$$\begin{cases} v = R \cdot i + \dfrac{d\psi_{EPM}(i,z)}{dt}, \\ m \cdot \dfrac{d^2 z}{dt^2} = F_{EPM}(i,z) - m \cdot g - f_z. \end{cases} \tag{2}$$

In order to do research, the computer model of the hybrid electromagnetic suspension is developed by MATLAB/Simulink software package and shown in Figure 2.

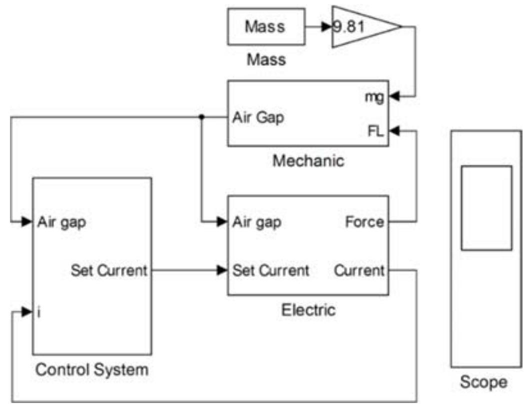


Figure 2. Block diagram of a hybrid electromagnetic suspension

The computer model consists of the following components: the unit for solution of electrical processes equations – Electric; the unit for solution of mechanical processes equations – Mechanic and control system unit – Control System.

2.1. Electric unit

The Electric unit is shown in Figure 3 is designed for solution of differential equations of electrical processes.

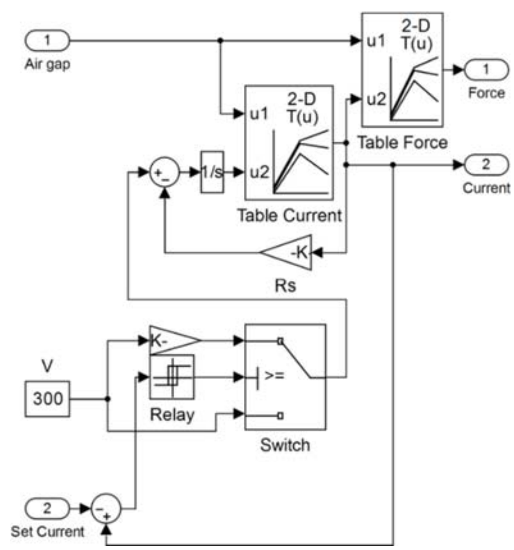


Figure 3. Electric unit structure

The main element is a *Table Current* unit, which contains the tabular data of the electromagnet windings current dependence as a function of air gap and flux linkage $i = f(z,\psi)$. This dependence is obtained by processing the calculation results of the hybrid electromagnetic suspension 3D model and, as a result, we get the following dependence: $\psi = f(i,z)$. *Rs* element takes into account the voltage decrease at the copper resistance of electromagnet windings. The control of voltage supply to electromagnet windings is performed by *Switch* unit. To keep the set current value, *Relay* unit is used which generates the hysteresis effect when commuting the *Switch* key. The allowable amplitude hysteresis value is determined by the capability of the element base of semiconductor devices using in the supplying system of the hybrid electromagnetic suspension.

The lower the hysteresis amplitude, the more precisely the regulation is carried out and the effective value of the current in the electromagnet windings is decreased, whereas the frequency of semiconductor keys switching is increased. The levitation force is determined by the obtained current value; for this purpose, the *Table Force* block is provided, which contains tabular data of the levitation force dependence of the hybrid electromagnetic module as a function of air gap and current in windings $F_{EPM}(i,z)$ as shown in Figure 4.

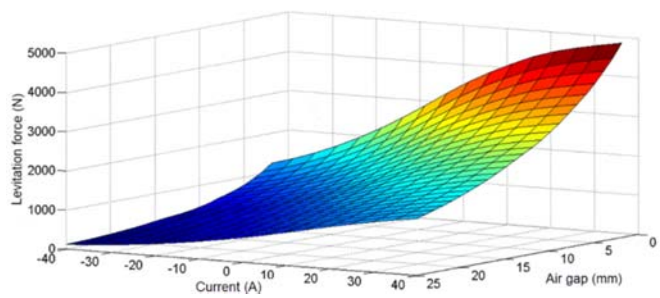


Figure 4. Levitation force dependence $F_{EPM}(i,z)$

2.2. Mechanic unit

The mechanic unit is shown in Figure 5 is designed to solve the differential equations of vehicle vertical movement. In addition, there is a Reaction Force unit, which is used to limit the object movement within the permissible air gap. The limitation occurs both from above (in case of the air gap decreasing to zero) and from below (in case of the air gap increasing to the maximum set value). Using this unit allows us to reach the prototype similarity to the real object and reduce the time needed for control algorithms debugging.

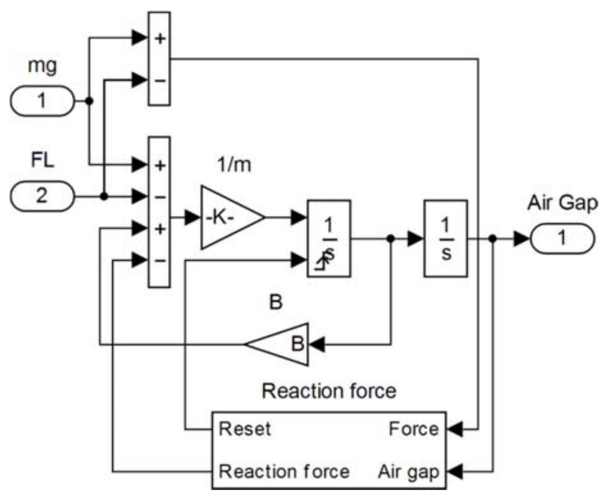


Figure 5. Mechanic unit structure

2.3. Control system unit

The Control System unit is shown in Figure 6 is developed in accordance with the hybrid electromagnetic suspension block diagram shown in Figure 1, and it consists of the current high-speed controller (PID Controller 1) in the electromagnet windings as a function of the quadratic deviation of the air gap from the set value. The second controller (PID Controller 2) is slower and it is designed to correct the air gap setting in order to minimize the average current in electromagnet windings.

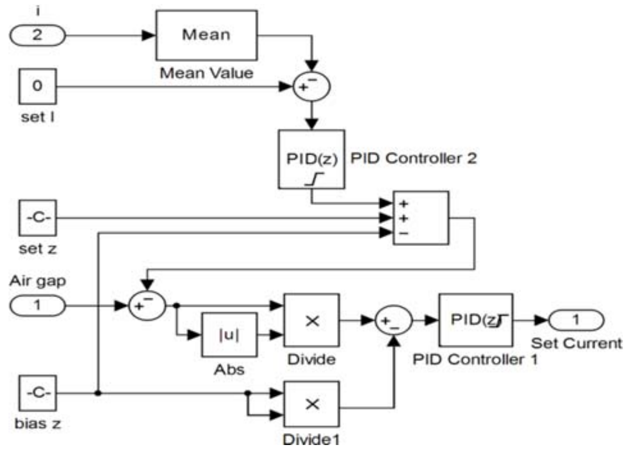
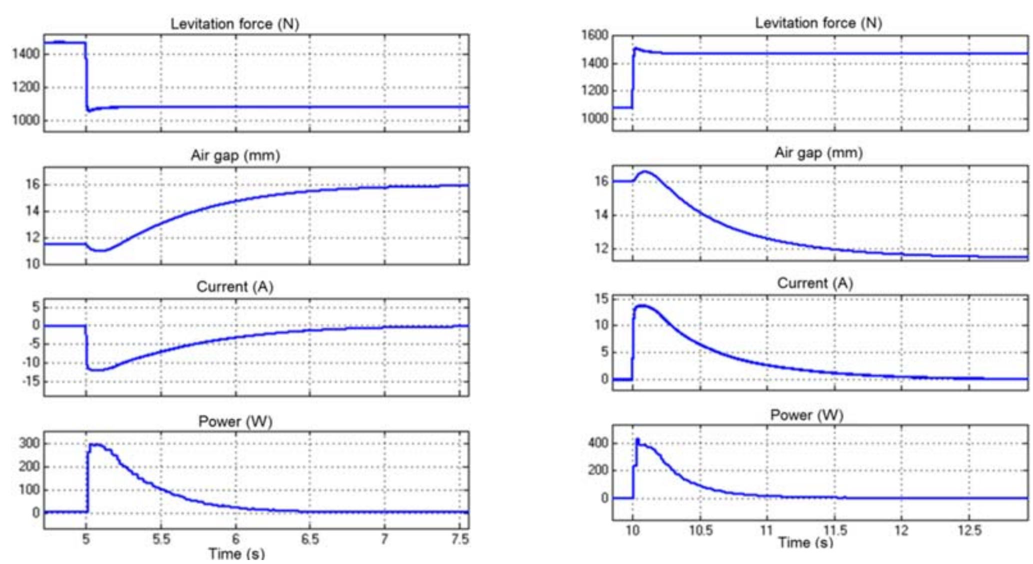


Figure 6. Structure of the Control System unit

3. RESULTS AND ANALYSIS

3.1. Variation in vertical load

At the first stage of the research, the system stability has been simulated when a sharp changing of the vertical load (shedding/rise). Transient processes are investigated when there is an abrupt change of the vertical load due to the mass changing by 50 % per one hybrid levitation module. At the time t = 5 s, the load is decreased. At the time t = 10 s, the load is increased. Figure 7 shows oscillograms of the levitation force, air gap, current in the control winding, and power consumption during the transient process.



(a) (b)

Figure 7. (a) Oscillograms of the processes when the work load is decreased by 50 % and (b) increased by 50 %

Based on the computer simulation results, it is obvious that the proposed system of the hybrid electromagnetic suspension and the developed control system succeed in working out in time the load changing which falls at the levitation module. It needs 2.5 s to stabilize the transient process after the dramatic load changing. The greatest energy consumption occurs at the time of a sudden load change. The peak power expended on stabilization increases with the increase of the magnitude of the abrupt load changing. The energy consumption when the load rising is higher than when the load shedding.

3.2. Movement with account of the track structure perturbations

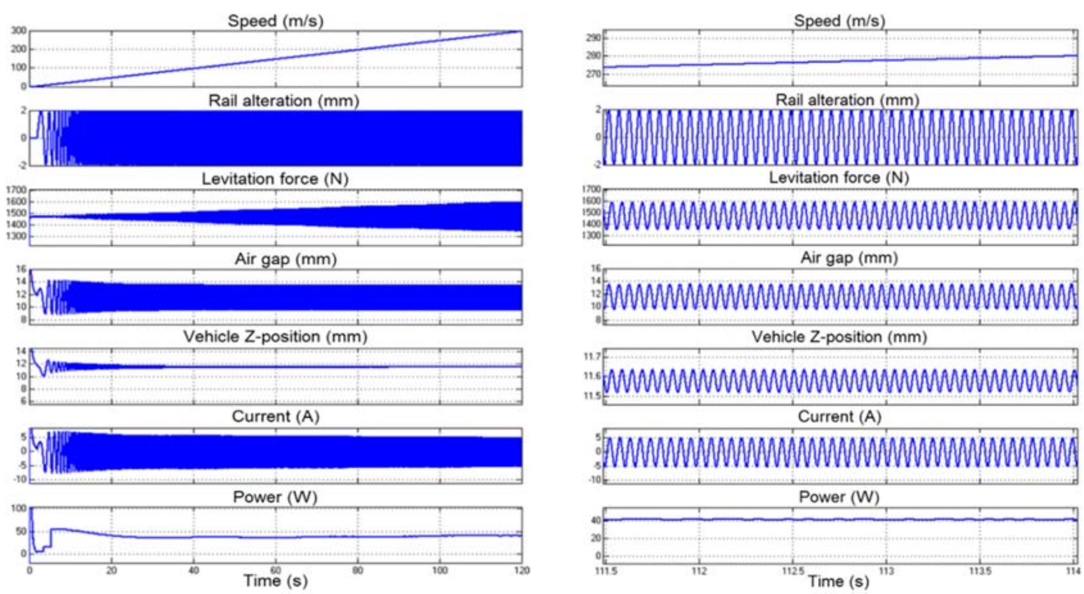
The second stage of the research is the simulation of the levitation process in the movement with account of the track structure perturbations. The levitation simulation in movement has been performed under different loads per one module. This article demonstrates the simulation results for a full load of 150 kg per a module when simulating the track structure perturbations.

The track irregularities due to the track "sagging" at the supporting poles are taken equal to 4 mm per 30 meters of the track. The initial air gap is 22 mm. During the first two seconds, the vehicle starts climbing and the rated working gap is set, at which the average current value tends to zero. At the time of 2 s, the HSVT starts accelerating. For simulation of the hybrid electromagnetic suspension, the acceleration is taken to be 2.5 m/s2. It is assumed that the suspension rails of 30 m long are sagged by 4 mm, which is represented by a sinusoidal signal (Rail alteration) with amplitude of 2 mm. The alternating frequency of the air gap grows proportionally to speed.

Figure 8 show the results of the computer modeling. Oscillograms are developed with visual aids of MATLAB software package. The following oscillograms are presented in Figure 8 (from the top to the bottom):

a. oscillogram of the speed change (Speed);
b. oscillogram of the sinusoidal signal (Rail alteration), which simulates the track structure sagging;
c. oscillogram of the levitation force change (Levitation force);
d. oscillogram of the air gap change (Air gap);
e. oscillogram of the vehicle vertically position (Vehicle Z-position);
f. oscillogram of the current change in the control windings of the magnetic suspension system (Current);
g. oscillogram of the power consumption change (Power).

The given above oscillograms demonstrate the time period of 0 to 2 s, which corresponds with the time of system transition to the levitation mode. The time period of 2 to 120 s corresponds with the time of vehicle acceleration with the constant acceleration of a = 2,5 m/s^2.



(a) (b)

Figure 8. Oscillogram of the processes occurring in the traction levitation system when acceleration with account of the track structure irregularities (a) and enlarged fragment (b)

When the vehicle climbs, the consumed power of one hybrid electromagnet is 1600 W (not indicated in Figure 8, whereas when moving, the power reaches approximately 50 W per one hybrid electromagnet. The vehicle position in space along z-axis is practically unchanged which caused by the system inertness and gap signal filtering in the control system with the variable frequency depending on speed. Figure 8 show that the air gap size changes in the same way as the rails deviation. As the speed increases, the air gap value almost changes in accordance with the given external interferences. At the same time, the vertical position of the HSVT is practically unchanged (no pounding of HSVT) and the HSVT displacement amplitude (without shock-absorbers and vibration dampers) in space at the speed of 1000 km/h is 0.06 mm.

3.3. Movement on a steep track gradient

The third research stage is to simulate the levitation process in the movement with account of the steep track structure perturbations. The simulation of the transient process, which occurs when going from the horizontal track section to the rise with specified slope and further movement along the slope, is performed at the linear speed of the HSVT equaled to 278 m/s and the steep track gradient equaled to 40 ‰. Figure 9 shows the oscillograms of the movement on a steep track gradient.

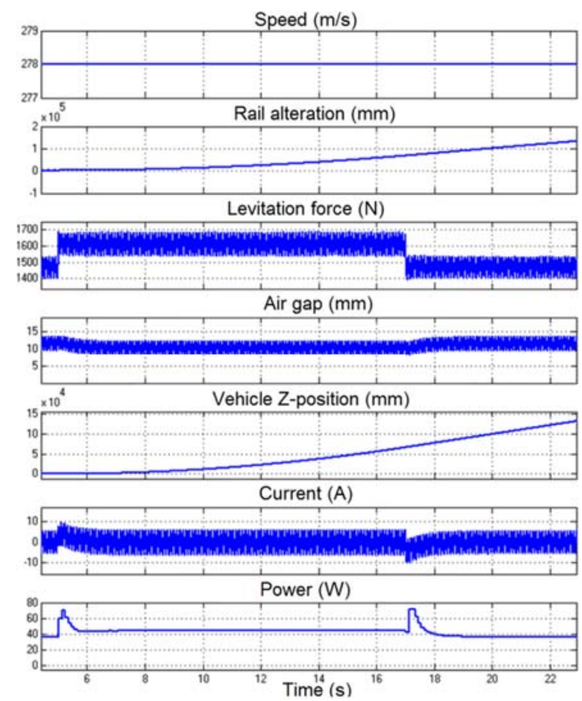


Figure 9. Oscillogram of the processes occurring in the levitation system when movement on a steep track gradient

It follows from the oscillograms that in a time interval from 5 s to 12 s, there is a smooth transition from a horizontal track section to the steep track gradient of 40 ‰; the length of the transition section is 3336 m. There has been the fluctuating change of the air gap value with the deviation amplitude of 20 % relatively the mean value and the frequency of about 10 Hz. This fluctuating nature of the air gap value change occurs due to the track irregularities. The presence of the transition section and the movement at the steep track gradient of 40 ‰ do not practically effect on the overall picture of the processes without account of track irregularities. The peak power consumption is observed at the beginning and ending of the transition section.

According to the modeling test results, the power required for levitation keeping in steady modes is 40 W per one module (full load of 150 kg per a module) when steep moving with account of track irregularities. The specific energy consumption needed for levitation is 0.27 W/kg. The calculation results performed for electrodynamic suspension is given in [14], which shows that the specific energy consumption needed for levitation is 96.8 W/kg. Thus, the research carried out has proved the applicability of the hybrid electromagnetic suspension for levitation generation in high-speed vacuum vehicles.

4. CONCLUSION

The article has been reviewed the hybrid electromagnetic suspension designed for a high-speed vehicle. The joint application of an electromagnet and permanent magnets for levitation allows us to achieve the significant reduction of the energy consumption to ensure the vehicle levitation. The levitation force is generated by permanent magnets while the electromagnet controls the air gap.

According to simulation results of the traction levitation system of the high-speed vacuum transport, we can make the following conclusions:

a. The confirmation of the “zero power” algorithm efficiency in the levitation mode has been obtained;
b. The levitation air gap value depends on the vertical load value and it is regulated in the range from 10 to 16 mm;
c. The amplitude current value of the hybrid electromagnetic suspension is 5 a;
d. The maximum current value in the control windings of the levitation modules does not exceed 12 a. This current is needed for a short time only during transient modes;
e. In steady levitation states the current value in the control windings of the levitation modules tends to zero;
f. The maximal electric losses in the levitation electromagnetic modules (full load of 150 kg) of traction levitation system in the steady state do not exceed 40 w;
g. At the section of 40 ‰ slope, the power required by the levitation system when moving at the slope is almost equal to the power consumed by the levitation system at the horizontal section with account of track structure perturbations.

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