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Comparison between a Maglev Electromagnetic Suspension System and a Hybrid Suspension System Equipped With Permanent Magnets

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Abstract

The theoretical comparison results of dynamic properties between electromagnetic and hybrid suspension systems obtained at the non-linear Simulink models are given. It has been discovered that, the integration of the permanent magnet into the magnetic circuit gives the system essentially non-linear properties that should be taken into account when designing the control system. It has been shown that, the application of the hybrid suspension system, equipped with permanent magnet, integrated into the electromagnet magnetic circuit, gives the possibility to reduce power consumption and losses.

Keywords: Vacuum Maglev, permanent magnet, hybrid suspension system, control system, Simulink model.

INTRODUCTION

Maglev transportation has advantages of safe, comfort, low noise, small turning radius and strong climbing ability [1]. It is a promising way of rail transit, which has received extensive attention in recent years. Countries such as Germany, Japan, China, South Korea and America have carried out relevant research on maglev technology and all have made great progress [2, 3].

The further Maglev development is connected with the aim to increase the speed due to the overcoming including the aerodynamic resistance to motion. This resistance and the noise, occurring due to bearing members of the magnetic suspension, are significantly reduced if they are placed into the rarefied medium pipeline.

At the present time, the new direction of magnetic levitation transport system called Vacuum Maglev is being developed [4]. One of the Vacuum Maglev design problems is the heat rejection in the rarefied medium.

One of the sources of heat generation is energy losses occurring in the magnetic suspension system. The studies performed have shown that the loss reduction is achieved in the hybrid suspension system, equipped with the permanent magnet included into the magnetic circuit of the electromagnet [5].

Strong magnets are used to create the basic levitation force, while electromagnets are used for system stabilization. The force, generated by the permanent magnet, with the certain air gap is equal to the gravity of the object and therefore, when the object is levitated, the electric power is not consumed.

Theoretically, in the steady mode the system should not consume energy from the power supply source and supply at the same time the magnetic suspension by means of the permanent magnet. The practical implementation of the system has confirmed that the hybrid suspension system reduces the energy consumption as well as the heat generation and ensures the magnetic suspension, but at the same time, the complexity of the control algorithm significantly increases. [6]. Despite the control algorithms sophistication, there are some control problems of the suspension system with hybrid electromagnet. For example, the researches performed have found that one of the problems is the vibration induced by dynamic interaction between a hybrid magnet and a rail [7]. To a certain extent, the control problems are generated by the engineering methods of the system design based on the linearization of the control object in the vicinity of the operating point. This fact “smooths out” specific features of the control objects and that worsens the regulation quality.

Taking into account the fact that, the operating quality of the magnetic suspension system is related to the Maglev safety movement, it is reasonable to make a theoretical comparison of dynamic properties between electromagnetic and hybrid suspension systems at the non-linear models. It needs to detect the specific features, inducing by the permanent magnet, for further estimation the possibility to implement the hybrid suspension system in the high-speed Vacuum Maglev system.

RESEARCH PROCEDURE

The single-point model of the suspension system (fig.1) is considered, which consists of the actuating electromagnetic element, inducing the electromagnetic force F_{EM} ,(F_{PM}), which interacts with a secondary ferromagnetic element through the specified air gap z. Elastic vibration and dynamic deformation in the system are ignored in the model. The actuating element of the electromagnetic suspension system is an electromagnet having a simple U-shaped magnetic circuit with windings around the pole. In the hybrid suspension system the U-shaped magnetic wire of the same size additionally equipped with the permanent magnets, installed at the poles ends.

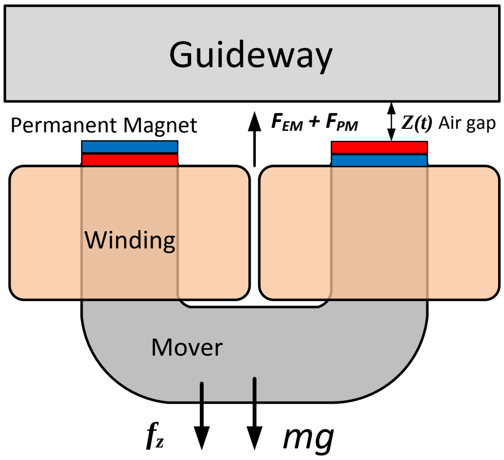


Figure 1: The Schematic diagram of the single-point model of the hybrid suspension system

To ensure the system compatibility, the permanent magnets characteristics are chosen in such a way as to provide the interacting force with the secondary ferromagnetic elements through the specified air gap with no current in the winding; the interacting force should be equal to the force generated by nominal current in the winding in the absence of the permanent magnets.

The research has been carried out at the non-linear Simulink models of the systems where the structure and parameters of control system regulators are the same. At the same time, the magnetic system characteristics have been obtained during 3D FEM analysis. Flux linkages of permanent magnets winding as well as magnetic properties of materials saturation have been taken into account. The calculation test results have been recorded in the file and processed in Mathcad system.

SIMULATION OF THE SUSPENSION SYSTEM

Simulink-models of the system are structured in accordance with the following mathematical description. The processes occurring in the electromagnetic suspension system are described as the following equation system:

$$\begin{cases} \dfrac{di(t)}{dt} = \dfrac{1}{\dfrac{\partial \Psi(i(t),z(t))}{\partial i}} \cdot \left(u(t) - i(t) \cdot R - \dfrac{\partial \Psi(i(t),z(t))}{\partial z} \cdot \dfrac{dz(t)}{dt} \right), \\ m \cdot \dfrac{d^2 z}{dt^2} = F_{EM}(i,z) - m \cdot g - f_z \end{cases} \quad (1)$$

The processes occurring in the hybrid suspension system are described as the following equation system:

$$\begin{cases} \dfrac{di(t)}{dt} = \dfrac{1}{\dfrac{\partial \Psi(i(t),z(t))}{\partial i}} \cdot \left(u(t) - i(t) \cdot R - \dfrac{\partial \Psi(i(t),z(t))}{\partial z} \cdot \dfrac{dz(t)}{dt} - \dfrac{d\Phi_{PM}(z)}{dt} \cdot w \right), \\ m \cdot \dfrac{d^2 z}{dt^2} = F_{EM}(i,z) + F_{PM}(z) - m \cdot g - f_z \end{cases} \quad (2)$$

where $i(t)$ – Current of magnetic coil

z – Gap in electromagnet and track

w – Turn of magnetic coil

Ψ – Flux linkage of an electromagnet winding

Φ_{PM} – Magnetic flux in the gap from a permanent magnet

g – Acceleration of gravity

m – Total mass of suspension object

R – Active winding resistance

$u(t)$ – Voltage of magnetic coil

F_{EM} – Electromagnetic force

F_{PM} – Permanent magnet force

f_z – The external disturbance force

t – Time

The input data for Simulink model of the system is the results of magnetic systems 3D FEM analysis.

The following dependencies have been obtained:

- flux linkage dependence on the current and gap value $\Psi(i,z)$;
- electromagnetic force dependence on the current and gap value $F_{EM}(i,z)$;
- force dependence, generated by the permanent magnet, on the gap value $F_{PM}(z)$;
- dependence of the magnetic flow through the pole surface, generated by the permanent magnet, on the gap value $\Phi_{PM}(z)$.

Figure 2 shows that dependencies $\Psi(i,z)$ are linear. This allows us to describe the function $\Psi(i,z)$ using rather simple analytical expression and by its differentiation to get partial current and gap derivatives including in the expressions (1, 2).

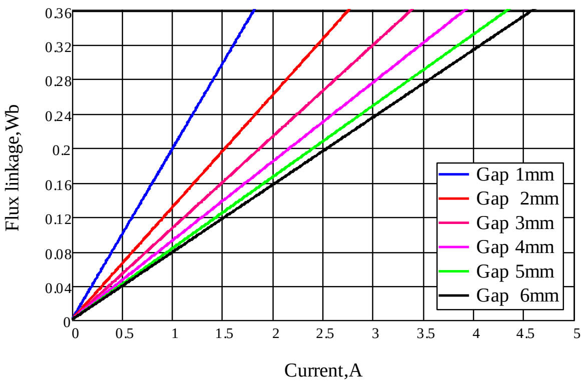


Figure 2: Flux linkage $\Psi(i,z)$

The analytical expressions have been also obtained for $F_{EM}(i,z)$, $F_{PM}(z)$, $\Phi_{PM}(z)$. The analytical dependencies received are inputted into the Simulink model of the system as Matlab-functions by means of "MATLAB Fcn". At the output of the block the signal, corresponding to the introduced function, is generated.

Figure 3 demonstrates the given above. The analytical expression, describing the electromagnetic force $F_{EM}(i,z)$, is introduced into the block window with "MATLAB Fcn" parameters using MATLAB language.

The given approach allows realizing a rather accurate model, which provides a way for detailed researching of the processes occurring in the system.

The structure of the general block diagram of Simulink-model (fig. 4) is the same for the suspension systems under consideration. Simulink-model includes the subsystems simulating electromagnetic and electromechanical processes, describing in the equations of the systems 1 and 2, as well as the subsystem of the Controlled Voltage Source. The subsystems are covered by current and gap feedback. A PID controller is included in the feedback loop for the gap.

The subsystem Simulink-model, simulating electromagnetic processes (fig.5), includes "MATLAB Fcn" Simulink blocks, which simulate the following: $F3$ – the magnetic flow of the permanent magnet Φ_{PM}, $F4$, $F5$ – derivatives of the gap and current flux linkage. The grey colour in the scheme indicates the blocks belonged to the hybrid suspension system.

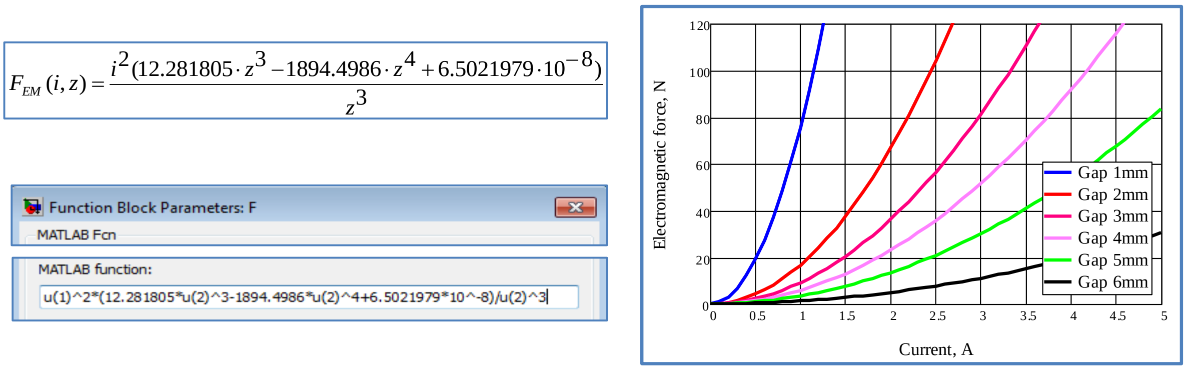


Figure 3: Creating a Matlab Function

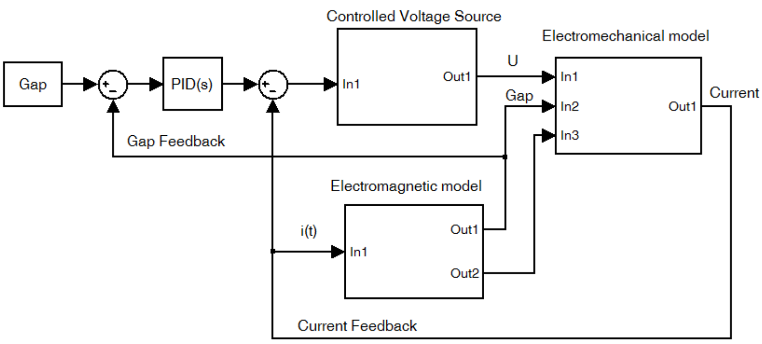


Figure 4: Block diagram of the Simulink model

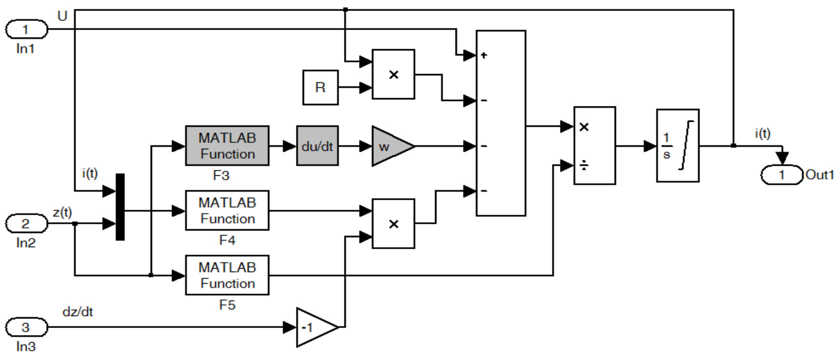


Figure 5: Block diagram of the Electromagnetic Subsystem

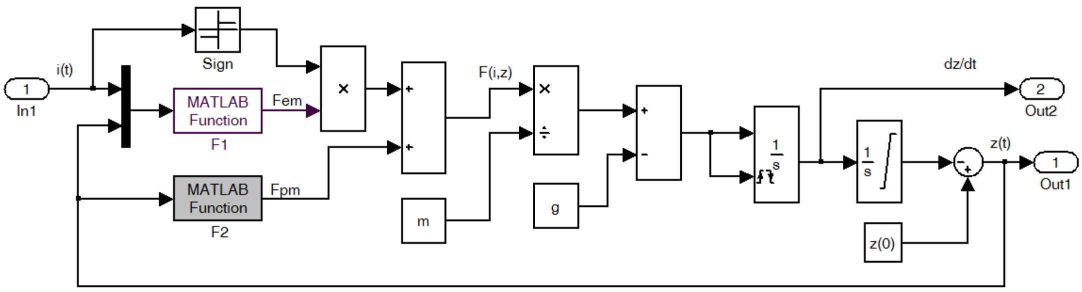
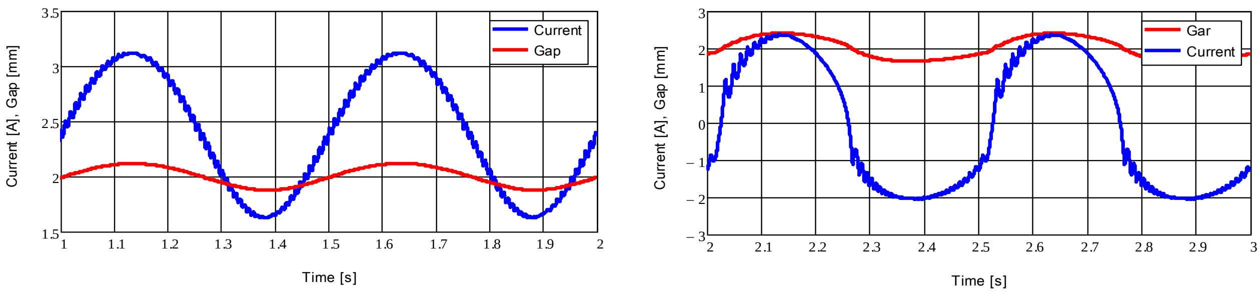


Figure 6: Block diagram of the Electromechanical Subsystem



a b

Figure 7: Simulation results of disturbance tracking;
(a) Electromagnetic suspension system, (b) Hybrid suspension system

The subsystem Simulink-model, simulating electromechanical processes (fig.6), includes “MATLAB Fcn”Simulink blocks *F1*, *F2*, which describe $F_{EM}(i,z)$, $F_{PM}(z)$ expressions.

RESULTS AND DISCUSSION

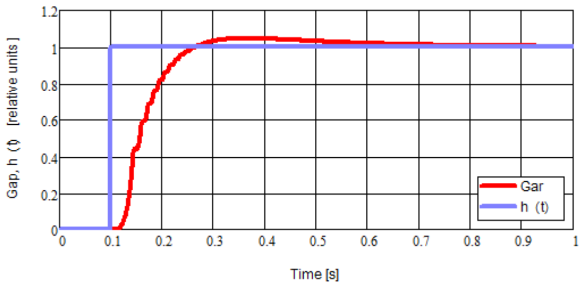
In order to carry out the calculation tests, we chose the operating point of the system corresponding with the following values: z = 2mm, I = 2.4A, F_z = 100 *H*. The calculation test has been performed to check the properties of the systems models in vicinity of the specified operating point. To do this, the sinusoidal input disturbance, simulating the mass changing in the range of m =10 ±5 *kg*, is set and the reaction of each system is detected. Figure 7 presents the oscillograms of current and gap movements.

The data given above proves that both systems with the same specified gap values and regulator settings are stable and are possible to balance external disturbances by mass equal to approximately ± 50% of the nominal value. The difference is that in the electromagnetic suspension system, the current in the winding has a positive polarity, and in the hybrid suspension system, it varies with respect to zero. The mode quantitative estimations are the following: the effective value of the currents for the electromagnetic system is I_{EM} = 2.34A, for the hybrid system is I_{PM} = 1.74A and accordingly the consumed power is P_{EM} = 19.49W, P_{PM} = 10.78W. Thus, the experiment confirms that, other things being equal, the energy efficiency of the hybrid suspension system is significantly higher than in the electromagnetic suspension system.

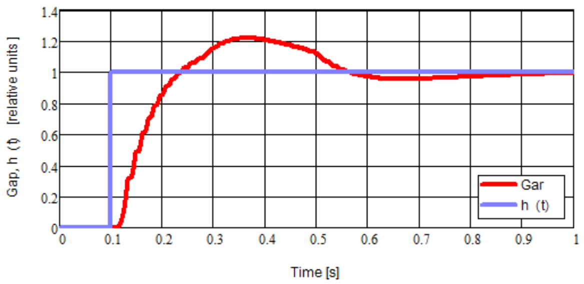
At the same time, the dynamic error of keeping the set gap in the hybrid suspension system is 34.7%, while in the electromagnetic suspension system it is 5.1%. The nature of the current change comes under notice: in the electromagnetic suspension system, the current form practically repeats the sinusoidal waveform of disturbance, while in the hybrid suspension system, distortion of the current shape is observed - the rate of current variation in the range ± 1 A sharply increases.

It may be suggested that, the integration of a permanent magnet into the magnetic circuit enhances the nonlinearity of the power element as a dynamic link.

This is also confirmed by experiments carried out with a stepwise change of the driving and disturbing effects. Figure 8 shows oscillograms of transient processes with a stepped gap specification. The oscillograms comparison shows that in the hybrid system the overshoot is much higher (more than 20%) than in the electromagnetic suspension system, which indicates a lower stability margin value of the system.



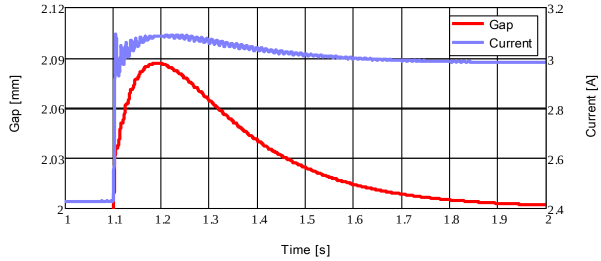
(a)



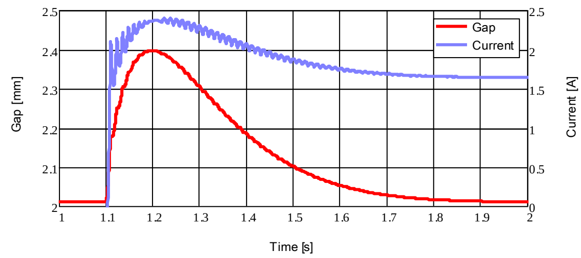
(b)

Figure 8: Transient processes with stepped Gap setting; (a) Electromagnetic suspension system, (b) Hybrid suspension system

Figure 9 shows the oscillograms of transient processes with a stepwise mass specification. The analysis of the oscillograms proves that the systems compensate the disturbing effects for approximately the same period of time. The hybrid system was in steady state before the action under current close to zero. With mass increasing, the current was set at a value compensating the mass increasing, and this value is almost half as large than in the electromagnetic suspension system. Dynamic error in the gap is much higher in comparison with the electromagnetic suspension system.



(a)



(b)

Figure 9: Transient processes with stepwise setting of mass; (a) Electromagnetic suspension system, (b) Hybrid suspension system

The above comparison of the systems demonstrates that, the dynamic properties of the hybrid suspension system with the same regulator settings are significantly worse than in the electromagnetic suspension system. Obviously, to obtain acceptable dynamic properties of the hybrid suspension system, a more complex control algorithm is required. To develop a regulator, first of all, it is necessary to classify the type of the nonlinear dynamic link, to which the hybrid power element can be assigned. To clarify this issue, a numerical experiment has been performed, during which the set gap value varied smoothly in the range from 3 mm to 1 mm. At the same time, the current and gap changes were recorded. The results of the experiment (figure 10) show that the system tracks the change in the set gap value until the operating point at z = 2mm is reached.

The current should theoretically assume a zero value at this point. However, in the vicinity of this point, there is a sharp drop in current to zero and a subsequent abrupt transition to the negative range of values. Further gap reduction leads to a current increase in absolute value.

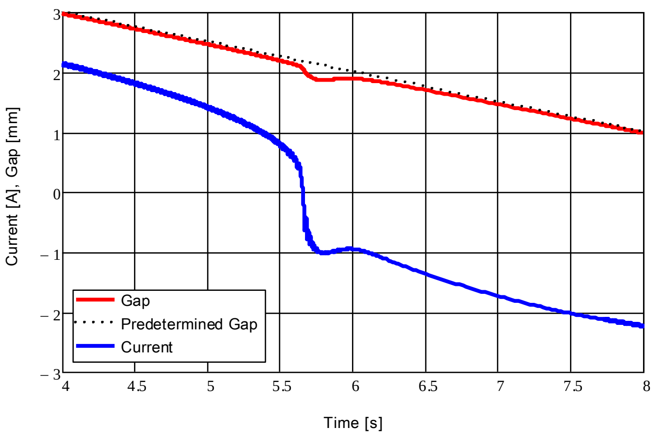


Figure 10: Simulation results of gap variation

It can be easily noticed that, the current change is relay-typed. In this connection, it can be assumed that, the hybrid electromagnet, as an actuating element of the suspension control system, has the properties of a relay dynamic link. To confirm this assumption, an experiment was conducted in which the behavior of the system at the operating point in the steady-state operating mode was investigated. In this mode, in the absence of disturbances, the current must be zero, i.e. suspension should be carried out by the force of a permanent magnet. However, the processes, presented in

Fig. 11, at the operating point of the hybrid suspension system indicate the presence of an autooscillatory process in the vicinity of the operating point.

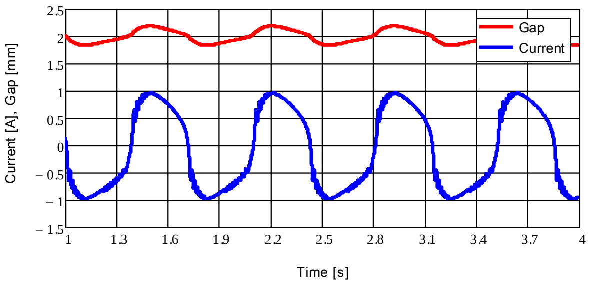


Figure 11: The simulation results of the auto oscillatory process

In that mode the system keeps the stability, the current amplitude changes in the range of ±1A, the effective current is I = 0.753A, the gap oscillatory amplitude is 0.2mm, natural oscillation frequency is 1.34 Hz.

CONCLUSION

The theoretical studies performed confirm that, all other things being equal, the energy efficiency of the hybrid suspension system is significantly higher than in the electromagnetic suspension system. At the same time, it has been discovered that, the integration of the permanent magnets into the magnetic circuit of the suspension system dramatically changes its dynamic properties. The system becomes essentially non-linear, with properties close to relay control systems. This complicates the control algorithm. Therefore, further studies, related to the possibility of implementation a hybrid suspension system at a high-speed transport, should be aimed at the assessing the quality of nonlinear control processes under various control algorithms.

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