Analysis of transient processes in levitation electromechanical systems including effects of magnetic potential hole

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Abstract. A mathematical model of a dynamic system including superconducting electric circuits and effects of the magnetic potential hole is presented. Motion transmission of the magnetic cushion rapid train, known as maglev train, which uses natural magnetic static levitation, is modelled on this basis. Starting from the model, transient electromechanical processes in an integrated dynamic system are analysed. The model is presented as a system of non-linear differential equations in the normal Cauchy’s form. The equations are integrated by means of explicit numerical methods. Results of computer simulations are illustrated as graphs whose behaviour is analysed.

1. Introduction
The rapid progress of global industry pushes modernisation of existing and design of new branches of transportation linked with logistics. Increasing speed of travel is obviously a key requirement of the transport system. This applies to rail passenger transportation [1,2,3].

From the perspective of applied physics, achievement of high speeds is evidently associated with losses of energy dispersed as thermal energy, with air resistance, friction processes, etc. A great number of scientific and engineering publications concern modernisation of vehicle shapes to reduce drag factor, adaptation of rail configuration to high speeds, replacement of classic mechanical with magnetic bearings, and the like. [4,5]. First vehicles were developed in the second half of the last century where friction between the train and rail was eliminated by means of a new type of Maglev magnetic cushion suspension. A train in motion is in levitation without any contact with a railroad [6,7].

New materials can now be produced where the so-called high-temperature superconductivity occurs at relatively high temperatures [8]. The phenomenon has its industrial applications [9].

Maglev Shanghai and Japan Maglev trains are among the best known projects. Operating principles of both the suspension types are a little different [2,3]. Levitation processes in these suspensions are similar, on the other hand, and take advantage of static magnetic levitation. The static levitation requires complicated control systems.

Another method of producing magnetic levitation is presented in this paper. This is the so-called natural magnetic levitation, where a control system is completely absent. This type of levitation is described in [10]. The idea relies on superconductivity of materials whose conductance $\rho=0$. This type of magnetic levitation is known as magnetic potential hole [10].
2. Magnetic levitation

It is known a stable levitation system of two magnets is impossible in normal circumstances. This is substantiated by Earnshaw’s theorem on impossibility of stable systems described with the inverse-square law, applicable to magnetic systems as well [10]. However, Earnshaw’s theorem does not apply to magnetic systems including parts with a magnetic permeability below one. Such a levitation system is not subject to the theorem, a fact used by the German physicist Braunbeck in his experiments. He has demonstrated superconductivity considerably improves the process of levitation. Diamagnetics are the typical superconducting materials. Braunbeck effect can be treated as magnetic levitation in the event. Magnetic permeability of an ideal diamagnetic is \( \mu = 0 \). Similar experiments were conducted by the German physicist Meissner on superconducting systems [10].

The idea behind magnetic potential hole is rather complicated, therefore, its principles will be briefly discussed. A superconducting diamagnetic ring is placed in the magnetic field of a fixed magnet. Since the ring material is diamagnetic and has a specific mass, the material should drop were the ring a classic electric circuit. The famous law of magnetic flux trapping applies to a superconducting material, which implies magnetic flux in superconducting systems remains fixed (trapped) [10]. If the diamagnetic ring drops under the influence of gravitation, however, the total magnetic flux will change, since the circuit’s magnetic induction changes according to the definition of magnetic flux function:

\[
\Phi(x, y, z, t) = \int_{S} \mathbf{B}(x, y, z, t) \cdot d\mathbf{S}(x, y, z)
\]

A paradox arises: the ring surface is unchanged while the induction changes. In line with (1), the flux in the magnetic circuit must change then. What in fact takes place in the system? To ensure conformity of both the laws of physics, current across the superconducting ring is of such a value as to uphold the principles of associated flux trapping [10]. In the event, the magnetic flux \( \Phi_0 = \text{const} \):

\[
\Phi_0 = \Phi(x, y, z, t) + Li(x) = \text{const}
\]

We analyse the electromechanical system of maglev train suspension considering magnetic potential hole in this paper. The circuit diagram of maglev train suspension in the motion transmission system is illustrated in Figure 1.

![Circuit diagram of maglev train suspension.](image-url)

The following nomenclature is used: \( F_1 \) – force acting on the top circuit wire, \( F_2 \) – force acting on the bottom circuit wire, \( F \) – force balancing \( F_1 \) and \( F_2 \), \( P = mg \) – force of gravity of a train weighing \( m \), \( g \) – gravitational acceleration, \( I \) – current the superconducting circuit, \( I_0 \) – constant magnetising current, \( r \) – radial coordinate, \( r_0 \) – distance from the superconducting electric circuit to the upper magnetising wire, \( a, l \) – dimensions of the superconducting electric circuit, \( \alpha \) – current angular coordinate.

A wire with current \( I \) across it generates a magnetic field constant in time. According to the law of current flow for \( z=1 \) coils, the following will be expressed then [11]:

\[
\int \mathbf{H} \cdot d\mathbf{l} = \sum i
\]

where \( \mathbf{H} \) – vector of magnetic field intensity, \( d\mathbf{l} \) – part of the closed integration circuit, \( \sum i \) – sum total of all currents across the circuit.
(3) takes the magnetic eddy field into account. The superconducting electric circuit with the dimensions \((l \times a)\) m is mounted in a train carriage, for instance. The carriage is then lifted by cylinders to a height \(r_0\) and a cryogenic system is switched on at the same time, which generates superconductivity. The law of magnetic flux trapping applies in the system as a result. The cylinders are then off and the train has been suspended motionless in the air following the effect of potential hole (2). Let it be noted that, as energy dissipation is virtually absent from the system, the system of train motion transmission will execute permanent oscillatory processes in space. On the basis of Figure 1 and equation (3), the same will be expressed in the scalar format [12]:

\[
H = \frac{I}{2\pi r} \Rightarrow B = \frac{I\mu_0}{2\pi r} \tag{4}
\]

where \(B\) – projection of magnetic induction vector on to axis \(\alpha\), \(\mu_0\) – magnetic permeability of the air.

Magnetic flux and current \(i\) will be calculated by:

\[
\Phi = \frac{II\mu_0}{2\pi} \ln \left( \frac{r + a}{r} \right) \tag{5}
\]

\[
i = \frac{II\mu_0}{2\pi L} \ln \left( \frac{(r_0 + a)r}{(r + a)r_0} \right) \tag{6}
\]

The circuit inductivity will be derived from:

\[
L = \frac{\mu_0}{\pi} \left[ (a + l) \ln \left( \frac{2al}{R \left( a + \left( a^2 + l^2 \right)^{1/2} \right)} \right) - 2 \left( a + l - \left( a^2 + l^2 \right)^{1/2} \right) \right] \tag{7}
\]

where \(R\) – radius of the frame wire.

Energy dispersion is virtually absent from levitation electromechanical systems including the effect of magnetic potential hole. This means oscillatory processes practically fail to disappear from motion transmission and the train is unable to discharge its function. An electric circuit containing a high resistance is introduced to the train’s motion transmission system. In compliance with Faraday’s law of electromagnetic induction, the electric circuit will move in a constant magnetic field, cf. Figure 1. This means an electromotive force will be induced under the influence of variable magnetic induction:

\[
\int_{\Gamma} \mathbf{E} \cdot d\mathbf{A} = -\frac{\partial}{\partial t} \int_{\Gamma} \mathbf{B} \cdot d\mathbf{S} \Rightarrow e(t) = -\frac{d\Phi}{dt} \tag{8}
\]

It can be claimed with certainty; therefore, current in the electric circuit will flow across the circuit’s resistance. Note that after the oscillations vanish, magnetic induction will not change in time and electromotive force will not be induced in the circuit. The damping circuit does not operate in the steady state [13, 14, 15].

The equation of oscillating motion of rapid maglev train prototype suspension will be written as:

\[
\frac{dv}{dt} = g - \frac{il\mu_0}{2\pi rm} \frac{a}{r + a}; \quad \frac{dr}{dt} = v \tag{9}
\]

Let us explain the physical principles present in the electromechanical system. The magnetic field plays the role of transforming dissipation energy that is, converting electrical into mechanical energy. Resistance of the damping circuit can be calculated based on this assumption.

Analysing the system relative to the dissipation factor \( \nu \) under zero initial conditions, the following can be expressed:
For the purpose of analysing transient oscillatory processes in motion transmission of the prototype Maglev train, the following equations are integrated: (9) – for the system without the damping system as well as the additional formulas: (4) – (7), (10).

3. Results of computer simulation

A prototype rapid train that contains motion transmission on a maglev magnetic cushion is analysed. An assumption is added that magnetic potential hole is present in the levitation system. At the time of the simulation, the train’s linear velocity is assumed to be zero or constant where the train travels in an absolutely straight line. Two experiments were conducted, one in the absence of a damping circuit and the other, in its presence. These are the parameters of the levitation electromechanical system: \( l=1 \cdot 10^6 \text{A}, \: m=20 \text{kg}, \: a=0.1 \text{m}, \: l=20 \text{m}, \: r=0.05 \text{m}, \: R=5 \cdot 10^{-6} \text{m}. \) Motion equations of the system are integrated with the explicit Runge-Kutta fourth-order method including a constant step of integration \( h=1 \cdot 10^{-5} \text{s}. \)

![Figure 2. Spatial oscillation amplitude of the coordinate x of the train’s mass centre for the first experiment.](image)

![Figure 3. Temporary current in the superconducting circuit for the first experiment.](image)

Figure 2 shows amplitude of the train motion oscillations as a function of time for the first experiment. Energy is not dissipated in an absent system; therefore, the system oscillations do not vanish. Figure 3 depicts temporary current in the superconducting circuit for the first experiment. It is important to note Figures 2 and 3 are very similar. This means value of the current dependent on oscillations of its mass centre. The current oscillation is ca. \( I_{\text{max}}=10,5 \text{kA}. \)

![Figure 4. Spatial oscillation amplitude of the coordinate x of the train’s mass centre for the second experiment.](image)

![Figure 5. Temporary current in the superconducting circuit for the second experiment.](image)
Figure 4 shows amplitude of the train oscillations as a function of time for the first test as part of the second experiment. A comparison of Figures 2 and 4 suggests diverse physical processes in the electromechanical system. A damping circuit is mounted in the train. This leads to energy dissipation and, as a result, maintenance of the train in a stable state $X_c=0.065$ m.

Figure 5 presents the function of current in the superconducting circuit. The system can be seen to enter the steady state $I_C=6$ kA. It is evident increasing the train’s weight pushes the system out of the magnetic cushion.

4. Conclusion
Application of superconductivity allows for introducing diamagnetic elements to levitation systems. This in turn enables to ignore Earnshaw’s theorem and produce the effect of magnetic potential hole. Rail industry, in particular, maglev trains are among the main areas where static magnetic levitation can be taken advantage of. These trains utilise motion transmission along magnetic cushions. Application of high-temperature superconductivity opens extensive prospects for use of natural levitation and the effect of magnetic potential hole in the industry. This is also true of maglev trains.

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