Simulation of electromagnetic suspension functioning processes in the MATLAB/Simulink system

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Abstract. In various fields of technology, the electromagnetic method of suspending various elements has a number of advantages, but the limits of the stability of the system and the justification of its optimal parameters require additional research. According to the well-known Irnshaw theorem, in technical applications, there are certain limitations on solving the engineering problem of stable suspension of moving bodies using electric or magnetic fields, often in combination with a gravitational field. An effective way to solve the problem of ensuring the stability of electromechanical systems based on magnetic suspension is to use automatic feedback control in the control circuit. In order to obtain the necessary accuracy and quality of the regulated transient, automatic control systems can use PID controllers. The problem of selecting the parameters of PID controllers is based on mathematical modeling, which is implemented using computer systems that provide the construction and research of designed electromechanical systems, for example, MATLAB with the Simulink module. The computer simulation of transients carried out in the Simulink system allowed us to obtain the dynamic characteristics of the PID controller with variations in their main parameters. The developed electromagnetic suspension circuit for stability requires a position sensor that is electrically connected to the PID controller in the feedback loop. Mathematical modeling of the dynamics of the electromagnetic suspension system should take into account the nonlinear nature of the main elements, including the PID controller, and their characteristic parameters. Simulation of the dynamics of the electromagnetic suspension system under study can be carried out and visually visualized in the MATLAB/Simulink environment in a wide range of parameter variations.

1. Introduction
The electromagnetic method of suspension of movable elements in various fields of technology has a number of advantages [1–3, 5, 6], however, the limits of the stability of the system and the justification of its optimal parameters require additional research. A well-known design variant of a magnetic
suspension is a Levitron, which, rotating, is able to “hover” in the air over a special platform that forms a magnetic cushion. The first patent for the levitron, 4382245, USA, was obtained by an American inventor (Roy Harrigen, 1983), which has already expired. Engineers William Hons and Edward Hons received several patents for improvements to this device: 5404062, 5883454, etc.

Magnetic shock absorbers are known, the principle of operation is based on the appearance of induced voltage in the inductor coil, which is wound on a frame located on the axis of movement of the shock absorber piston, which has a permanent magnet [1, 2, 3]. The solution to the problem is the use of pulse converters of electrical energy parameters allows you to solve the problem of converting the voltage level coming from the magnetic generator-shock absorber to the level suitable for charging the battery [5-9].

The well-known Irnshaw theorem states that any equilibrium configuration of point charges is unstable if they are not affected by forces other than the Coulomb forces of attraction and repulsion. In technical applications, Irnshaw’s theorem is associated with certain restrictions on solving the engineering problem of stable retention (or suspension) of a certain body with the help of fields (electric, magnetic, often in combination with the natural field of gravity), that is, without direct contact with solid and generally real retaining structures. However, these restrictions can be circumvented. The main methods used for this are as follows:

It is possible to use a magnetic field by a body with a negative magnetic susceptibility (a diamagnet) or a superconductor-an ideal diamagnet. In this case, it is possible to achieve natural stability without the use of any additional fields (and without energy costs). It is enough to choose the correct configuration of the field sources and the shape of the diamagnetic body. To ensure the stability of the magnetic suspension, it is possible to use additional non-potential forces, or automatic control systems of the holding field. An example of a technical implementation is a levitron that uses a rotating top for levitation. In this case, the magnet in the shape of a top is located in a potential pit, and the gyroscope effect is used to overcome the instability to the slope.

An effective way to solve the problem of ensuring the stability of mechanical systems based on magnetic suspension is to use automatic feedback control in the control circuit. In order to obtain the necessary accuracy and quality of the regulated transient, automatic control systems can use PID controllers.

PID controllers are based on the system accounting for the mismatch of the set and current positions of the movable suspension elements and form additive control signals formed as a sum of 3 terms [14,16,17]. The first component is formed in proportion to the residual, which is the difference between the input signal and the feedback signal. The second component is proportional to the integral of the mismatch signal, and the third component is proportional to the value of the first derivative of the mismatch signal.

The problem of selecting the parameters of PID controllers requires mathematical and/or computer modeling [18], which is convenient to implement using computer systems. In particular, the MATLAB software package with the Simulink module provides the construction, modeling and research of designed electromechanical systems using the Simulink and SimPowerSystems blocks.

Additionally, by combining the functionality of Simulink and SimPowerSystems (SPS), you can simulate the dynamics of the devices under study, as well as perform various types of analysis. In particular, it is possible to calculate the dynamic mode of transient or steady-state operation of the system, calculate the frequency characteristics, analyze the stability zones, and perform a harmonic analysis of the processes under study.
2. Materials and methods
The analysis of electromagnetic systems for the suspension of mobile elements allowed us to justify the generalized design scheme of the experimental installation used for modeling and studying the system, shown in Figure 1.

![Figure 1. Block diagram of the experimental setup for the study of the simulated system [21]](image1)

The structure of the generalized computer model in the MATLAB system with a window is shown in Figure 2. To simulate systems in the Simulink program, you must first run the MATLAB package. After opening the main window of the MATLAB program, you need to run the Simulink program.

![Figure 2. Structure of the computer model in the MATLAB/Simulink system [20]](image2)

The algorithm for creating a model in the Simulink environment provided for a sequence of the following steps:
- a. creating a new model file;
- b. constructing a model consisting of functional blocks from the corresponding sections of the library;
- c. to change the default block parameters, use the parameter editing window;
- d. connect the circuit elements by selecting the block source of the signal, then press Ctrl on the keyboard to select the block receiver. To create a branch point, you need to move the cursor to the intended node of the connecting line and, by pressing the right mouse button, stretch the line;
e. after drawing up the calculation scheme, you need to save it in a file by selecting the menu item File → Save As... in the library browser window or from the MATLAB system command window.

The SimPowerSystems Block Library (the Power System Blockset version of MATLAB 6.1 and earlier) is one of many additional Simulink libraries focused on device-specific modeling. SimPowerSystems contains a set of blocks for modeling electrical and electromechanical devices. The library includes models of passive and active electrical elements, energy sources, electric motors, transformers, and similar devices.

The SimPowerSystems library is quite versatile. If the required modeling block is not available in the library, it is possible to create your own block, using both existing Simulink blocks for creating subsystems, and based on the blocks of the main Simulink library and controlled voltage sources. Therefore, SimPowerSystems can currently be considered one of the best packages for modeling electromechanical systems [10].

The simulation of the PID controller functioning as part of the electromagnetic suspension system was carried out according to the dependence (1)

\[ u(t) = K_p \left( e(t) + K_{ip} \int_0^t e(\tau) \, d\tau + K_{dp} \frac{de}{dt} \right) \tag{1} \]

where \( K_p \), \( K_{ip} \), and \( K_{dp} \) - the dimensionless gain coefficients of the proportional, integrating, and differentiating components of the PID controller, respectively.

The mathematical model of the electromagnetic suspension for subsequent research was taken as a set of the following differential equations obtained from the consideration of the forces acting on the elements of the simulated system. The force acting on the suspended element from the side of the electromagnet coil is

\[ F_{mag} = Ci(t)/d^2 \tag{2} \]

where \( i(t) \) is the current through the electromagnet, (A); \( d \) is the vertical position in the accepted coordinate system, (mm); \( C \) is a constant determined by the magnetic properties and geometric parameters of the electromagnet.

The equation of dynamics of the simulated system has the form

\[ md\ddot{d} = mg - Ci(t)/d^3 \tag{3} \]

where \( m \) - the reduced mass of the levitating magnet, taking into account the fraction of the mass of the acrylic plate, \( g \approx 9.81 \) - acceleration of gravity, m/s^2.

The relationship between the voltage and current of the electromagnetic coil can be expressed as follows:

\[ v(t) = Ri(t) + L \frac{di}{dt} \tag{4} \]

where \( R \) is the resistance of the solenoid, Ohms; \( L \) - inductance of the electromagnet, H;

\( v_0 \) - the equilibrium voltage (V) of the coil for hanging the levitating plate; \( d_o \) - the point of the equilibrium distance, mm.

The results of computer mathematical modeling are visualized using the oscilloscope block.

3. Results and discussion

For example, a Hall sensor can be used to simulate the determination of the coordinate of the suspended element in the feedback loop. The sensor allows you to get an output voltage of a given shape

\[ e_H(t) = \alpha + \frac{\beta}{d^3} + \gamma i(t) \tag{5} \]
where \( \alpha, \beta, \gamma \) - are the constant parameters of the sensor.

Solving together a system of equations (1) ... (4), for example, by numerical method, it is possible to obtain the dynamic state of the simulated system.

For computer simulation of the dynamic state of the simulated system, we use the built-in functions of the MatLab/Simulink system.

The Simulink Library Browser Block Library browser window contains the following elements (Figure 3):

![Simulink Library Browser](image)

**Figure 3.** The "Simulink Library Browser" panel; a) "Mathematics" tab; b) "Sources" tab

The toolbar includes buttons for the most frequently used menu commands; a comment window for displaying an explanatory message about the selected library section or block; a list of library sections; a window with a list of library sections or blocks, as well as a Status Bar that contains a hint for the action being performed.

The analysis of the design schemes of electromagnetic suspension systems allowed us to justify the design scheme presented in Figure 4.

Before performing calculations, you must first set the calculation parameters. The calculation parameters are set in the control panel of the Simulation and Configuration Parameters menu.
The calculation is started by selecting the Simulation → Start menu item. The calculation process can be completed ahead of schedule by selecting the Simulation/Stop menu item. The calculation can also be stopped (Simulation-Pause) and then continued (Simulation-Continue). The converter model uses both the blocks of the basic Simulink library (oscilloscope, step signal block, etc.) and the blocks of the SimPowerSystems library (voltage sources, control system, RLC circuits, current and voltage meters).

The SimPowerSystems block library provides a section containing blocks for modeling power electronics devices and their control systems. The method of creating a SPS model is not fundamentally different from the method of creating a model based on the basic Simulink library. Just as for a normal Simulink model, you need to put together the computational blocks in the diagram, set their parameters, perform the connection blocks and set the parameters for calculating the model as a whole. For SPS models, an accelerated calculation mode and all the features of Simulink are available, including the Simulink Performance Tools, linear analysis, debugger, and so on.

However, the SPS models also have some specific features. The inputs and outputs of the SPS blocks, unlike the Simulink blocks, do not show the direction of signal transmission, since they are actually equivalent to electrical contacts. In this case, the electric current can flow through the inputs of the unit in two directions: both inside the block and outside. The connecting lines between the blocks simulate the connections of electrical wires, through which electric current can also flow in two directions. In contrast, in Simulink models, the information signal propagates only in one direction - from the output of one block to the input of another.

Note that the Simulink and SimPowerSystems blocks cannot be directly connected to each other. The signal from the S-block can be transmitted to the S-block via controlled current or voltage sources, and vice versa - using current or voltage meters. When calculating a circuit containing nonlinear blocks, you should use the methods that give the best results in terms of performance:

- ode15s-a multi-step method of variable order (from 1 to 5), using numerical differentiation formulas;
ode 23 trapezoid method with interpolation.

The diagram must contain at least one of the measurement blocks (Current Measurement, Voltage Measurement, or Multimeter), which is related to the specifics of converting the SimPowerSystems model into an equivalent calculated Simulink model.

Despite the advantages of using PID controllers, there are also negative effects that occur when implementing the channel of the derivative of the error signal \( \dot{e}(t) \) (Figure 5).

![Figure 5. Modeling of transients under variation of PID-controller parameters](image)

This is due to the fact that when amplified, the frequency increases proportionally and significantly. The main disadvantages are the increased amplification of the high-frequency harmonics of the error signal. Since they are of the nature of noise, as a result, the ratio of the useful component of the control signal to the noise signal decreases, which causes destabilization of the control object.

Therefore, a detailed study of the simulated system is required, taking into account the entire set of its parameters.

4. Conclusion

The analysis of the technical solutions of the designs of devices based on electromagnetic suspension and the means of their mathematical and computer modeling allowed us to formulate the following conclusions.

The developed scheme of the electromagnetic suspension of the transported platform requires, to ensure the stability of operation, the presence in the feedback loop, a position sensor electrically connected to the controller, mainly of the PID type. When modeling an electromagnetic suspension system, it is necessary to study the dynamics of the simulated system, taking into account the entire set of its parameters.

Mathematical modeling of the dynamics of the electromagnetic suspension system should take into account the nonlinear nature of the main elements, including the PID controller, and their characteristic parameters.

Simulation of the dynamics of the electromagnetic suspension system under study for various structural schemes in a wide range of parameter variations can be systematically implemented and visually visualized in the Matlab/Simulink environment.

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