Dynamic model of the electromagnetic oscillating system with energy losses

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Abstract: The relevance of the research lies in the need to improve the accuracy of dynamic calculations of electromagnetic oscillating systems used in technical systems for the generation of vibrations with a frequency of up to 100 Hz. The research considers the solution of the problem of creating an accurate dynamic single-mass oscillating system with an electromagnetic drive that characterizes the different operation modes and allows a comprehensive analysis of electromechanical processes by means of structural modeling methods. The distinctive feature of this model is the ability to take into account the nonlinearity of the magnetic circuit, leakage fluxes, properties of elastic linkages, viscous friction and sliding friction, external influence and energy losses of electrical and mechanical nature in an electromagnetic oscillating system. To solve the problem of calculating the magnetic field, the standard finite-element modeling FEMM software was used. To calculate the dynamic part of the problem, the calculation algorithm was developed that was implemented by means of structural modeling method in Matlab Simulink software environment. By the example of calculation of periodic electromechanical processes in the electromagnetic oscillating system, the possibilities of the model for a comprehensive analysis of operation processes are considered. According to the results of the research, recommendations for improving the accuracy of calculations of electromechanical processes were obtained.

1. Introduction

Vibration technologies are widely used in the industry for supplying many modern technological processes and industries. A promising area of research in this field is the improvement of machines and mechanisms based on the oscillatory motion electromagnetic drive [1–6].

The advantages of using the electromagnetic drive are relatively high reliability, the ability to reduce energy consumption when operating in resonant and near-resonant modes, as well as the easiest way to control the amplitude of oscillations regardless of frequency [7–13].

The current methods of accurate accounting of the design parameters of the electromagnetic drive and the implementation of new operating cycles allow improving their power and energy performance to varying degrees [14–25].

To improve the utilization efficiency of such an electric drive in processes already at the design stage, there is a need to solve the problem of calculating the dynamic characteristics of the drive operation that are directly related to the creation of accurate dynamic models [26–29].
The main difficulty in the implementation of dynamic characteristics of the model is the accuracy in determining electromagnetic force and flux linkage that vary over time and depend on the current and axis of motion of the movable core.

The use of initial data in the form of a set of static parameters of flux linkage and electromagnetic force determined by analytical methods of the magnetic circuit theory or by an approximate pattern of the magnetic field does not completely take into account local saturation of magnetic circuit sections and leakage fluxes. This is the main source of errors in the calculation of dynamic characteristics.

2. Materials and methods

To improve the accuracy of the calculation of electromagnetic drive dynamic characteristics, initial data in the form of a set of static parameters obtained by calculating the magnetic field were used.

The essence of this approach is that at the first stage using the numerical method dependences of electromagnetic force and flux linkage on the current and the motion of a mechanical system are determined. At the second stage, the obtained arrays of values of static parameters for the force and the flux linkage are used in the calculation of dynamic characteristics [30, 31].

Thus, the problem of the dynamic characteristics calculation is solved in two stages that is widely used in the practice of electromechanical system modeling.

The creation of an accurate dynamic model of a single-mass oscillating system with electromagnetic drive characterizing the different operation behavior, was carried out using the structural modelling unit.

The possible design of electromagnetic oscillating system with elastic linkages is shown in Figures 1.

![Figure 1. The electromagnetic oscillating system](image1)

![Figure 2. The example of magnetic field calculation in the form of magnetic flux lines.](image2)

The electromagnetic drive contains the magnetic circuit 1 made of sheets of electrical steel, the coil 2 fastened on the magnetic circuit, and the movable core 3 installed in the air gap, connected to the core reset system. The mechanical reset system of the movable core 3 contains the elastic element 4 and the added mass 5 rigidly connected to the core.

When the coil is de-energized at rest of the mechanical system, the initial depth of the core assembly penetration \( \delta_0 \) is determined relative to the pole tips of the magnetic circuit.

When the periodic current flows through the winding of the coil, the alternating electromagnetic force \( f_{em} \) occurs that is counteracted by the mechanical force of elastic linkages \( f_k(x) = kx \) and the dry friction force \( f_r \).

To simplify the existing analysis, the magnetic field is assumed to be plane-parallel for the calculation. It is also believed that there are no eddy currents in the stacked magnetic circuit, and hysteresis losses are minimal.
In the general case, the dynamic processes, occurring when the electromagnetic oscillating drive is switched on, are characterized by a system of differential equations according to the second Kirchhoff’s law for the electric circuit and D’Alembert principle for a single-mass mechanical system:

\[ u(t) = i_r + \frac{d\psi(i,x)}{dt}, \]  

\[ m \frac{d^2x}{dt^2} = f_{em}(i,x) - kx - b_0 \frac{dx}{dt} - f_s \text{sign} \frac{dx}{dt}, \]

where \( u(t) \) – the voltage of the coil winding; \( i \) – the coil current; \( \psi = f(i,x) \) – flux linkage depending on the position of the movable core and the flowing current in the coil; \( r \) – the active resistance of the coil; \( m = m_1 + m_2 \) – the mass of moving parts; \( m_1 \) – the mass of the movable core; \( m_2 \) – the added mass; \( f_{em} = f(i,x) \) – the electromagnetic force depending on the position of the core and the flowing current; \( k \) – the stiffness factor of the elastic element (the spring); \( b_0 \) – the coefficient of viscous friction of elastic couplings; \( f_s \) – the dry friction force.

To determine the static parameters \( \psi(i,x) \) and \( f_{em}(i,x) \) included in equation (1), (2), the solution of the field problem for the calculation of the magnetic field in the active zone of the electric drive was performed. The numeric calculation of the magnetic field was performed using finite-element modeling in the FEMM software environment. The example of the numeric calculation of the magnetic field is shown in Figure 2 in the form of magnetic flux lines.

Based on equations (1) and (2), the structure chart of a dynamic model was developed (Figure 3). The implementation of the calculation algorithm for electromechanical processes is performed in the program Matlab Simulink.

![Figure 3](image.png)

**Figure 3.** The structure chart of the dynamic model of the electromagnetic oscillating system drive

Setting the function of two arguments and interpolation of static parameters of the model \( \psi(i,x) \) and \( f_{em}(i,x) \) in the process of counting are performed using the block of two-dimensional table Look-Up Table (2D). The detailed structure chart of the Mechanical subsystem in accordance with equation (2) is shown in Figure 4.
Significant influence on the dynamics of the electric drive have parameters that take into account the mechanical properties of the model. This primarily refers to the effort opposing the motion and depending respectively on moving and the speed of the movable electromagnetic drive system.

In this regard, to improve the accuracy of the calculations, mathematical analogs of the mechanical characteristics of the model shall be reflected accordingly that coordinates space data of the armature position in the process of movement.

![Figure 4](image)

**Figure 4.** The detailed structure chart of considering the mechanical properties of the «Mechanical subsystem» model

The input signal for the model is a source of periodic voltage in the form of positive pulses with amplitude $U_m$ and mains frequency of 50 Hz.

3. **Main results of research**

The diagrams obtained as a result of modeling allow one to observe changes in the time of current $i(t)$, motion $x(t)$ and speed of the movable core in the transient mode $v(t)$. Figures 5, 6 and 7 show time charts of these values changes in the load rise mode in the form of the added mass $m_2$ attached to the movable core at the given time (sec.) $t = 0.4$ s. As follows from the charts, this affected the reduction of the maximum current 1.08 times, the oscillation amplitude - 1.36 times, and the maximum speed of the movable core motion - 1.71 times, respectively.

When comparing the obtained dependences with the experimental ones, good compliance of qualitative and quantitative characteristics was found only in the case of accurate consideration of the analogs of the model mechanical characteristics. The discrepancy between the calculated characteristics of the motion and the current with the experimental data correspond to an error of 5-8% generally accepted for engineering calculations.

Thus, the developed dynamic model may be effectively used for the study of electromechanical processes, as well as in the analysis and synthesis of control over electromagnetic drives of vibration process plants and devices by structural modeling methods.
Figure 5. The time chart of the transient current in the load rise mode

Figure 6. The time chart of the transition process of the movable core motion in the load rise mode

Figure 7. The time chart of the transition process of the movable core speed in the load rise mode

The presented algorithm of the electromagnetic calculation and the option of the circuit implementation of the structure dynamic model allow taking into account the saturation and leakage fluxes occurring in the magnetic circuit.

The established set of interrelated electromagnetic and mechanical values makes it possible to simply vary a significant set of input parameters and to study the operation processes, both in steady-state and transient unsteady modes with a large unlimited set of output variables. It is found that the accuracy of dynamic calculations depends to a significant extent on the accuracy of the mathematical analogs of mechanical characteristics. In particular, this concerns the consideration of processes related to energy dissipation, both due to own damping properties of individual links and elastic linkages depending on the speed of movement, and due to the dry friction forces.
4. Conclusion
Under the example of the calculation of periodic electromechanical processes in an electromagnetic oscillating system powered by a sinusoidal voltage source under half-wave rectification circuit, from the possibilities of the dynamic calculation to a thorough analysis of operational behaviors in transitional and quasi-steady processes by methods and means of structural modeling.

For the case of the approximate nature of considering analogs of the model mechanical characteristics or considering only the prevailing forces of resistance to motion, the solution of the problem of the dynamic calculation may differ significantly from the processes in real physical systems and may give rather only approximate results.

To improve the accuracy of the dynamic model when considering the parameters of elastic linkages, it is necessary to take into account the processes of energy dissipation, both due to the own damping properties of elastic couplings, and due to the dry friction forces. The error in the calculations does not exceed the permissible value of 5-8%.

The obtained results of structural modeling and considered proposals for the implementation of the dynamic model may be widely used in engineering practice in the design, as well as to solve complex problems of analysis and synthesis of the electromagnetic oscillating drive.

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