Application of numerical simulation of magnetic field for the analysis of dynamic characteristics of an electromagnetic motor

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Abstract. The paper presents an algorithm for finding the optimal ratios of design parameters of an electromagnetic motor using numerical simulation of the magnetic field. One of the stages of the algorithm is the calculation of the dynamic characteristics of the electromagnetic motor using numerical simulation of the magnetic field. The main problem of the ongoing research of the cylindrical linear motor is the increase of its power and energy characteristics. The solution of the problem is directly related to the study of the influence of the mode and design parameters of the electromagnetic motor on the output operating characteristics. The dependencies obtained by means of numerical simulation make it possible to give a qualitative and quantitative evaluation of the influence of design parameters on the operating characteristics of the motor and confirm the results obtained by using physical models. The proposed algorithm makes it possible to obtain the optimal design of an electromagnetic motor and to reduce the time of its development.

1. Introduction

The cylindrical design of an electromagnetic motor is widely used in various technological industries [1–4]. Many scientific publications are devoted to the problem of calculation and design of electromagnetic motors of cylindrical construction [5–10]. The ongoing research helps to solve the problem of finding the optimal ratios of design parameters of an electromagnetic motor with the analysis of dynamic characteristics. The solution of the electromagnetic motor optimal design problem is based on the previous research presented in [11]. The investigated model of the electromagnetic motor is a multifactor system, which is characterized by a number of output operating characteristics, such as shock energy, drive and maximum current, power-supply source voltage, etc.

The main purpose of the numerical simulation of the dynamic operation processes in the electromagnetic motor is the increase of its power and energy characteristics. The considered simulation is directly related to the study of the influence of mode and design parameters of the electromagnetic motor on its output operating characteristics. The numerical simulation is necessary to establish the influence of values of design factors varying in certain ranges and to provide the maximum values of the output parameters of the electromagnetic motor.

The optimization of design parameters helps to achieve high efficiency of electric energy consumption and to increase efficiency of electromagnetic motor.
The object of the research is the electromagnetic motor with spring return of the cylindrical composite armature. The design of the electromagnetic motor is shown in Figure 1. The electromagnetic motor consists of the steel cylindrical stator 1 and the cylindrical composite armature 2, the excitation copper coil 3 and the spring 4 returning the armature 2. The stator is rigidly fixed on the working surface. The armature 2 moves linearly along its symmetry axis.

When the electromagnetic motor is running, voltage pulses of a given shape and duration are applied to the winding of the coil. The current flowing in the winding creates the electromagnetic field and the electromagnetic force acting on the cylindrical armature. The electromagnetic forces are several times greater than the mechanical forces when the spring is compressed and the armature moves downwards. When the armature is moved to the stop the coil is left without electricity. The armature is returned to its initial state by the forces of the return spring.

2. Algorithm of the optimization problem solution

The solution of the optimization problem for choosing the number of turns of the excitation coil based on the analysis of the dynamic characteristics of the motor is presented in [11]. The solution has been obtained by means of numerical simulation of the magnetic field in the volume occupied by the electromagnetic motor shown in figure 1. The program complex for the magnetic field numerical simulation was developed at the Department of Applied Mathematics of Novosibirsk State Technical University. The possibility of the use of the program complex for finding the optimum number of turns of the electromagnetic motor coil is shown in the work [11]. The example of the magnetic field numerical simulation results is shown in the form of lines of magnetic flux equal level in figure 2.

The dynamic characteristics of the electromagnetic motor considered in this paper are analyzed by the mentioned above program complex. The program complex gives the opportunity to study the number of winding turns effect on the output energy and the maximum winding current.
Based on the results of earlier studies, it is necessary to take into account that the electromagnetic field in the motor structure in Figure 2 is completely described by the following non-linear initial boundary value problem [11]:

\[-\text{div}\left(\frac{1}{\mu(B)} \text{grad}\,A_\phi\right) + \frac{A_\phi}{\mu(B)r} = \sigma E_\phi,\]

where \(E_\phi\) is the electric field intensity in the winding; \(A_\phi\) is the scalar potential; \(B\) is the induction of the magnetic field; \(U(t)\) is the voltage supplied to the winding; \(\Omega_1, \Omega_2, \Omega_3\) are the motor areas occupied by winding, armature, stator and airspace; \(S_q\) is the conductor cross-sectional area; \(l\) is the conductor length; \(\mu\) is the magnetic permeability; \(\mu_0\) is the air magnetic permeability; \(\sigma\) is the electrical conductivity of the winding; \(\sigma_{st}\) is the steel electrical conductivity.

The equation of steel magnetization expressed by dependence \(B = \mu H\) is shown in Fig.2.

The components of the magnetic induction vector and electric field strength are calculated using the values \((A_\phi)\) found in the task solution (1)–(6):

\[B_z = -\frac{\partial A_\phi}{\partial z}, \quad E_z = \left(\frac{\partial A_\phi}{\partial r} + \frac{A_\phi}{r}\right),\]

\[E_\phi = \frac{2\pi}{l} \int_{S_q} \int_{\Omega_1} -\frac{\partial A_\phi}{\partial t} r \, dr \, dz + \frac{U(t)}{l}\]

\[E_\phi = -\frac{\partial A_\phi}{\partial t}\]

in the area of \(\Omega_1\), in the area of \(\Omega_2\).

The capability of using the components of the magnetic field induction vector and electric field strengths found in (7)–(9) for the calculation of the force acting on the armature, the currents flowing in the winding, the eddy currents induced in the armature and stator, and the coordinate of the armature movement, etc. is shown in the work [11].

The equations (1)–(9) completely describe the state of the electromagnetic field in the electromagnetic motor (Figure 1) and helps to calculate its characteristics when the armature is accelerated.

The following forces act on the armature (Figure 1):

\(F^M(t)\) is the force caused by the magnetic field change;
\(F^k(t)\) is the return spring elastic force acting on the movable armature;
\(F^A(t)\) is the Ampere force caused by the interaction of the magnetic field with eddy currents in the armature.

The expression for calculating \(z\)-component of each of these forces is stated below.

The elastic force is calculated from the known values of the coefficient of the spring stiffness \(k\) and the distance \(Z(t)\) where the armature has already moved by the current in time \(t\): \(F^k_z(t) = -kZ(t)\).
The elastic force and the Ampere force acting on the conductive armature are retarding forces. Thus, the resulting force acting on the armature at a moment \( t \) is equal to:

\[
F_z(t) = F_z^M(t) + F_z^A(t).
\]

3. Results and Discussion

The dynamic characteristics obtained by the numerical simulation for the model and optimal search algorithm evaluation are shown in Figure 3. The output energy of the motor \( A_{st} \), the maximum current in the winding \( i_{\text{max}} \) and the magnitude of the armature current \( i_{\text{start}} \) are reflected by the dynamic characteristics.

![Figure 3. Dynamic characteristics of the electromagnetic motor](image)

The power-supply source voltage \( U = 100...250 \text{ V} \) and the number of winding turns \( w = 100...1300 \) are used as variable input parameters.

The analysis of the obtained dependences indicates the existence of optimal values of coil turns in the range of \( w = 500...700 \) which is in complete agreement with the studies obtained in [34] using numerical simulation and experimental studies. The established dependences in figure 3 also indicate the existence of optimum values of the maximum coil current \( i_{\text{max}} = 20...50 \text{ A} \) and armature start current \( i_{\text{start}} = 7...12 \text{ A} \) depending on the source supply voltage. If the number of turns of the coil decreases, relative to the optimum value, the energy at the output decreases, and the coil current and armature current increase sharply. This results in a large loss of power-supply source energy. As the number of turns of the coil increases relative to the optimum value, the energy loss decreases, but this leads to a decrease in the main working parameter of the electromagnetic motor energy at the output.
The established dependences (Figure 3) give possibility to estimate the influence of design parameters at the stage of calculation and the time of the motor design process.

4. Conclusion
The numerical simulation of the dynamic characteristics gave the opportunity to obtain a new algorithm for the calculation of optimal parameters of electromagnetic motors. The usefulness of the established dependences (Figure 3) is the capability of the estimation of the electromagnetic motor design parameters and synthesis of the optimal design of electromagnetic motor.

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