Finite-element modelling of electrodynamic processes as a method of determining the optimal number of turns on a winding of a machine press electromagnetic motor

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Abstract. This article presents the optimization problem solution employing the methods of finite-element modelling of electrodynamic processes for choosing the number of winding turns in an electromagnetic motor driving a machine press. The subject of the investigation is a new methodology for identifying optimization solutions to a differential equation describing the finite-element model of the electromagnetic motor and analyzing its calculated dynamic characteristics. The object of the investigation is a cylindrical construction of an electromagnetic motor with two working gaps and a combined composite armature. The basis of the finite-element model is a computational scheme and a software package created at the Department of Applied Mathematics at Novosibirsk State Technical University. It is illustrated that the applied computing apparatus and the software package allow performing an accurate search for the optimal number of turns on a winding of an electromagnetic motor at the design stage with due consideration for the required geometric parameters and the magnetic properties of the structural materials employed for obtaining the maximum final velocity of the armature in motion.

1. Introduction
Linear electromagnetic motors are widely used for driving machines and mechanisms for various technological purposes [1–3]. It is especially relevant to use the system in the electric drive of press equipment with the linear movement of working parts [4–7]. Cylindrical electromagnetic motors with two air working gaps and a combined composite armature have been widely used in the press equipment drive [8–9]. Issues related to the calculations and design of such motor constructions are well studied and thoroughly presented in the scientific literature [10, 11]. However, despite the existing recommendations for their designing, calculation methods have one drawback. This drawback lies in the fact that the well-known designing recommendations are obtained based on the calculation of static characteristics with a fixed armature [12–15]. For example, the determination of the geometric dimensions of an electromagnetic motor is based on the relation between the static electromagnetic force and the radius or diameter of the moving armature. The volume occupied by the winding of the motor coil is calculated based on the established optimal ratios of geometric dimensions. The required number of the winding turns, and the conductor cross-section is selected based on the volume of the winding space and the need to set the required
magnetizing force. The value of the winding magnetizing force is determined based on the motor steel cross-section and the permissible induction value in steel sections. In the equal volume occupied by the winding with the conductor, the magnetizing force value can be changed using the conductor cross-section and the value of the current flowing through the conductor. Due to this fact, it is possible to increase or decrease the conductor turns number within a given winding space.

The same magnetizing force value can be created by increasing the conductor turns number while simultaneously reducing the current flowing through the conductor. It can also be made by reducing the conductor turns number with the simultaneous increase of the current flowing through the conductor.

The current design recommendations do not provide a comprehensive answer on how to select the optimal number of the winding conductor turns. The answer to this question can only be obtained by calculating the dynamic characteristics of an electromagnetic motor with a moving armature.

The further task of the investigation is to develop a method for calculating the electrodynamic processes of the machine press electromagnetic motor and to perform an optimization analysis using finite-element modelling methods.

This result allows obtaining sufficiently accurate characteristics of the electromagnetic field with consideration to the geometric motor dimensions, the motion of the moving structural elements, the influence of eddy currents and the magnetic properties of the structural materials. The forces acting on the armature can be calculated based on the obtained characteristics of the electromagnetic field. It makes it possible to determine the armature displacement at any instant in time and perform the necessary optimization calculations.

The results of the investigation show that the use of the finite-element method for electromagnetic fields modelling in an electromagnetic motor allows performing high-precision and quick calculations of the required dynamic characteristics of the motor.

2. Materials and methods
Calculation and analysis of electromagnetic processes and dynamic characteristics are carried out for the electromagnetic motor shown in Figure 1.
The electromagnetic motor consists of a steel cylindrical stator 1, a cylindrical composite armature 2, a field magnetizing coil 3 wound by a copper conductor and a return spring for returning the armature 2. The return spring is not shown in Figure 1. The stator is considered to be rigidly fixed to the working surface. Armature 2 commits linear motions along the vertical axis.

When a voltage pulse is applied to the coil, the armature moves downwards and strikes under the influence of electromagnetic forces. Upon completion of the stroke, the armature returns to its original position under the action of the return spring forces. The process is further repeated with specified periodicity.

The electromagnetic field in the motor construction (Figure 1) is completely described by the following non-linear initial boundary value problem [16]:

\[ -\text{div} \left( \frac{1}{\mu(B)} \text{grad} A_v \right) + \frac{A_v}{\mu(B)r^2} - \frac{A_v}{r} \frac{\partial}{\partial r} \left( \frac{1}{\mu(B)} \right) = \sigma E_v, \]

(1)

\[ A_v|_{r=0} = 0, \quad A_v|_{r=a} = 0; \]

(2)

\[ (\text{winding area} - \Omega_1): \quad E_v = -\frac{2\pi}{l} \int_1^a \int_0^b \left( \frac{\partial A_v}{\partial t} \right) r dr dz + \frac{U(t)}{l}, \]

(3)

\[ \sigma = \sigma_q, \quad \mu = \mu_b; \]

(4)

\[ (\text{armature and stator area} - \Omega_2): \quad E_v = -\frac{\partial A_v}{\partial t}, \quad \sigma = \sigma_a, \quad \mu = \mu(B); \]

(5)

\[ (\text{airspace area} - \Omega_3): \quad \sigma = 0, \quad \mu = \mu_0. \]

(6)

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

The curve of steel magnetization expressed by dependence \( B = \mu_s H \) is shown in Figure 2.

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

\[ B_v = -\frac{\partial A_v}{\partial z}, \quad B_z = \left( \frac{\partial A_v}{\partial r} + \frac{A_v}{r} \right), \]

(7)

\[ E_v = \frac{2\pi}{l} \int_1^a \int_0^b \left( \frac{\partial A_v}{\partial t} \right) r dr dz + \frac{U(t)}{l} \text{ in the area of } \Omega_1, \]

(8)

\[ E_v = -\frac{\partial A_v}{\partial t} \text{ in the area of } \Omega_2. \]

(9)

Further in [16] it is shown how we can calculate 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, using the values of the components of the magnetic field induction vector and electric field strengths found in (7) – (9).

Equations (1) – (9) completely describe the state of the electromagnetic field in the electromagnetic motor construction as shown in Figure 1 and allow calculating its characteristics in the process of accelerating the armature.

In the motor construction (Figure 1), the armature experiences the following forces at any instant of time:

\[ F^M(t) \] – the force caused by a change in the magnetic field in the armature;
\[ F_k(t) \] – the return spring elastic force acting on the movable armature;
\[ F_A(t) \] – ampere force caused by the interaction of a magnetic field with eddy currents in an armature.

Let us consider the expressions for calculating \( z \)-component of each of these forces.
The elastic force can be calculated by using the known values of the coefficient of spring stiffness \( k \) and the distance \( Z(t) \) at which the armature has already moved by the current point in time \( t \):
\[ F_k(t) = -kz(t). \]

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:
\[ F_z(t) = F^{\text{el}}_z(t) + F^{\text{A}}_z(t) + F^{\text{el}}_z(t). \]

3. Results and Discussion
The motor calculation model according to equations (1) – (9) is based on the computational scheme and software package created at the Department of Applied Mathematics in Novosibirsk State Technical University moderated by Professor Yu. G. Soloveichik [16].
The main task solved by the modelling of electromagnetic motor dynamic characteristics is increasing its power and energy indicators. This is achieved by studying the conversion of electrical energy in the motor. This is also achieved by studying the influence of its geometric dimensions and properties of the applied structural materials on the dynamic motor characteristics.
The optimal number of turns in the motor winding is determined by results of the finite-element modelling of electrodynamic processes. The duration of the armature movement \( t_o \) from the upper to the lower position was taken as an evaluation criterion. By reducing the movement duration, the speed of the armature increases at the end of the movement, which leads to an increase in kinetic energy at the end of the movement.
In the initial position, the armature is in its upper limit position due to the elastic forces of the spring. When a voltage pulse is applied to the coil winding, the current flows through the conductor and creates an electromagnetic force. The armature makes a working stroke during the period \( t_o \) and takes the lower limit position. When the coil winding is de-energized, the armature under the action of the elastic forces of the spring takes the upper limit position.
The parameters of the electromagnetic motor model (Figure 1) are presented in table 1.

| Table 1. The parameters of the electromagnetic motor model |
|------------------------------------------------------------|
| Magnitude | Designation in Figure 1 | The size, mm |
| The armature radius | \( R_1 \) | 28.5 |
| The stator radius | \( R_3 \) | 51 |
| The winding radius | \( R_2 \) | 42.5 |
| The stock radius | \( R_0 \) | 7 |
| The coil length | \( L_1 \) | 80 |
| The disc height | \( h_1 \) | 9 |
| The pole height | \( h_2 \) | 10 |
| The armature length | \( L_2 \) | 79 |
| The stop height | \( h_3 \) | 10 |

The investigation of the dynamic dependence of the movement time on the winding turns number is shown in Figure 3.
The dependences are obtained for fixed source voltages supplied to the coil winding \( (U = 100...250 \text{ V}) \) when the winding turns number changes within the limits established by calculation \( (w = 100...1300) \). Figure 3 shows the optimum number of winding turns for which the movement time
of the electromagnetic motor armature is minimal in case of the minimum movement time of the armature. The calculated dependences (Figure 3) are completely consistent with the behaviour of the curves obtained experimentally in [6].

![Figure 3. Dynamic characteristics of the armature movement](image)

Changing the power source voltage does not significantly affect the established optimum, which is in the range of values $w=450...550$, as shown in Figure 3.

It should also be noted that a decrease in the number of turns relative to the established optimum that has a greater effect on increasing the armature movement time ($t_m$).

4. Conclusion

The finite-element modelling of the magnetic field within the volume of an electromagnetic motor (this motor has two air working gaps and a combined composite armature) allowed finding a solution to the optimization problem of determining the number of winding turns based on the dynamic characteristics analysis of the created model.

It is illustrated that the applied computing apparatus and the software package allow performing an accurate search for the optimal number of turns on a winding of an electromagnetic motor at the design stage. The solution is attained with due consideration for the required geometric parameters and the magnetic properties of the structural materials employed for obtaining the maximum final velocity of the armature in motion.

References

[1] Ivashin V V and Pevchev V P 2012 Electromagnetic drive for impulse and vibro-impulse process Proc. of Institutions of Higher Education. Electromechanics (1) 72–75

[2] Ryashentsev N P and Ryashentsev V N 1985 Electromagnetic Drive of Linear Machines (Novosibirsk: Science)

[3] Simonov B F, Neyman V Y and Shabanov A S 2017 Pulsed Linear Solenoid Actuator for Deep-Well Vibration Source Journal of Mining Science 53(1) 117–125

[4] Usanov K M, Moshkin V I and Ugarov G G 2006 Linear Impulse Electromagnetic Drive of Machines with Self-Contained Power Supplies (Kurgan: KSU)
[5] Ugarov G G et al. 1997 Operating Cycle of an electromagnetic percussion machine with storage of magnetic energy during the no-load period Journal of Mining Sciences 33(3) 253–257

[6] Neiman V Yu and Smirnova Yu B 2006 New principles and increase of energy efficiency of electromagnetic machines Proceedings of the 1st International Forum On Strategic Technology (Ulsan: University of Ulsan) 314–315

[7] Ugarov G G and Neiman V Y 1996 Evaluation of operating conditions for electromagnetic impactors Journal of Mining Science 32(4) 305–312.

[8] Usanov K M et al. 2017 Strike action electromagnetic machine for immersion of rod elements into ground IOP Conference Series: Earth and Environmental Science 032050

[9] Usanov K M, Moshkin V I, Kargin V A, Volgin A V 2015 The Linear Electromagnetic Motors and Actuators Pulse Processes and Technologies (Kurgan: Publishing house of Kurgan state University press)

[10] Ryashentsev N P, Ugarov G G and Levitsin A V 1989 Electromagnetic Presses (Novosibirsk: Science)

[11] Batischev D V and Pavlenko A V 2012 On designing electromagnetic drives operating under conditions of high vibrations Russian Electrical Engineering 83(8) 423

[12] Malov A T et al 1979 Electromagnetic Hammers (Novosibirsk: Science)

[13] Prikazchikov A V et al. 2011 Improved method of design simulation of force-controlled valve electromagnet in scheme with ballast resistor Russian Electrical Engineering 82(1) 55–60

[14] Zaitsev Y M et al. 2015 Minimizing the power consumption of a clapper-type dc electromagnet in intermittent operation Russian Electrical Engineering 86(8) 474–478

[15] Shoffa V N, Russova N V and Sviintsov G P 2002 Optimal symmetric u-shaped two-coil dc electromagnets with prismatic cores in intermittent operation Russian Electrical Engineering 73(2) 63–68

[16] Solovejchik Yu G, Persova M G and Nejman V Yu 2004 The finite-element simulation of the electrodynamic processes in a linear electromagnetic motor Elektrichestvo (10) 43–52