Influence Of Cuts In The Housing And Armature Of The Forced Electromagnet Of The Fuel Injection System On Its Speed

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Abstract. *Electromagnetic mechanisms are widely used in various systems due to the simplicity of their design and reliability in operation. One such system is the fuel injection system for an internal combustion engine. The electromagnets installed in such systems should have a number of special properties: they should have small dimensions, high speed, which is ensured by forcing, a small mass of moving elements, an increased residual air gap, a small armature stroke and minimal eddy currents in the magnetic core. The reduction of eddy currents is carried out by the use of steels with increased resistivity and special cuts in the housing and armature, which significantly complicates the design of the electromagnet, but is an effective approach for reducing losses in DC electromagnetic systems. To assess the influence of the design of an electromagnet on its speed, the article present a comparative analysis of the solution of the problem of dynamics in a 3D formulation for a forced armored DC electromagnet and an improved electromagnet with reduced eddy current losses due to special structural cuts in the housing and armature.*

Keywords

Dynamic characteristics, electromagnetic mechanism, speed of electromagnets.

1. Introduction. Problem Definition

Electromagnetic mechanisms are widely used in many automation devices and, in particular, in devices for electronic fuel injection in internal combustion engines. Such electromagnetic mechanisms must have high speed, small size and be reliable. The speed is ensured by the low inertia of the moving elements and by forcing – the supply of increased voltage to the electromagnet winding, which decreases in time to values that ensure reliable holding of the armature in the attracted position. Reducing the voltage on the winding not only reduces the thermal load on the elements of the electromagnet, but also provides a quick return of the armature to its initial state under the action of the return spring. The speed of such electromagnets is also ensured by constructive measures: 1) an increased residual air gap, which reduces the equivalent inductance, thereby reducing the time constant of the system; 2) a decrease in the value of eddy currents in the magnetic core due to cuts in the housing and armature of the electromagnet; 3) the use of steels with increased resistivity; 4) a slow speed of the armature. Since such electromagnets operate in a cyclic mode, the calculation is reduced to determination of the dependence of the armature stroke on the value of the applied voltage in one cycle. Here, by the end of the cycle, all parameters of the electromagnet should return to their initial state, which also significantly depends on the value of the time constant of the system and the value of eddy currents.

To determine the dynamic characteristics of the electromagnetic mechanism, it is necessary to solve a coupled system of differential equations of the electric circuit, the electromagnetic field and the equations of motion of the moving parts of the electromagnet in a transient formulation, since transients are decisive in the operation of such devices. When analyzing the operation of forced electromagnets, it is necessary to take into account the nonlinear characteristics of the magnetic core's material (during forcing, the value of magnetic flux density reaches the saturation value), as well as the resistivity of the magnetic core's material, which significantly affects the value of eddy currents.

A number of publications are devoted to calculations [1]-[16], optimization [5], [6], and experimental investigations [11], [17]-[24] of high-speed electromagnets of electronic fuel injection systems and similar mechanisms. For example, in [1], [3], [4], [12] the authors analyze the operation of an electromagnet together with a control circuit based on the analogy of the equations of the electric and magnetic circuits as well as using similar techniques, which made it possible to determine the time constant of the system and calculate the dynamic parameters of the electric circuit and the electromagnet.

Similar calculations were also carried out in [13] based on the electrical analogy technique in combination with the Rothers method (calculation of the air gap conductivity) under the assumption of a uniform distribution of the magnetic flux density over sections of the magnetic core. The values of the electromagnetic time constant as a function of the air gap and the value of the magnetic flux density were obtained, which, together with the simulation of the movement of the mechanical part, made it possible to evaluate the characteristics of the movement of the electromagnet and compare the obtained data with the experiment. More detailed electromagnet calculations were carried out in [11] using the MATLAB® SIMULINK® tool.

Calculations of the dynamics of an electromagnet, taking into account losses in steel [3], [9], [19] by, as one of possible approaches to be used, dividing the magnetic core into a number of parallel sections, are presented in [1]. In [17], [23] investigation of the influence of the design parameters of an electromagnet on its static characteristics was made.

A comprehensive theoretical and experimental investigation of an electromagnetic valve with subsequent verification of the results on a special experimental setup was carried out in [2], [18]. Theoretical analysis of dynamic characteristics was carried out using an applied code based on the Finite Element Method. In [19], when investigating the characteristics of a high-speed armored electromagnet, heat losses in the winding and heat losses from eddy currents in the housing were determined. Dynamics calculations, as in [2], are often carried out by the Finite Element Method using a specialized software codes. Research of the effect of applied voltage value on the response time of an electromagnet in a 3D formulation was carried out in [3], [4].

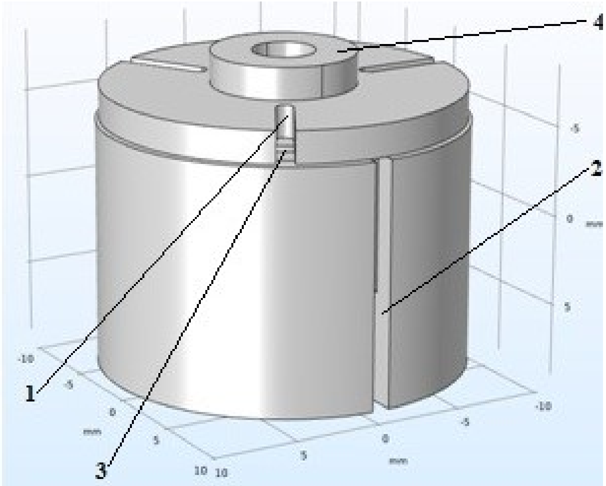


Fig. 1: 3D model of the electromagnet prepared in AutoCAD and imported to Comsol Multiphysics: 1 - the cutouts in the armature; 2 - the cuts in the housing; 3 - the winding placed inside the housing; 4 - the plane of attachment of the return spring.

Thus, the analysis of the literature data shows that the most correct calculations of the dynamics of an electromagnet should be recognized in [3], [4], in which the analysis of a 3D model based on the Finite Element Method using special computer codes like Comsol Multiphysics is carried out.

It should be noted that in the most above-mentioned works the main attention is paid to the calculations of a design given a priori (cut magnetic core, cutouts in the armature). The authors proceeded from the assumption that the value of the time of attraction and return of the armature to its initial position is most affected by eddy currents, which are determined by the rate of change of the input signal and the resistivity of the electromagnet's material [14], [24]. Moreover, it was assumed that the determining factor is the time of starting the armature of the electromagnet [14], [24], which determines the response time.

However, in the above-mentioned publications it is not shown how quantitatively these structural changes (cuts, cutouts) affect the parameters of an electromagnet compared to a conventional armored electromagnet. That is, the following question arises: does the complication of the design of the electromagnet (cuts in the housing and armature) correspond to the expected improvement in its parameters? To answer this question, it is necessary to calculate the dynamics of two electromagnet designs, one of which is basic (a conventional armored magnet without structural changes), and the other one is shown in Fig. 1 – this is an improved design of the electromagnet with a cut housing and cutouts in the armature. The entire fuel system is not shown, due to the rather complex design, and it does not affect the operation of the electromagnet. Fuel parameters also do not affect the operation of the valve's electromagnet due to the small area of the shut-off valve itself.

Special cuts in the armature and housing (see Fig. 1) are intended to reduce the effect of eddy currents; the housing also has holes for attaching an electromagnet [3], [4].

As mentioned above, the cuts in the housing and armature significantly complicate the design (see Fig. 1) and increase its cost of, so a comparative analysis of the parameters of a conventional armored electromagnet (a basic design) with the parameters of an electromagnet of a modified design seems relevant.

The goal of the work is to compare the dynamic characteristics of the basic electromagnet and the electromagnet with cutouts in the housing and armature, followed by the selection of the most acceptable, in terms of speed, option. Comparative analysis is carried out on the basis of the calculation of the dynamic characteristics of electromagnets in a 3D problem formulation.

2. Initial Data

The calculations were carried out for 3D models (see Fig. 1). The initial data for the analysis are given in Table 1.

The dimensions of the magnet are: the diameter of the housing is 20 mm, the height is 10 mm (see Fig. 1). The values and shape of the forced voltage on the winding of the electromagnet are set a priori (see Fig. 2).

The calculations were first carried out for the given magnetic core's material of the 16MnCr5 brand with resistivity of 0.18 $\mu\Omega \cdot m$. The main magnetization curve of the material is shown in Fig. 3.

3. A Mathematical Model

The calculation of the dynamics of the electromagnet is based on differential equations of: the electromagnetic field without taking into account the displacement currents; the movement of the moving parts of the electromagnet (armature and concomitant elements); the equations of the electric circuit. In this work, to perform calculations, a mathematical model developed by the authors earlier [15], [16] and modified to achieve the goal of this investigation is implemented

Tab. 1: Initial data.

Parameter	Value
Initial spring tension, N	70
Spring constant, N/m	57
Moving reduced mass, g	5.3
Number of winding turns	52
Armature stroke, μm	70
Air gap, μm	120
Winding resistance, Ω	0.38
Cycle duration, ms	5

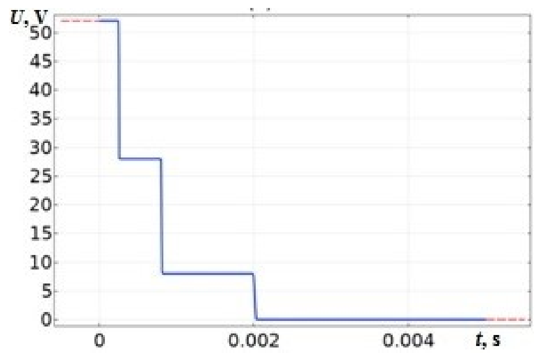


Fig. 2: The shape and values of the voltage on the winding as the function of time set by external source (microprocessor control).

Electromagnetic field equations are the following:

$$\begin{cases} \nabla \times \mathbf{H} = \mathbf{j}; \\ \mathbf{B} = \nabla \times \mathbf{A}; \\ \mathbf{j} = \sigma \cdot \mathbf{E} + \mathbf{j}_e; \\ \mathbf{E} = -\dfrac{\partial \mathbf{A}}{\partial t} + \mathbf{v} \times \mathbf{B}, \end{cases} \tag{1}$$

where $\mathbf{H}$ is the magnetic field strength; $\mathbf{j}$ is the total current density; $\mathbf{B}$ is the magnetic flux density; $\mathbf{A}$ is the magnetic vector potential; σ is the conductance of the magnetic core's material; $\mathbf{E}$ is the electric field strength; $\mathbf{j}_e$ is the current density from external sources; $\mathbf{v}$ is the speed of body's movement in the magnetic field.

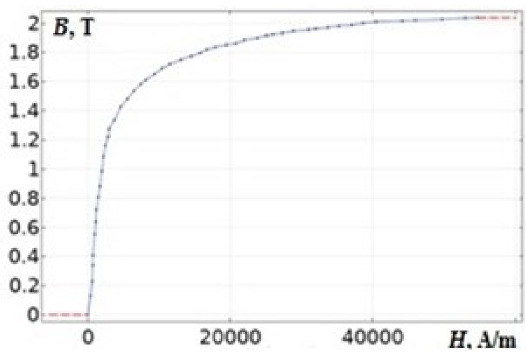


Fig. 3: Magnetization curve of the material of the 16MnCr5 brand.

A detailed form of the system of Eq. (1) in the 3D formulation is extremely bulky and in this article is not presented.

The system (1) should be supplemented by the equation of the motion of the electromagnet's armature, taking into account the reduced mass of moving parts:

$$\begin{cases} \dfrac{d\,(m \cdot \mathbf{v})}{dt} + \alpha \cdot \mathbf{v} = (\mathbf{Q} - \mathbf{F}) \cdot key; \\ \dfrac{dz}{dt} = \mathbf{v}, \end{cases} \qquad (2)$$

where m is the reduced mass; $\mathbf{v}$ is the speed; α is the damping coefficient; $\mathbf{Q}$ is the electromagnetic force determined by the Maxwell stress tensor; $\mathbf{F}$ is the counteracting force; key is the boolean variable, which together with α, takes into account the restriction of the armature displacement between the stops.

The boolean variable key is a complex logical expression due to the following conditions: in the initial position, the electromagnet armature must be stationary while the total force is negative (the armature rests on stops); with a positive value of the total force, the armature starts to move and stops when a certain stroke value is reached (the final position of the armature); when the network voltage decreases (reverse movement of the electromagnet armature), the armature must be stationary until the total force is positive (the armature is on the stops), and the reverse movement begins with negative values of the total force; when the armature reaches the initial value of the air gap (initial position), the armature of the electromagnet gets on the stops and the movement stops.

The initial conditions are zero ones. The counteracting force was determined on the basis of the stroke and constant of the return spring (see Table 1).

$$L_e \cdot \frac{di}{dt} + (R_k + R_d \cdot key_1) \cdot i = U + E, \qquad (3)$$

where L_e is the external inductance; i is the winding current; R_k is the active resistance of the winding; R_d is the additional resistance connected to the winding after the voltage is switched off and allows to reduce the overvoltage level to acceptable values; key_1 is the boolean variable; E is the EMF of the winding; U is the voltage applied to the winding (see Fig. 2).

In general, increasing the additional resistance reduces the time for the electromagnet to return to its original state, but increases the overvoltage when switched off. The value of this resistance (3 Ω) was chosen based on the allowable overvoltage values and the return time.

The boolean variable key1 is due to the fact that when the network voltage is switched off, the additional resistance Rd is connected in series to the electromagnet winding, that: protects the electromagnet winding from overvoltages; accelerates the process of current decay in it, which reduces the time of the armature return to its initial position.

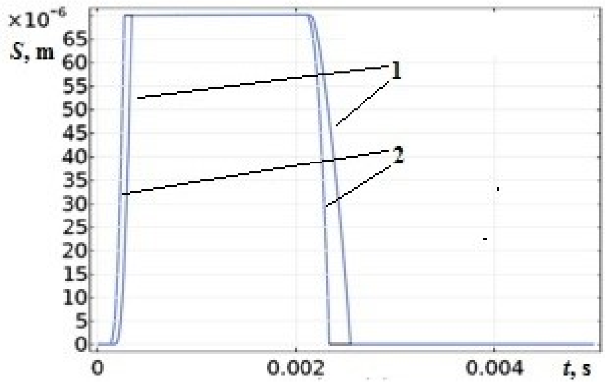


Fig. 4: Dependencies of the armature stroke (forward and reverse stroke for one cycle) for the basic design option (1) and the improved one (2).

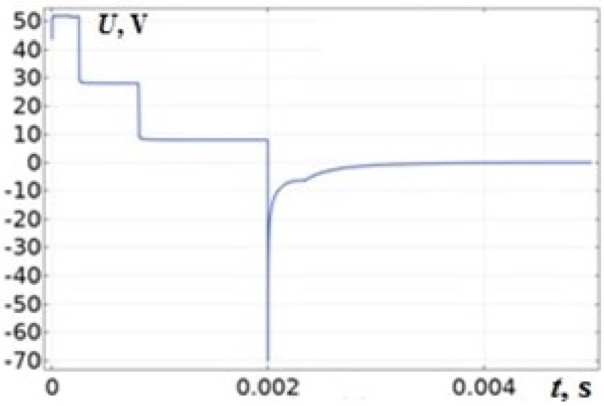
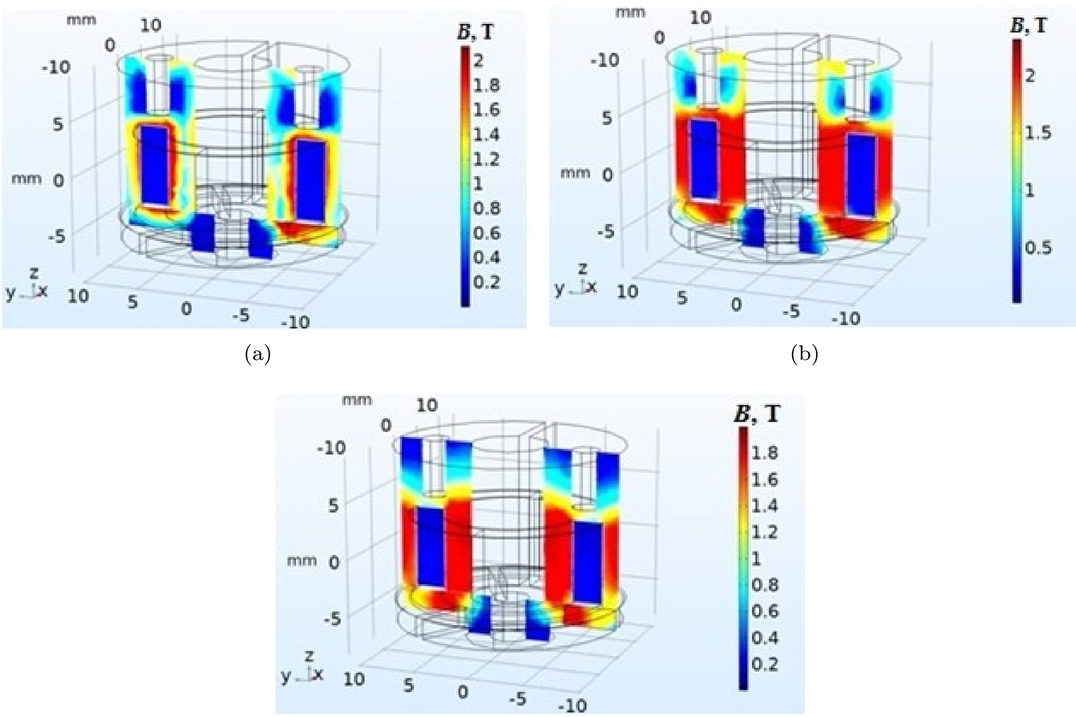


Fig. 5: Voltage on the electromagnet winding taking into account transients and the additional resistance in the winding circuit.

The external leakage inductance is small, but this makes it possible to stabilize the solution process, making it more stable. The EMF of the winding is determined based on the following considerations:

$$\begin{cases} E = -w \cdot \dfrac{d\Phi_\Psi}{dt}; \\ \Phi_\Psi = \dfrac{1}{w} \cdot \displaystyle\int_w \Phi \cdot dw = \dfrac{1}{S} \cdot \iint_S \Phi \cdot dS; \ \Phi = \oint_l \mathbf{A} \cdot d\mathbf{l}; \\ E = -\dfrac{w}{S} \cdot \displaystyle\iint_S \left(\oint_l \frac{d\mathbf{A}}{dt} \cdot d\mathbf{l} \right) \cdot dS, \end{cases} \qquad (4)$$

whereΦ_Ψ is the magnetic flux, reduced by flux linkage; w is the number of winding turns; Φ is the magnetic flux; S is the cross-sectional area of the winding; $\mathbf{A}$ is the magnetic vector potential; l is the integration contour.



(a) (b) (c)

Fig. 6: The values of the modulus of the magnetic flux density in the housing of the electromagnet at different times, (a) $t = 0.1$ ms, (b) $t = 0.2$ ms, and (c) $t = 0.3$ ms.

The system of equations (1)-(4) is a mathematical model of the dynamics of the electromagnet, which is solved using a specialized computer code. Modelling of the movement of the electromagnet armature is carried out by deformation of the elementary volumes of space in accordance with the solution of system (2) [15].

4. Calculation Results

Calculations of the dynamic were carried out with the same initial parameters for two design options: 1) the basic option: the armored electromagnet with the solid housing and the armature; 2) the improved version of the design: there are the longitudinal cut in the housing and three cutouts in the armature (see Fig. 1).

The results of calculation of the dynamics of the armature stroke in one cycle for the basic and improved electromagnets are shown in Fig. 4. The winding voltage is shown in Fig. 2.

Table 2 shows the response time (from applying voltage till the armature reaching the final position according to Fig. 4) and the return time of the armature to its initial position for the basic and improved electromagnets.

As can be seen from Table 2, the response and return times are in the order of fractions of milliseconds and range 13.5-17% of the operating time (the time the winding is energized is 2 ms). To the greatest extent, design changes have an impact on the return time of the electromagnet armature to its initial state, reducing it by 37% compared to the basic design. The response time is reduced by 20.5% compared to the basic design option.

Tab. 2: Initial data.

Design	Response time, ms	Return time, ms
Basic	0.34	0.54
Improved	0.27	0.34

Fig. 5 shows the voltage on the winding. The voltage shape on the winding differs from the source voltage shape due to the connection of the additional resistance to the winding, the value of which determines the overvoltage values when the winding is switched off as well as the rate of current decay in it.

Fig. 6 shows the values of the magnetic flux density in the improved magnet in the $y - z$ plane - the plane perpendicular to the cut plane in the housing.

Based on Fig. 6 it can be concluded that almost the entire working cycle (0-2 ms) the magnetic system is in a saturated state, which contributes to a decrease in the time constant of the electric circuit for a given volume of steel and the number of winding turns.

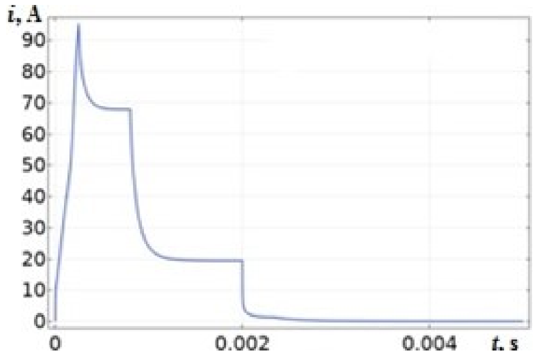


Fig. 7: Winding current.

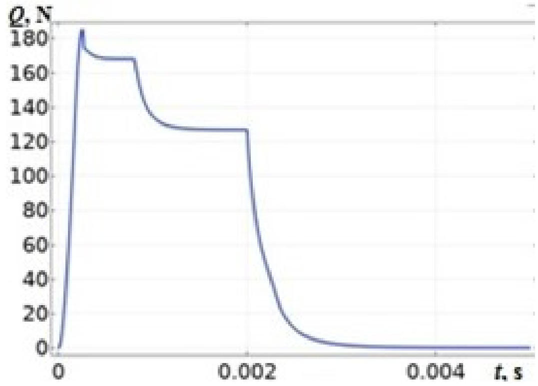


Fig. 8: Electromagnetic force.

As calculations show, an increase in the voltage applied to the winding at the initial moments of time to 62 V reduces the response time to 0.24 ms (0.03 ms less compared to the improved design) or 0.1 ms compared to the basic electromagnet. However, it leads to an increase in the maximum winding current by 42%

Fig. 7 shows the value of the winding current, and Fig. 8 presents the value of the electromagnetic force for the improved design of the electromagnet.

As follows from Fig. 7, 8, the rate of increase of the current and the electromagnetic force is high (of the order of $1 \cdot 10^6$ N/s) and cannot be significantly increased by further increasing the voltage applied to the winding. A possible way to further increase the speed is to reduce the initial value of the counteracting force within acceptable limits. Thus, a 2-time decrease in the initial force gives a response time of 0.24 ms, which is 11% less compared to the response time of the improved electromagnet.

Fig. 9 shows the distribution of eddy currents in the magnet housing and the effect of a cut in the housing on their nature. Despite the low informativeness of Fig. 9, it gives an idea of the complex nature of eddy currents, the calculation of which is possible only in a 3D formulation of the problem.

The interesting issue of the effect of eddy currents on the operating time of the electromagnet can be investigated by comparative calculations of the dynamics of the electromagnet for various values of the resistivity of the magnetic core's material. Since these values for applicable steel brands vary within (10-100)$\cdot 10^{-8}\Omega \cdot m$, the calculations were carried out for three options: $10 \cdot 10^{-8}\Omega \cdot m$, $18 \cdot 10^{-8}\Omega \cdot m$, and $100 \cdot 10^{-8}\Omega \cdot m$. The calculation results are shown in Fig. 10, 11. As expected, eddy currents have the greatest effect on time the armature returns to its initial position, however, this effect is not as significant as the effect of design changes.

When investigating the operation of electromagnetic mechanisms, especially in forced operating modes, it is necessary to know the temperature to which the electromagnet winding is heated. In this research, jointly with the electromagnetic calculation, the simulation of the average heating temperature of the winding for one working cycle (5 ms) was carried out. The initial heating temperature was chosen equal to 100^oC (the maximum possible temperature of the engine operation) at which the active resistance of the winding is maximum.

The calculation is carried out according to the following heat transfer equation in a transient mode, jointly with the system (1)-(4):

$$\rho \cdot \cdot \frac{\partial T}{\partial t} - \nabla \cdot (k(T) \cdot \nabla T) - q(T) = 0, \tag{5}$$

where $\rho(T)$ is the equivalent density of the winding material; $C(T)$ is the equivalent heat capacity of the winding material; $k(T)$ is the equivalent thermal conductivity of the winding material; $q(T)$ is the volumetric density of internal heat sources [15] dependent on temperature, which in turn is a function of time. Since the heating temperature was a priori unknown, the calculation was initially carried out for thermophysical parameters that depend on temperature.

The operating mode of the winding is adiabatic. The calculation of the average temperature over the volume of the winding is carried out according to the formula:

$$T_s = \frac{2 \cdot \pi}{V_k} \cdot \int_{V_k} T \cdot r \cdot dr \cdot dz, \tag{6}$$

where T_s is the average temperature; V_k is the winding's volume; T is the winding's temperature distributed over the volume.

Since a change in the temperature of the winding affects the value of the current in it, then in Eq. (3) it is necessary to change the value of the resistance of the winding

$$R_{kT} = R_{k0} \cdot (1 + \alpha \cdot (T_s - T_0)), \tag{7}$$

where R_{kT} is the resistance of the heated winding; R_{k0} is the initial resistance of the winding; α is the temper-

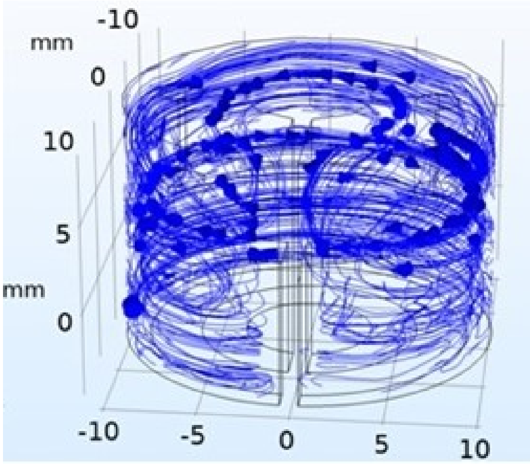


Fig. 9: The nature of eddy currents in the magnet housing at 0.13 ms.

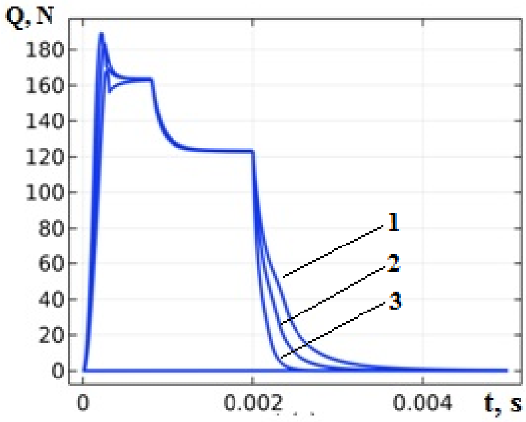


Fig. 11: Electromagnetic force as a function of material resistivity: $10 \cdot 10^{-8}\Omega \cdot m$ (1), $18 \cdot 10^{-8}\Omega \cdot m$ (2), $100 \cdot 10^{-8}\Omega \cdot m(3)$.

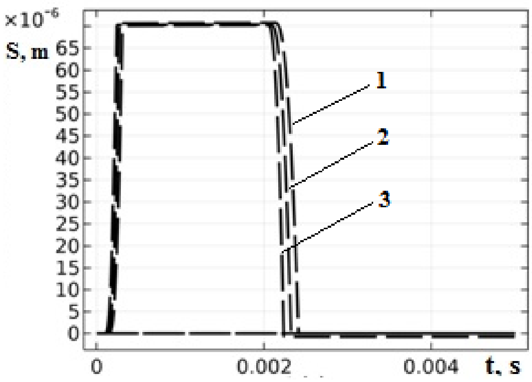


Fig. 10: Electromagnet actuation dynamics as a function of material resistivity: $10 \cdot 10^{-8}\Omega \cdot m$ (1), $18 \cdot 10^{-8}\Omega \cdot m$ (2), $100 \cdot 10^{-8}\Omega \cdot m(3)$.

ature coefficient of resistance; T_S is the average heating temperature of the winding; T_0 is the initial temperature.

The solution of Eq. (5) is carried out together with the solution of the system (1)-(4), and the values of the average temperature and resistance are calculated according to Eq. (6), (7) at each time step.

Fig. 12 shows the results of calculation of the rise of the average winding temperature over the initial temperature for one cycle in the adiabatic mode, which is 0.65^oC.

However, the question of the steady-state heating temperature remains open, since it requires additional investigation of the conditions for the heat transfer by thermal conduction and convection.

5. Conclusion

A technique for 3D calculation of the electromagnetic mechanism in a transient mode has been developed, tested and implemented.

During the operation of the electromagnet, at the initial moments of time (up to 0.1 ms), the skin-effect is clearly expressed. Cuts in the design of the armature and the housing of the electromagnet significantly affect the times of attraction and return of the magnet's armature by reducing eddy currents and therefore they can be recommended as structural elements that increase the speed of the system.

In the process of operation, the magnetic flux density in the housing reaches saturation values and is distributed extremely irregular, increasing significantly near the cut in the housing and around the cutouts in the armature. All these factors, taken together, reduce the equivalent conductivity of the magnetic core material by 2.33 times compared to the basic design, which allows the electromagnet to provide the required speed.

A further increase in the forced voltage is impractical, since it leads to a significant increase in the thermal load on the winding with a slight decrease in the response time.

Taking into account the fact that mathematical modelling is just an auxiliary tool that allows to investigate the direction of research in more detail, determine in advance the problems that arise in the research process and significantly save time, financial expenses and efforts spent in the laboratory on full-scale experiments, the authors intend to continue further work in direction of experimental validation of the results obtained.

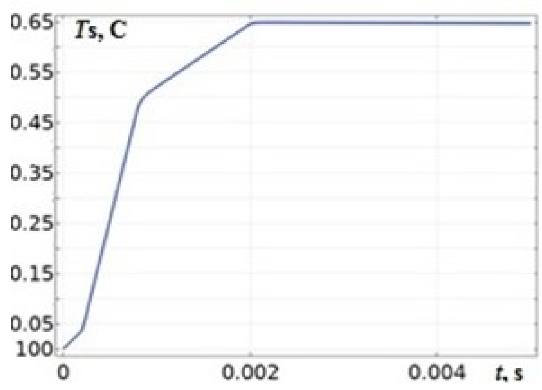


Fig. 12: Average temperature rise of the winding for one operating cycle of the electromagnet.

Author Contributions

Ye.B. and M.P. authors formulated the goals and objectives of the research, developed a mathematical model, and reviewed the literature on the problem. Ye.B. performed process calculations using the applied computer code. M.P. completed the design of the article in accordance with the requirements and translated the article into English. S.V. author performed graphical processing, representation and analysis of numerical results obtained.

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