Rev. Roum. Sci. Techn.– Électrotechn. et Énerg.
Vol. **66**, *4*, pp. 213–217, Bucarest, 2021

Électrotechnique et électroénergétique

NEW SOLUTION OF ELECTROMAGNETIC LAUNCHER

DRAGOȘ-ȘT. NICOLESCU[1], ALEXANDRU RADULIAN[1], MIHAI MARICARU[2], SEBASTIAN PRICĂ[3], NICOLAE MOCIOI[1]

Key words: Linear alternative current actuator, Thomson coil actuator, Propulsion system, High force, High speed, Ferromagnetic circuit, Eddy current propulsion, Electromechanical device.

This paper presents the design, simulation, and experimental validation of a linear alternative current actuator. From this point of view, the main purpose of the paper is to analyze the working principle of the linear actuator and to explain how electromagnetic and mechanical parameters can modify the force produced by this device. By using a special design of the magnetic circuit, the proposed electromechanical device ensures high force, kinetic energy, and speed for the mobile part of the actuator.

1. INTRODUCTION

Electromechanical devices have a wide range of applications in different technical domains. The most well-known devices of this type are direct current motors, alternative current synchronous generators, and alternative current induction motors, as well as levitation systems, electromagnets, and other magnetic propulsion systems [1].

The choice of a specific electromagnetic actuator must consider certain parameters of interest, such as the force developed by its moving part, speed, developed torque, acceleration, etc.

A particular domain of high interest of these electromechanical devices refers to electromagnetic propulsion. The most well-known devices are the Thomson coil actuators [2, 3] and Railguns. These devices have working principles like linear electric motors. Some of them have permanent magnets and the coils are controlled considering the relative position of the fixed and moving parts. Other actuator types rely on a progressive magnetic field that induces eddy currents in the moving part, which interact with the inductor field. There is a large interest regarding electromagnetic propulsion systems, especially in the military research and development facilities for launching drones and unmanned aerial vehicles (UAV).

Attempts to use these devices in military equipment were not successful, because the obtained mechanical parameters did not achieve the expectations. However, one area in which these electromagnetic propulsion systems are widespread is electrical equipment and for example, Thomson Coil Actuators were successfully used in circuit breakers.

The article is organized as follows: in Section 2 it is presented the proposed linear actuator design and how it works; in Section 3 are presented the influences of electromagnetic and geometric parameters, while case study and computation of mechanical parameters are given in Section 4; in Section 5 it is presented the experimental model and finally, a brief conclusion and future work in Section 6.

2. PROPOSED LINEAR ACTUATOR DESIGN AND WORKING PRINCIPLE

In this paper, a model of alternative current electromagnetic actuator is proposed. The actuator is made of a ferromagnetic circuit, two excitation coils and the moving part (projectile). The excitation coils are powered by an alternating voltage source, and through them a time-varying electric current flows. According to Ampère's Law, the electric current which flows through the coil will produce a magnetic field, which is guided by the ferromagnetic circuit towards the projectile. The projectile has a special shape and is placed on the ferromagnetic circuit, in which, according to Faraday's law, due to the time-varying magnetic field, a voltage will appear. Given that the projectile is made of an electrically conductive material, the voltage induced in the circuit will produce a current which is also variable in time.

The electric current induced in the projectile, together with the magnetic field produced by the excitation coils creates a Laplace force, which will lead to the propulsion of the moving part of the actuator. Considering this, there are certain parameters that can be modified to influence the force produced by the actuator. By modifying the voltage applied on the excitation coils, the current which flows through them, and the magnetic field produced changes. Another way to modify the force produced by the actuator refers to the possibility of implementing a different geometry for the magnetic circuit and for the projectile.

In Fig. 1, a 3D view of the electromagnetic actuator is presented. The electromagnetic actuator has the following main components:

1 – magnetic circuit;
2 – air gap;
3 – mobile armature / projectile;
4 – excitation coils.

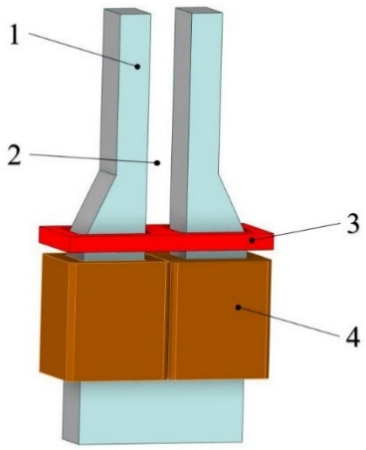

Fig. 1 – 3D view of the actuator design.

[1] ICPE, Department of Electrical Apparatus, Bucharest, Romania, dragos.nicolescu@icpe.ro
[2] "Politehnica" University of Bucharest, Department of Electrical Engineering, Bucharest, Romania, mihai.maricaru@upb.ro
[3] "Politehnica" University of Bucharest, Faculty of Electrical Engineering, Bucharest, Romania, sebastianprica@gmail.com

The air gap between the ferromagnetic columns of the actuator is 40 mm, and the stroke distance of the projectile inside air gap is 200 mm. To determine the magnetomotive force produced by the coils, the magnetic flux density must be known.

The reluctance of the magnetic circuit can be described with the following equation:

$$R_{total} = R_{\mathrm{Fe}} + R_{air\ gap} = = \frac{\delta_{Fe}}{\mu_0 \times \mu_{\mathrm{Fe}} \times S_{\mathrm{Fe}}} + \frac{\delta_{air\ gap}}{\mu_0 \times S_{air\ gap}}, \qquad (1)$$

where: R_{total} [H^{-1}] is the total reluctance of the magnetic circuit, R_{Fe} [H^{-1}] is the reluctance of the ferromagnetic core and $R_{\mathrm{air\ gap}}$ [H^{-1}] is specific to the air gap; δ_{Fe} [m] is the length of the ferromagnetic core reluctance and $\delta_{\mathrm{air\ gap}}$ [m] is the length of the air gap reluctance; S_{Fe} [m^2] is the surface considered for the reluctance of the ferromagnetic core and $S_{\mathrm{air\ gap}}$ [m^2] is the surface considered for the reluctance for the air gap; finally, μ_0 [H/m] is magnetic permeability of the vacuum and μ_{rFe} is the relative permeability of the material from which the ferromagnetic core is made.

Considering the reluctance of the ferromagnetic circuit negligible in comparison with that of the air gap, the total reluctance can be approximated as follows:

$$R_{total} » R_{air\ gap} = \frac{\delta_{air\ gap}}{\mu_0 \times S_{air\ gap}}, \qquad (2)$$

Relation (2) can be used only when the magnetic circuit is not saturated. Also, the magnetic flux can be computed using the following formula:

$$\varphi = \oint_{\Sigma} \mathbf{B} \cdot \mathbf{n}\, \mathrm{d}\, A, \qquad (3)$$

where: **B** [T] is the magnetic flux density and $\sum$ is the surface through which the flux flows [4].

If the magnetic field is perpendicular on the surface, the following expression can be used to compute the magnetic flux:

$$\varphi = B \cdot A. \qquad (4)$$

Using the last three equations, the magnetomotive force can be computed using the next formula:

$$\theta = \frac{B \times \delta_{air\ gap}}{\mu_0}. \qquad (5)$$

If the magnetic flux density where the projectile is located is 1 T, and the air gap has a value of 40 mm, by using relation (5), the resultant magnetomotive force is 32000 At. The magnetomotive force is produced by two identical coils. Considering this, each of the two coils must produce a magnetomotive force of 16000 At.

3. NUMERICAL COMPUTATION OF THE PROPOSED LINEAR ACTUATOR

The proposed linear actuator can be analyzed using different approaches. The actuator can be simulated using a 2D model. To determine the kinetic energy and the speed gained by the mobile armature, the force must be computed for every position of the projectile along its path. The electromagnetic solution was determined using the FEMM package, in which a special LUA script was implemented to solve the problem mentioned above [5].

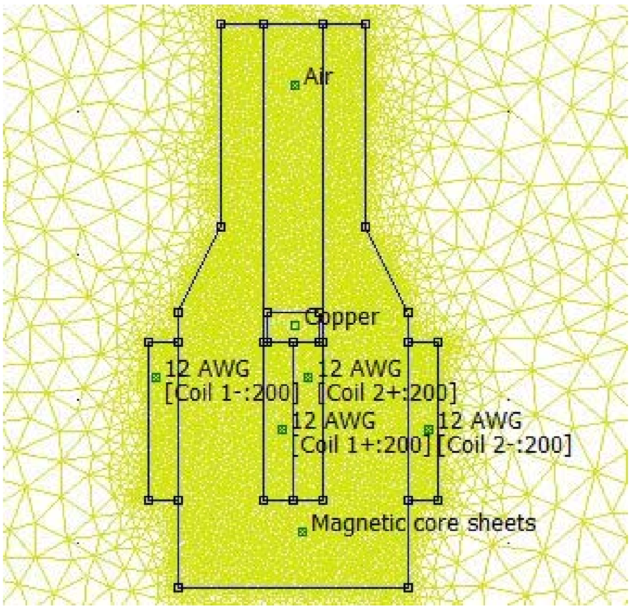

Fig. 2 – Numerical simulation of the actuator.

The problem described in the program is a planar type one, the frequency used is 50 Hz, and the depth implemented is 30 mm, which is also the thickness of the magnetic circuit. The geometry of the mobile armature can be approximated also as a planar type one. The current in the coils is set at 80 A, and the number of turns is 400, and thus the magnetomotive force produced is 32 000 At.

The magnetic circuit is made of steel with a thickness of 0.018-inch sheets, to limit the induced eddy currents [6]. The B-H characteristic used in computations is presented in Fig. 3.

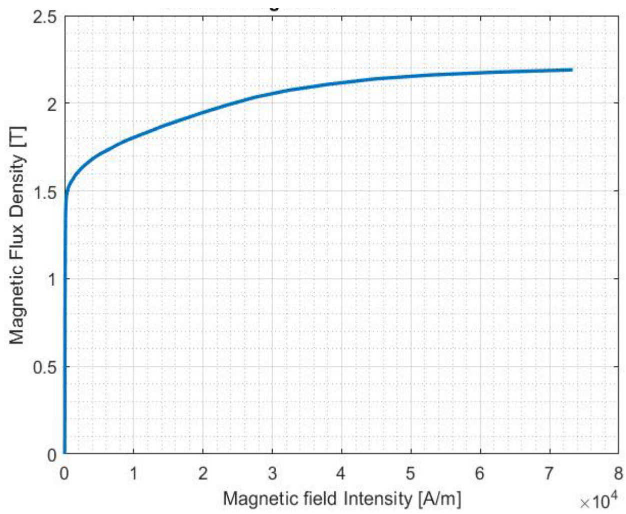

Fig. 3 – *B-H* characteristic of the material used for the magnetic circuit of the actuator [7].

For the boundary of the domain, Dirichlet condition was implemented, in which the magnetic vector potential is zero. To verify the symmetry of the magnetic field, the entire actuator was simulated.

3.1. ELECTROMAGNETIC PARAMETERS

In this section, the simulation results of the alternative current actuator are presented. The magnetic field produced by the coils is directed by the ferromagnetic circuit toward the air gap, where the projectile can be seen. The magnetic flux is always concentrated below the projectile, as seen in Fig. 4. The magnetic field induces eddy currents in the projectile, which produce their own magnetic field. The magnetic field produced by the excitation coils flows through the magnetic circuit, which can also be seen in Fig. 4. The position of the mobile armature along its trajectory also influences the path of the magnetic circuit.

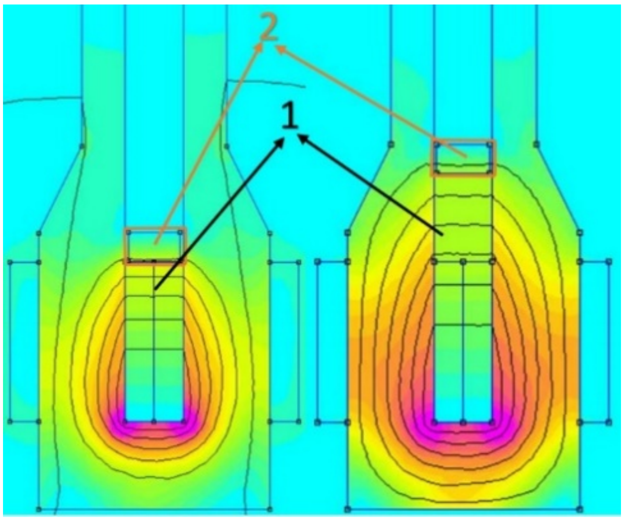

Fig. 4 – Magnetic field (1) directed by ferromagnetic circuit below the projectile (2).

The Laplace force can be computed for every infinitesimal part of the projectile (respectively, in every point of it), and it is proportional with the magnetic flux density and current density in that point.

By summing the forces produced in every point of the projectile, the total force can be computed. As stated by Ampère's circuital law, the magnetomotive force produced by the coils is proportional with the current which flows through them [8].

The relationship between mechanical force and magnetomotive force is valid when the magnetic core is functioning of every point of *B*-*H* characteristic. This implies that the relationship between the magnetic field intensity **H** and magnetic flux density **B** is linear, or the relative permeability of the material has a constant value [9]. When the projectile is placed in the initial position (and the travelled distance is zero), the force produced by the actuator has the highest level. In Table 1 there are being presented some of the forces produced by the actuator for different values of magnetomotive forces when the projectile is in the initial position (at the beginning of the stroke).

Table 1

Mechanical force as a function of magnetomotive force

Magnetomotive force [At]	Mechanical force [N]
16000	60
24000	135
32000	240

According to Faraday's law [10], the induced eddy currents are proportional with the magnetic flux, thus leading to the conclusion that the force produced by the actuator is proportional with the square of the magnetomotive force produced by the coils, as shown in Fig. 5.

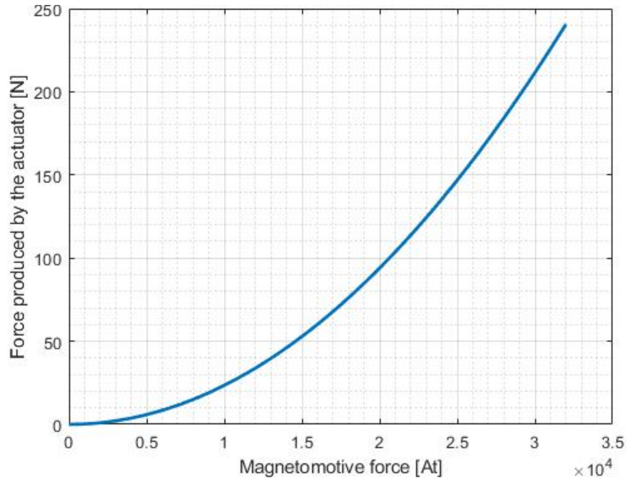

Fig. 5 – Relation between mechanical force and magnetomotive force.

3.2. COMPUTATION OF MECHANICAL FORCE

As seen in the previous table, the mechanical force is dependent of the magnetomotive force. If the magnetomotive force doubles (from 16 000 At to 32 000 At) then the mechanical force becomes four times higher (from 60 N to 240 N), which corresponds with the previous statement.

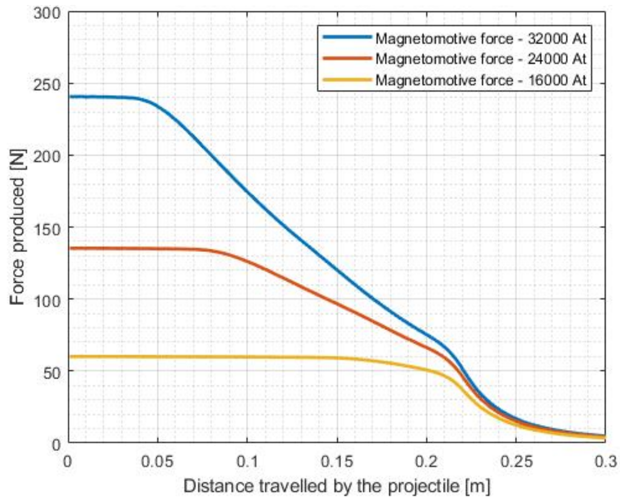

Fig. 6 – Relation between mechanical force and distance, for different magnetomotive forces.

As seen in Fig.6, the force produced by the actuator as a function of distance is different at modified magnetomotive force produced by the coils.

However, the material considered in simulations has a non-linear *B*-*H* characteristic, and this implies that the saturation process can occur [11]. This happens when the magnetic reluctance of the air gap is small enough, and the flux density increases. The magnetic reluctance of the air gap modifies with the travelled distance of the projectile because the surface through which the magnetic flux passes is increased.

Because the magnetic reluctance is inversely proportional with the surface, this means the magnetic flux increases with the distance travelled by the projectile. However, the surface of the ferromagnetic circuit is constant, and this implies that the magnetic flux density increases, and the saturation process begins. Because the permeability of the ferromagnetic material decreases, the magnetomotive force along its reluctance increases. This leads to a high level of magnetic energy lost by the air gap, which is instead directed in the magnetic core, and this results in a lower mechanical force produced by the actuator.

4. NUMERICAL COMPUTATION OF MECHANICAL PARAMETERS

In this section, the mechanical parameters computed with MATLAB are presented. The most important mechanical parameters are the acceleration and speed of the projectile, as well as the kinetic energy obtained by it. The first parameter that can be easily computed is the acceleration, which can be determined by using the force produced by the actuator and the mass of the projectile. Using Newton's Second Law, the relationship between the parameters mentioned in the previous statement can be written as:

$$\mathbf{a} = \frac{\mathbf{F}}{m}, \tag{6}$$

where: $\mathbf{a}$ [m/s^2] is the acceleration, $\mathbf{F}$ [N] is the force and m [kg] is the mass of the projectile. Preliminary calculations provide a mass of 3 kg for the projectile, because it is made of copper, which has a high electrical conductivity. The force and the position of the projectile were determined earlier using FEMM package and a special LUA script. The projectile has a maximum acceleration at the beginning of the stroke, where the force has the highest value. The acceleration of the projectile has a positive value (as seen in Fig. 7), which leads to the fact that the speed is increasing.

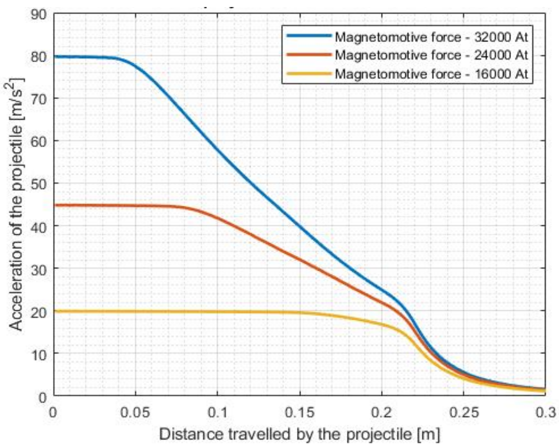

Fig. 7 – Relation between acceleration of the projectile and travelled distance.

For the computation of the speed obtained by the projectile, the kinetic energy, which is also the work, must be calculated. The work produced by the projectile can be computed by integrating the force over the trajectory of the projectile:

$$\int_{\Gamma} F \, \mathrm{d}l = \int_{d_0}^{d_1} F \, \mathrm{d}l, \tag{7}$$

where: F [N] is the force, d_0 is the initial position of the projectile, d_1 is the final position and Γ is the trajectory from d_0 to d_1. Using numerical integration, the kinetic energy (which is also the work in this case) produced by the projectile can be computed as seen in Fig. 8.

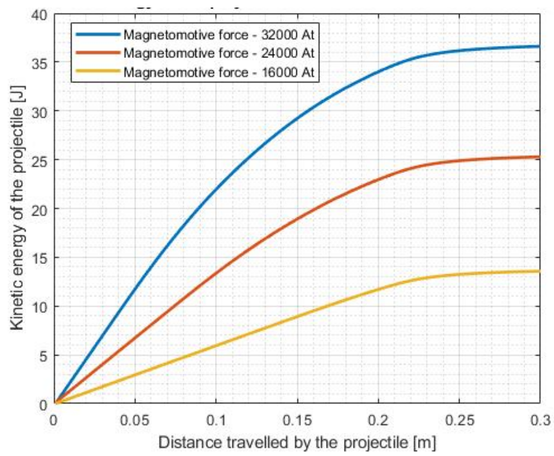

Fig. 8 – Kinetic energy as a function of trajectory / travelled distance.

As stated before, the kinetic energy is equal to the work done by the actuator in accelerating the projectile with mass m. The relation between speed, mass and energy is:

$$E_{d_1} = \frac{m \cdot v_{d_1}^2}{2} = \int_{d_0}^{d_1} F \, \mathrm{d}l, \tag{8}$$

where: E_{d_1} [J] is the kinetic energy and v_{d_1} [m/s] is the speed gained by the projectile while moving on the trajectory from point d_0 to d_1. The previous equation can be written as:

$$v_{d_1} = \sqrt{\frac{2}{m}} \cdot \sqrt{\int_{d_0}^{d_1} F \, \mathrm{d}l}. \tag{9}$$

The speed has the following characteristic, as it can be seen in Fig. 9.

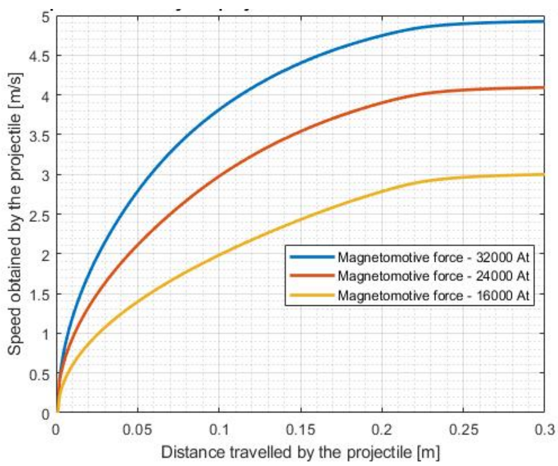

Fig. 9 – Speed as a function of trajectory / travelled distance.

The speed has a maximum value of 5 m/s for a magnetomotive force of 32 000 At, 4 m/s for 24 000 At and 3 m/s for 16 000 At. As seen in the above figure, the projectile gains a higher speed in the first part of its trajectory. On the last part of its trajectory, the gained speed has an approximatively constant value. This happens because the acceleration produced by the actuator on the projectile has a maximum value at the beginning of the stroke and a minimum value at the end of the stroke.

5. EXPERIMENTAL MODEL

To validate the working principle of the actuator, an experimental model was created. The geometric dimensions of the ferromagnetic circuit are equal to those of the simulated model. The magnetic circuit was made of laminated silicon steel sheets, with a thickness of 0.5 mm each. The coils are made of 4 mm^2 copper wire.

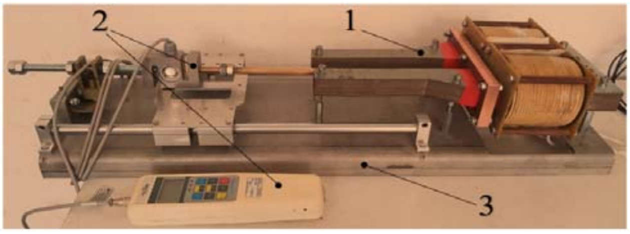

Fig. 10 – Physical model of the alternative current actuator.

To measure the force produced by the actuator and to validate the computed results, an experimental setup was used, as shown in Fig. 10. As seen in the previous figure, the alternative current actuator (1) was placed on a stainless-steel support (3), to maintain it in a fixed position. Also, in the previous figure, a digital force gauge (2) is presented, which is used to measure the force produced by the device. The electrical and mechanical parameters are presented in Tables 1 and 2.

The experimental measurements results are quite like those of the computed model. The slight difference between these results may be due to mechanical manufacturing, assembling and digital force gauge resolution.

Table 2

Electromagnetic actuator's a.c. parameters

$Z_{sc} = \sqrt{R_{sc}^2 + X_{sc}^2}$ [Ω] (impedance of a single coil)	22.5
$X_{sc} = \omega L$ [Ω] (reactance of a single coil)	22.5
R_{sc} [Ω] (resistance of a single coil)	0.24
$Z_{pc} = Z_{sc}/2$ [Ω] (impedance of parallel coils)	11.3
$X_{pc} = X_{sc}/2$ [Ω] (reactance of parallel coils)	11.3
$R_{pc} = R_{sc}/2$ [Ω] (resistance of parallel coils)	0.12
N (number of turns for both coils)	400
$\theta = N \cdot I$ [At]	32 000

Table 3

Electromagnetic actuator's mechanical parameters

Alternative current actuator mechanical parameters Force produced by actuator as a function of magnetomotive force		
Magnetomotive Force [At]	Force Computed [N]	Force Measured [N]
4 000	4.4	5
8 000	18	20
12 000	40	35

6. CONCLUSIONS

In this article, a new design for an alternative current actuator was presented. The working principle of the device was analyzed, and the simulation results were interpreted. To validate the working principle and the simulation results, an experimental model was made. In a future paper, an enhanced model of the actuator will be presented, which has improved mechanical parameters, and a new geometry for the projectile, which has a better drag coefficient.

ACKNOWLEDGEMENTS

This work was financially supported by ICPE through own contribution no. 2774/2019.

Received on September 13, 2021

REFERENCES

1. D. Nicolescu, F. Hănțilă, *Electromagnetic propulsion using eddy currents* (in Romanian), Bachelor Degree Thesis in Electrical Engineering at UPB, Bucharest, 2020.
2. G. Hortopan, V. Trusca, D. Pavelescu, M. Serbanescu, S. Nitu, *The fast phenomena technique* (in Romanian), Editura Tehnică, Bucharest, 1985.
3. D. Pavelescu, E. Ghetea, *Ultra-fast device with electrodynamic repulsion* (in Romanian), Revista de Electrotehnică, Electronică, Automatică (EEA), **8**, 1976.
4. A. Timotin, V. Hortopan, A. Ifrim, M. Preda, *Lessons of Basics Electrical Engineering* (in Romanian), Editura Didactică și Pedagogică, Bucharest, 1970, pp. 207-345.
5. D. Meeker, *Finite Element Method Magnetics – Version 4.2 – User's Manual*, 2018.
6. L.M. Dumitran, P.V. Noțingher, *Electrical Materials* (in Romanian), Editura MatrixRom, Bucharest, 2014, pp. 342-343.
7. M. Costea, B. Vărăticeanu, Constanța Bălan, *Operating time of a direct current electromagnet,* Revista de Electrotehnică, Electronică, Automatică (EEA), **60**, *1*, pp. 50-53, 2012.
8. E. Nicolau, *Introduction on modern theoretical electromagnetism* (in Romanian), Editura Academiei Republicii Socialiste Romania, Bucharest, 1974, pp. 167-180.
9. T. Leuca, C Mich-Vancea, Ș. Nagy, B. Stanciu, *Numerical Modelling for Different Geometry of the Electrothermal Systems by Induction Heating*, Revista de Electrotehnică, Electronică, Automatică (EEA), **59**, *1*, pp. 19-24, 2011.
10. F. Hănțilă, M. Vasiliu, *Time-varying electromagnetic field* (in Romanian), Editura Electra, Bucharest, 2005.
11. F. Hănțilă, E. Demeter, *Numerical solving of electromagnetic field problems* (in Romanian), Edit. ARI Press, Bucharest, 1995.