Rev. Roum. Sci. Techn.– Électrotechn. et Énerg.
Vol. **68**, *1*, pp. 36–41, Bucarest, 2023

MAIN ELECTRICAL COMPONENTS OF AN ASSAULT RIFLE WITH ADAPTIVE MECHANISM

DRAGOȘ-ȘTEFAN NICOLESCU[1], PETRU ROȘCA[2], ALEXANDRU RADULIAN[1], CRISTIAN PREDOI[2], ALEXANDRU MUNTEANU[2]

Keywords: Bistable permanent magnetic actuator; Electronic controller; Cooking off the gun; Nd-Fe-B permanent magnets; Ferromagnetic circuit, numerical analysis.

In this paper, the authors aim to explain a new model of an assault rifle with an adaptive mechanism, its working principle, and its main components: a new bistable actuator and its electronic control system. This system is used in an assault rifle to limit the self-initiation of the cartridge due to barrel heating without the operator pulling the weapon's trigger. The proposed actuator ensures a short time switching between its two holding positions. The novelty of the proposed actuator consists of using two Nd-Fe-B rare earth permanent magnets to maintain the mobile core, shaped like a cylindrical plunger, in two holding positions. The electronic controller measures the temperature of the weapon's barrel with a thermocouple and applies a voltage on the coils to switch between the two holding positions of the actuator. The actuator has been modeled and analyzed using the FEMM package, and the mechanical parameters were computed with MATLAB. An actuator and control system prototype was manufactured and tested to validate the results obtained from computer modeling. The results obtained from the tests validated the conditions and results from sections 2 and 3.

1. INTRODUCTION

Currently, one of the limitations in the operation of assault rifles is the emergence of self-initiation, namely the initiation of the cartridge because of barrel heating, without the operator pulling the weapon trigger. This phenomenon is known in the literature as a cook-off. The emergence of self-initiation reduces the weapon's performance by limiting the number of cartridges that can be fired in a sustained fire in a specific time and by reducing the safety of the shooters while using the weapon.

This phenomenon is instead studied in theory [1,2] or verified in practice, on existing weapons, by perfecting tests following NATO D14 Handbook on Evaluation Procedures for Future NATO Small Arms Weapon Systems (**AC/225**(**DSS**)- D(**2018**)0006), in particular, the chapter 2.14 - Cook-off and barrel heating [3]. The aim is to establish the reference temperature from which self-initiation occurs measured in several rounds that could be fired safely but without making it possible to prevent it.

To ensure a safe shooting for many rounds, these should be kept in a belt or magazine between trigger pulls, this mode of functioning is known in the literature as an open-bolt functioning weapon. In history, there are only a small number of assault rifles known worldwide to function based on a mechanism that ensures the transition from closed-bolt mode to open-bolt mode and vice versa. One of the developed solutions involves using materials with a high coefficient of expansion [4]. The automatic transition from closed-bolt to open-bolt mode is achieved by placing material near the loading chamber, which expands when the barrel is heated to a critical temperature. The expansion leads to the pushing of a switching device. Another solution is manually selecting the semi-automatic and automatic modes [5] at temperatures below the critical value. Still, the advantage generated by using the weapon in closed-bolt mode needs to be ensured. The most known variant is presented in [6] on a new weapon. A rail was attached to the weapon, on which a thermal actuator was mounted, driven by the heat released near the loading chamber.

The disadvantages of the presented solutions are that they are suitable for new weapons, possibly existing ones, but only with substantial changes. At the same time, thermal actuators are used for the reference temperature, which makes it impossible to adjust it depending on the firing rate or the type of ammunition.

Contrary to the above, a self-adaptive firing mechanism has recently been developed that can be easily implemented within an existing assault rifle, to ensure operational safety. The self-adaptive mechanism ensures switching between open-bolt and close-bolt functioning, and vice versa, based on a threshold value of the weapon barrel temperature in the loading chamber.

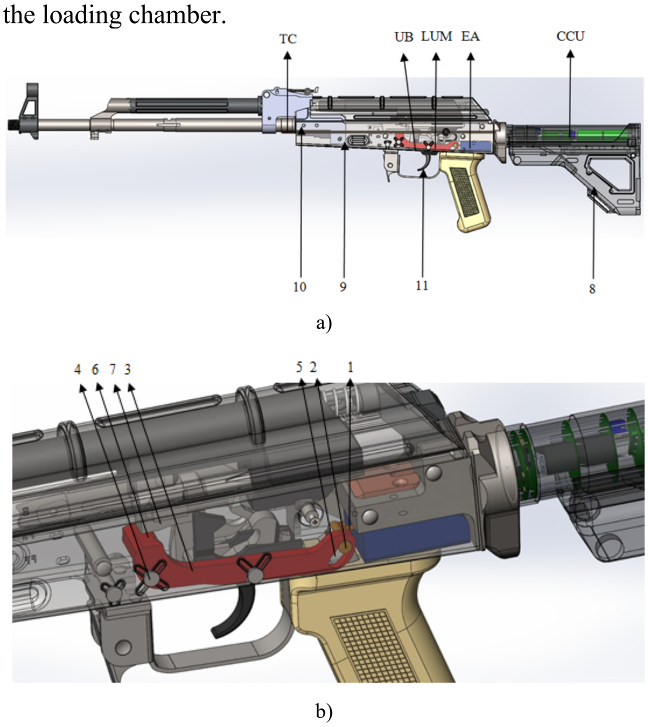


Fig. 1 – 3D CAD view of the assault rifle with adaptive mechanism: a) general view; b) overview of the mechanism box.

[1] ICPE, Department of Electrical Apparatus, Bucharest, Romania, E-mail: dragos.nicolescu@icpe.ro, alex.radulian@icpe.ro [2] Military Equipment and Technologies Research Agency, Bucharest, Romania, E-mail: prosca@acttm.ro, cpredoi@acttm.ro, amunteanu@acttm.ro

Figure 1 shows the structure of the assault rifle with an adaptive mechanism desired to be developed in Romania. The main elements of the rifle are CCU – command and control unit; EA – electromagnetic actuator; TC – thermocouple; LUM – lock-unlock mechanism; UB – unlock button; 1 – the rod of the electromagnet; 2 – translation rod; 2 – translation rod; 3 – lever; 4 – the fixed point of rotation of the lever; 5 – oval shaped hole; 6 – the contact surface; 7 – bolt carrier; 8 – buttstock; 9 – mechanism box; 10 – loading chamber; 11 – trigger.

This article presents the main component of the lock-unlock mechanism, which is the bistable permanent magnetic actuator and its electronic control system, as well as the working principle of the mechanism. Figure 2 shows the logic operation diagram of the self-adaptive mechanism.

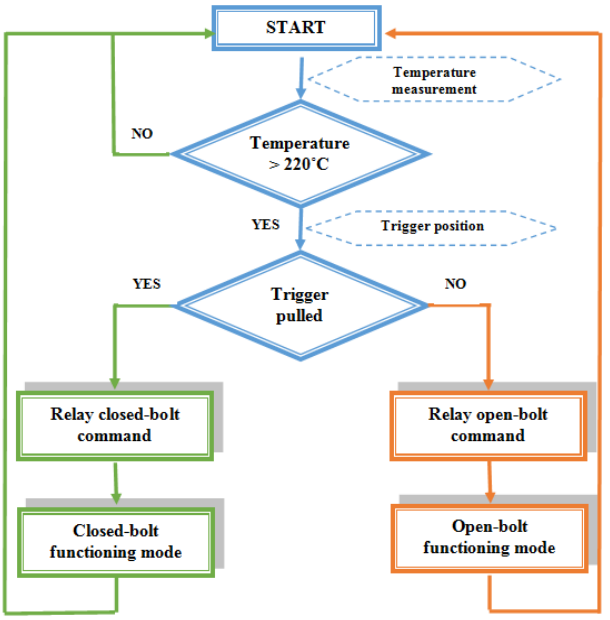


Fig. 2 – Logic operation block diagram of the self-adaptive firing mechanism.

The self-adaptive pulling mechanism consists of a thermocouple, an electronic control and command block, an electromagnet, a locking-unlocking mechanism, and an unlocking button.

The type K thermocouple is placed on the barrel next to the loading chamber, ensuring the temperature measurement using the electric voltage generated by the temperature difference between its two ends. The thermocouple is connected using metal wires to a converter within the electronic control and command block, which ensures the cold junction and digitizes the signal to read it in ˚C. The second junction - the reference or cold junction - is maintained at a constant temperature by placing the electronic control and command block in the rifle buttstock. This placement solution eliminates the errors generated by the placement in the lower receiver, where the temperature variation is much more significant.

The role of the electronic control and command block is to parse, with 100 Hz frequency, the analogic signals from the type K thermocouple to process it to ensure the transformation into ˚C and to compare those, in the first stage, with a reference value. Firing is performed until the setpoint is reached, with the weapon functioning in closed-bolt mode. When the temperature near the load chamber exceeds the setpoint, the electronic control and command block checks the position of the trigger using the signal received from the release button. If the trigger is pressed, the weapon is held or switched to closed-bolt mode, as appropriate, to allow firing. If the trigger is not pulled, the relay controlling the switching between closed-bolt - open-bolt mode is activated, which blocks the cartridge insertion phase in the camber and prevents the self-ignition phenomenon.

The electromagnet is the auto-adaptive mechanism kit part that ensures the positioning of the locking-unlocking mechanism in a locked or unlocked position, according to the received command from the electronic control and command block.

The article is organized as follows: the proposed bistable permanent magnetic actuator and its working principle are presented in section 2; the numerical computation and analysis, as well as the influence of electromagnetic parameters upon mechanical parameters, is presented in section 2.1; validation of the numerical results is presented in section 2.2; proposed electronic control system design and his working principle are presented in section 3; finally, conclusions and future work is presented in section 4.

2. PROPOSED ACTUATOR DESIGN AND WORKING PRINCIPLE

The new solution of the bistable permanent magnetic actuator has the following main components: fixed magnetic core, mobile magnetic core, permanent magnets, and excitation coils.

Permanent magnets produce the magnetic field necessary to maintain the mobile armature in one of the two holding positions. The excitation coils have the role of producing the magnetic field needed to move the mobile magnetic coil from one holding position to the other holding position.

The ferromagnetic circuit, consisting of fixed and mobile magnetic cores, leads the magnetic energy to the air gaps.

To switch the holding position of the mobile core, the excitation coils must produce a magnetic field in the opposite direction from the one produced by the magnets. Suppose the resultant magnetic has an opposite direction to that produced by the permanent magnets. In that case, it tends to minimize the air gap between the mobile and fixed ferromagnetic cores inside the coil [7]. The proposed bistable actuator's design is presented in Fig. 3.

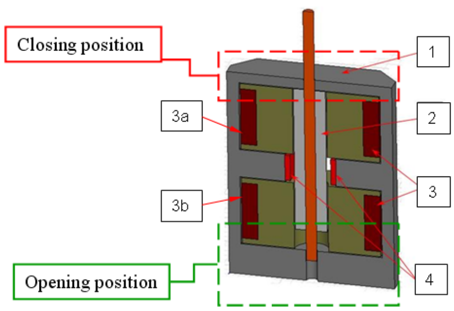


Fig. 3 – Design of the proposed bistable permanent magnetic actuator.

As shown in Fig. 3, the actuator has the following main components: 1 – fixed ferromagnetic core; 2 – mobile ferromagnetic core; 3 – excitation coils; 4 – Nd-Fe-B permanent magnets.

The bistable permanent magnetic actuator, linear type and supplied with direct current, must have the following specifications to perform its function properly:

- Minimum closing force (at maximum air gap): 2 N;
- Minimum holding force (at minimum air gap): 10 N;
- Stroke length: 4 mm;
- Minimum air gap: 0.1 mm;
- Rated coils voltage: 15 Vdc;
- Maximum impulse current: 4 A;
- Operating position: all positions.

2.1. NUMERICAL COMPUTATION OF THE PROPOSED ACTUATOR

The linear permanent magnet actuator was analyzed using the FEMM package by implementing a 2D model.

The force must be determined for every position along its trajectory to compute the work and speed gained by the mobile magnetic core. An LUA script was implemented in the FEMM package to move the mobile core along its path and compute the force for every position [8].

The problem described in FEMM is a planar one, in which the depth is 10 mm, and the frequency of the magnetic field and the frequency of the electric current in the coils is 0 Hz. The depth of the problem is equal to that of the ferromagnetic circuit.

The current in both coils is 4 Amps, and the number of turns for each coil is 250. Every coil produces a magnetomotive force of 1000 At. The ferromagnetic circuit is simulated using the B-H characteristic of pure iron. The coils are made of copper wire with a section of 0.07 mm^2 and a diameter of 0.3 mm. The permanent magnets used in the simulation are made of Nd-Fe-B alloy with high magnetic energy density (N50, respectively), as shown in Fig.4.

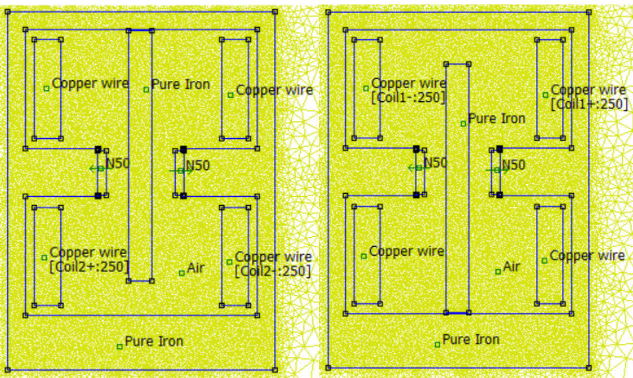


Fig. 4 – Numerical simulation of the bistable actuator in first holding position (right) and second holding position (left).

A Dirichlet condition was imposed on the domain's boundary, in which the magnetic vector potential **A** is considered zero [9]. The magnetic field produced by the coils and the permanent magnets is directed by the mobile armature and fixed magnetic core to both air gaps [10]. Only a single coil is used depending on the mobile magnetic core's position. As stated, the bistable actuator has a similar working principle with two opposing electromagnets and a typical mobile magnetic core. The magnetic field tends to flow through the path of maximum permeance, and as a result, the force produced by the bistable actuator decreases the air gap [11], as shown in Fig. 5 and 6.

The magnetic reluctance decreases by reducing the air gap between the mobile and fixed ferromagnetic circuits, corresponding to an increase in the magnetic flux. The increasing magnetic flux leads to an increase in the force developed by the actuator. As a result, the force has a maximum value for both holding positions of the bistable actuator when the air gap is minimum.

In both holding positions, the magnetic field produced by the permanent magnets is high enough, and the magnetic field produced by the coils is no longer needed to maintain the mobile component in that position [12]. In this case, the magnetic flux flows through the mobile and fixed magnetic core and the air gaps between these components, as shown in Fig. 7 and Fig. 8.

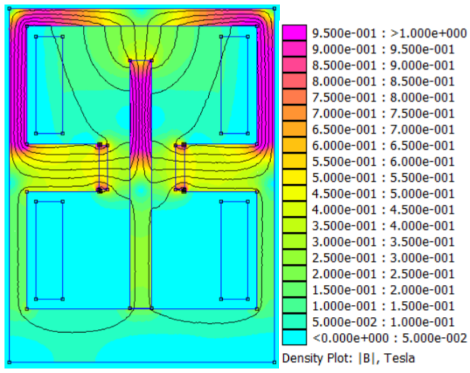


Fig. 5 – Magnetic flux inside the bistable actuator when the mobile core moves from the first holding position to the second holding position.

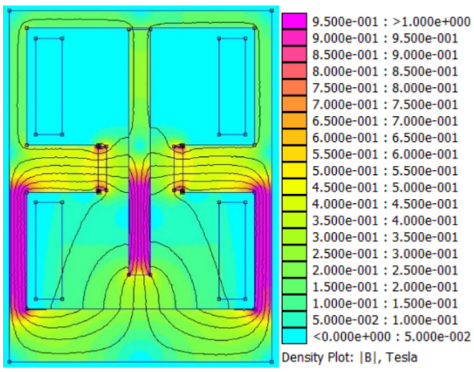


Fig. 6 – Magnetic flux inside the bistable actuator when the mobile core moves from the second to the first holding position.

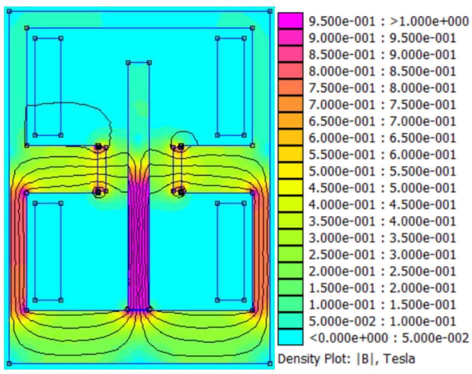


Fig. 7 – Magnetic flux produced by the permanent magnets inside the actuator when the mobile core is placed in the first holding position.

When the air gap has a minimum value, the current through the coils is zero. The magnetic flux needed to maintain the actuator in the closed position is produced by the permanent magnets without external power consumption, as shown in Fig. 7 and 8.

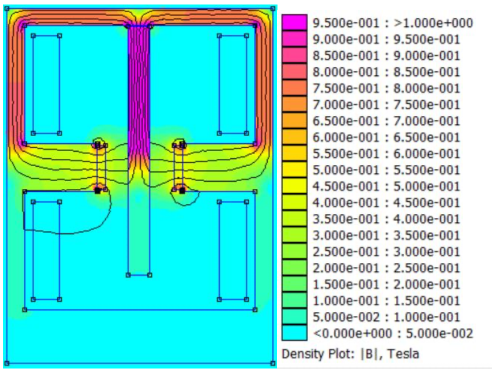


Fig. 8 – Magnetic flux produced by the permanent magnets inside the actuator when the mobile core is placed in the second holding position.

When the actuator is powered, the electric current is constant in excitation coils for each position of the mobile magnetic core along its path. The magnetic field produced by them is considered to have a constant value. By moving the magnetic core along its path, the reluctance decreases, and the magnetic flux increases considering the magnetomotive force constant. The increase of the magnetic flux also leads to an increase in the force produced by the bistable actuator, as shown in Fig 9 and 10.

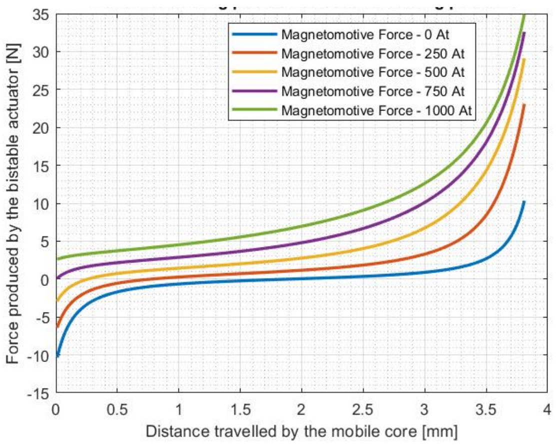


Fig. 9 – Force produced by the bistable actuator when the mobile core moves from the first to the second holding position.

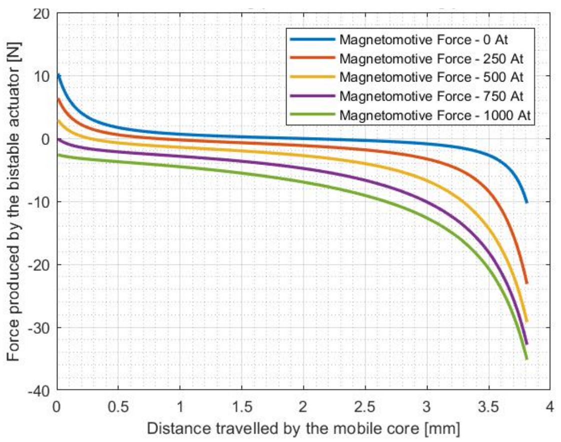


Fig. 10 – Force produced by the bistable actuator when the mobile core moves from the second to the first holding position.

As seen in the previous figure (Fig. 9), the force has a maximum positive value when moving from the first holding position to the second holding position and a maximum negative value when moving backward (Fig. 10). The physical interpretation is that the vector of the force is oriented from the first holding position to the second holding position in both cases.

If the current is low enough (which corresponds with a magnetomotive force from 0 to 500 At), the magnetic field produced by the coils is weaker than the magnetic field produced by the permanent magnets. The resultant magnetic field maintains the mobile core's original position.

If the electric current is high enough (which corresponds with a magnetomotive force from 750 to 1000 At), the magnetic field produced by the coils is stronger than the magnetic field produced by permanent magnets. Consequently, the resultant magnetic flux tends to close the air gap inside the coil.

As stated before, the air gap is minimum in both holding positions, and the magnetic flux needed to maintain the mobile core in these positions is produced by the permanent magnets. Depending on the energy density of the permanent magnets, the force produced by the bistable actuator in holding positions can be modified, as shown in Table 1. A higher energy density of the material used to produce the permanent magnets will lead to a higher force produced by the actuator [13].

Table 1

The computed force produced by the actuator in the closed position for different permanent magnets

Permanent magnet type	Mechanical force F [N] in first holding position	Mechanical force F [N] in second holding position
Nd-Fe-B N35	-7.22	7.21
Nd-Fe-B N40	-8.28	8.26
Nd-Fe-B N48	-9.33	9.31
Nd-Fe-B N55	-10.34	10.32

However, the energy density of the permanent magnet influences the electric current needed in the excitation coils. As the energy density of the permanent magnets increases, so does the electric current needed in the excitation coils to modify the holding position of the mobile core [14].

Regarding thermal stress, the magnets are located at a safe distance from the heat source (i.e., the gun barrel) so they are unaffected. At the same time, the excitation coils of the bistable actuator are powered for a short period, which leads to a negligible Joule effect so that the permanent magnets cannot reach Curie temperature.

2.2. VALIDATION OF THE NUMERICAL RESULTS

The experimental model of the bistable actuator was developed to validate the principle of the newly proposed mechanism. The overall picture of the actuator can be seen in Fig. 11.

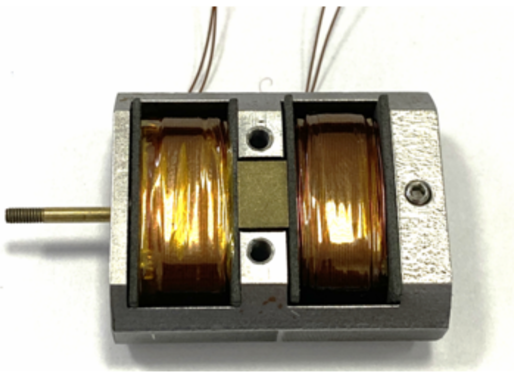
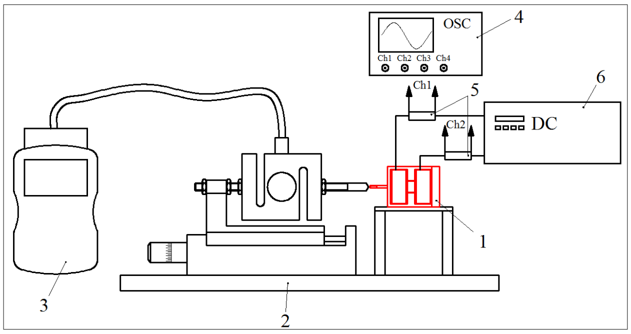


Fig. 11 – The prototype of the bistable actuator.

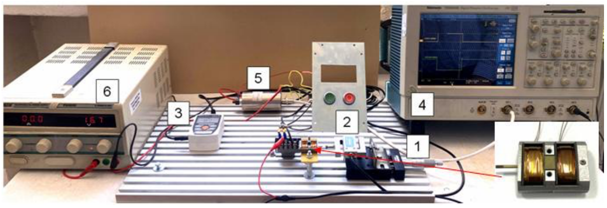
The actuator's dimensions are equal to those of the simulated model. The ferromagnetic core of the bistable actuator is made of AISI 1010 carbon steel coated with a layer of zinc to avoid corrosion. The magnetic properties of the magnetic steel used in the physical implementation of the experimental model are very similar to those of pure iron. Regarding this, the experimental model is accurate with the numerical model. AISI 1010 carbon steel was chosen considering the low manufacturing cost and low material processing time.

The permanent magnets have equal dimensions with those of the numerical model and are made of Nd-Fe-B 50, a high-density energy magnetic alloy.

The excitation coils are made of copper wire with a diameter of 0.3 mm and an area of 0.07 mm^2, according to the numerical computations. Each coil has 250 turns, and the current flow through these turns is 4 Amps. Considering this, the current density is approximately 56 A/mm^2, which is maintained in the coils at approximately 10 ms, and thus it will not lead to excessive heating.



a)



b)

Fig. 12 – Experimental setup for measuring the electromechanical parameters: a) block diagram; b) overview of the test circuit.

An experimental model was developed to validate the computer simulations and results, and the physical parameters were measured. As shown in Fig. 12, the actuator (2) was placed on aluminum support (1) to maintain the ferromagnetic core in a fixed position and move the mobile magnetic core along its trajectory. The force produced by the bistable actuator was measured using a digital force gauge (3). To move the mobile magnetic core along its path, the excitation coils were powered using a dc voltage source (6). The current generated by the voltage source was measured using a coaxial shunt (5), and the voltage drop on it was visualized with a digital oscilloscope (4).

According to the measurements from the experimental setup presented in Fig. 12, the mechanical and electrical parameters are shown in Table 2.

The parameters were measured when the bistable actuator was in two configurations, with and without permanent magnets. The resultant force when the mobile core is moving from one holding position to another is the sum of the force produced by the actuator without permanent magnets (12.5 N / -12.5 N) and the force produced by the actuator with permanent magnets when the mobile core is placed in a holding position (-10.3 N / 10.3 N).

Table 2

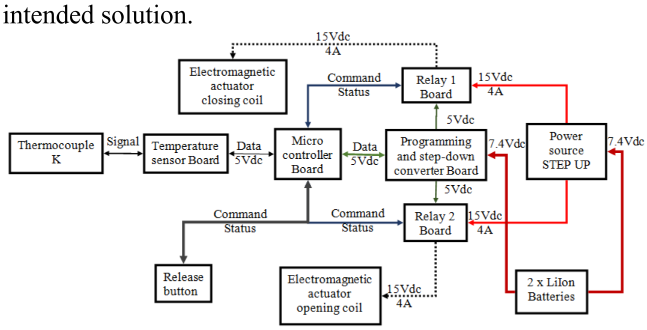
Proposed direct current actuator mechanical and electrical parameters.

Direct current actuator parameters	
U_{coil} [V] (Applied on each coil)	15 V
R_{coil} [Ω] (Individual) – experimental measurement	3.85 Ω
I [A] Current through coils – experimental measurement	3.9 A
$\Theta = N \cdot I$ [At] Magnetomotive force produced by a single coil – experimental measurement	975 At
$F_{holding}$ [N] Holding force (Measured) – with permanent magnets First / second holding position	-10,3 N / 10.3 N
$F_{holding}$ [N] Holding force (Computed) – with permanent magnets First / second holding position	-10.2 N / 10.2 N
F_{moving} [N] Force produced (Computed) – with permanent magnets in initial position When the mobile core is moving from first to second position / vice versa	2.6 N / -2.6 N
F_{moving} [N] Force produced (Measured) – without permanent magnets in the initial position When the mobile core is moving from first to the second position / vice versa	12 N / -12 N

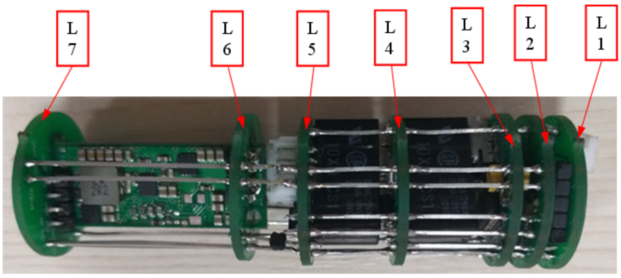
The measured resultant force in the initial position is 2.2 N / -2.2 N, and the computed resultant force is 2.6 N / -2.6 N (according to Fig. 9 and Fig. 10), which corresponds with the proper functioning of the actuator in the adaptive mechanism of the assault weapon.

3. PROPOSED ELECTRONIC CONTROL SYSTEM DESIGN AND WORKING PRINCIPLE

The major challenge in designing the electronic command and control block is the limited space in a cylindrical shape that must be installed, and the high acceleration produced by the firing weapon (approximately 1900 m/s^2). For this reason, an innovative solution was adopted by arranging the components on seven round plates, joined as a cylinder, by signal transmission and mechanical enhancing pins. Figure 13 presents each plate developed according to the military requirements of the intended solution.



a)



b)

Fig. 13 –Electronic control system: a) schematic circuit diagram; b) the developed model.

On the command-and-control block's first layer (L1), the temperature sensor is mounted to convert the analog signal from a thermocouple (type K) into digital data that the microprocessor can process.

On the second layer (L2), the processor is very close to the temperature sensor placed to ensure sampling speed and limit data loss due to a long transmit line or the alteration of the transmitted data.

On the third layer, there is the dc-dc step-down converter that ensures the microprocessor and sensor functioning voltage (5 V tolerance) and the USB-TTL conversion chip that ensures the possibility of programming the microprocessor with a computer. The fourth and fifth layer is represented by the relays that ensure electromagnet transition from one position to another, those capable of sustaining 25 Vdc at a peak consumption of 4 A. The following two layers represent the mechanical sustaining blocks of a dc-dc step-up converter that outputs 15 Vdc with 4 A peak for electromagnet functioning.

4. **CONCLUSIONS**

This paper presents the electronic components of an auto-adaptive firing mechanism recently designed that could be easily mounted on an existing AK-type assault rifle with an AR-style buttstock. This mechanism improves operational safety increase. The auto-adaptive mechanism is the switch between the closed-bolt state to the open-bolt state and vice-versa, induced by the overlap of the threshold value of the barrel temperature. Apart from military use, the innovative system containing the command-and-control electronic block, the actuator, and the embedded software application, could be used in any control system based on state change on threshold overlapping.

A novel solution for a bistable actuator was presented. Using a specially designed miniature electronic controller, the actuator's mobile core can be moved fast from one holding position to another. By implementing a new geometry with small dimensions and a proper choice and positioning of the permanent magnets, the bistable actuator can perform its function in the adaptive mechanism of the assault weapon. The small geometry dimensions and the holding force in both positions are the most important parameters of the bistable actuator. This paper presents the working principle of the actuator, as well as the mechanical and electrical parameters of this new device. In future work, the authors will improve the existing device's performance by increasing its mechanical parameters.

ACKNOWLEDGEMENT

This work was supported by a grant of the Ministry of Research, Innovation and Digitization, CNCS/CCCDI – UEFISCDI, project number PN-III-P2-2.1-PED-2019-1981, within PNCDI III.

Received on 26 May 2022

REFERENCES

1. H. Isık, F. Göktas, *Cook-off analysis of a propellant in a 7.62 mm barrel by experimental and numerical methods*, Applied Thermal Engineering, Elsevier (2016).
2. A. Rotariu L. Matache, F. Bucur, M Cirmaci-Matei, M. Mărmureanu, E. Trană, *Implementation of a Gumbel distribution function in interior ballistic calculations for deterred propellants*, UPB Scientific Bulletin., Series B, **82**, *1* (2020).
3. AC/225(DSS)D(2018)0006, *Evaluation procedures for future NATO small arms weapon systems (NATO D/14 Handbook)*, Land Capability Group Dismounted Soldier System (LCGDSS), NATO Army Armaments Group (NAAG) (November 2018).
4. R.D. Plumer, S. Barbara, H. Shrout, *Manual open- and closed-bolt weapon fire control with automatic heat responsive override*, Patent Ser. No. 8449826, U.S. / 09.11. 1971.
5. ***https://patentimages.storage.googleapis.com/80/c6/54/858b 414c8e d074/US7806039.pdf
6. ***https://defensereview.com/fn-hamr-heat-adaptive-modular-rifle-introduced -at-ausa-2010-fn-scar-meets-iar-infantry-automatic-rifle-fn-mk16-scar-l-goes-open-bolt-for-full-auto/
7. D. Nicolescu, A. Radulian, M. Maricaru, S. Prică, *High force heavy duty direct current actuator*, Revue Roumaine Des Sciences Techniques, Serie Électrotechnique et Énergétique, **66**, *1*, pp. 139–143, Bucarest (2021).
8. D. Meeker, *Finite Element Method Magnetics – Version 3.1 – FEMM 4.2 Manual* (2002).
9. D. Meeker, *Finite Element Method Magnetics – Version 4.2 – User's Manual*, 2018.
10. A. Radulian, M. Maricaru, I.V. Nemoianu, R. Crețu, *New solution of linear dc actuator with additional permanent magnets: working principle, design, and testing*, Revue Roumaine Des Sciences Techniques, Serie Électrotechnique et Énergétique, **62**, *1*, pp. 3-7, Bucarest (2017).
11 A. Radulian, N. Mocioi, *Numerical Modelling of an Electromagnetic Actuator for Vacuum Contactors*, International Conference and Exposition on Electrical and Power Engineering – EPE 2014, IEEE, Iasi, Romania, pp. 204 – 209 (16-18 Oct. 2014).
12. A.M. Chaly, O. I. Chervinskyi, V.N. Poluyanov, *New generation of vacuum circuit breakers with monostable magnetic actuator*, 18th International Conference on Electricity Distribution, Turin (6-9 June 2005).
13. Y. Yoo, D.K. Kim, B. Kwon, *Optimal design of a permanent magnetic actuator for vacuum circuit breaker using FEM*, Journal of Electrical Engineering & Technology, **1**, *1*, pp. 92–97 (2006).
14. A. Radulian, *Electromagnet in hybrid construction with excitation coil and permanent magnet*, Patent No. RO 129746 / 29.11.2019.