Ivo DOLEŽEL*
David PÁNEK**
Bohuš ULRYCH**

STATIC CHARACTERISTICS OF PULSED ACTUATOR WITH PLUNGER CONSISTING OF CARBON STEEL AND PERMANENT MAGNET

A novel type of pulsed electromagnetic actuator is presented and modeled. Its plunger consists of two separate (but mutually connected) cylindrical parts made of classical magnetic material and permanent magnet, respectively, and its motion is controlled by short current pulses of the defined amplitude. The paper starts with the definition of the technical problem and formulation of its mathematical model. This model is then solved numerically and the whole methodology is illustrated by a typical example. It is shown that unlike the classical devices the above actuator exhibits high holding force and low consumption of energy.

1. INTRODUCTION

Electromagnetic actuators (see, for example [1], [2] and [3]) represent important elements of numerous mechatronic systems. They are used in many industrial domains such as machinery, transport, chemical and food technologies, and also in robotic systems, for instance in biomedicine engineering. Mostly they are used for converting electric energy into mechanical forces or movement.

One of disadvantages of classical electromagnetic actuators is the fact that they require delivery of electric current during full time of their active operation. A longer time of operation, however, may result in a high consumption of electric energy and, consequently, in undesirable overheating of the system.

This disadvantage can be suppressed by the use of combined electromagnetic actuators, where the transient switching-on and switching-off processes are controlled by short electric pulses, but the steady-state switch-on regime is only realized by a permanent magnet, i.e., without delivery of any external energy to the system and its consequent overheating. One actuator of this type is analyzed in this paper. First, its arrangement is described together with the material properties of its individual structural parts. Then, its mathematical and computer models are

---

* Czech Technical University in Prague.
**University of West Bohemia in Pilsen.

given. Their solution allows predicting of its operation characteristics. The crucial point of the paper is presentation and discussion of the above characteristics obtained for one particular version of such an actuator. With respect to the possible extent of the paper, attention is only paid to the static situation in the actuator (i.e., switch-on and switch-off regimes), because users are mainly interested in the total forces generated by the device than in the times of the switching-on and switching-off processes.

2. FORMULATION OF TECHNICAL PROBLEM

2.1 Arrangement of the actuator

The structural arrangement of the combined actuator in both operation (switch-on and switch-off) regimes is shown in Fig. 1.

Fig. 1. Arrangement of the considered actuator, dimensions given in millimeters (switch-off left, switch-on right). **1**–permanent magnet, **2**–ferromagnetic element, **3**–nonmagnetic distance shell, **4**–coil controlling element **2**, **5**–coil controlling magnet **1**, **6**–ferromagnetic shell of the actuator with lid, **7**–nonmagnetic slotted leading shell, **8**, **9**–dilatation spacers, **10**–nonmagnetic distance spacer, **11**–nonmagnetic draw-bar, **12**–nonmagnetic pipe, **13**–connecting nut

The basic part of this axisymmetric actuator is its plunger that consists of a permanent magnet **1** and ferromagnetic element **2**. These two parts are connected mechanically by a nonmagnetic drag-bar **11** and equipped with other nonmagnetic elements **3**, **12** and **13**. The plunger is placed inside the ferromagnetic shell **6** of the actuator and its axial movement is there fixed by the nonmagnetic slotted leading shell **7**. Internal axial slotting of this shell eliminates the hydraulic resistances during the movement of the plunger inside shell **6**.

The movement of the plunger in the direction z_{on} (transition from the switch-off regime into the switch-on regime) or z_{off} (vice versa) is controlled by magnetic fields generated by field coils $C_1 \approx 4$ and $C_2 \approx 5$ carrying pulsed currents I_{on} (switching on) or I_{off} (switching off). More details will be given in subsections **2.2** and **5.2**.

The above coils are fixed by nonmagnetic distance spacers **8**, **9** and **10**. The drag-bar **11** transfers the generated force out of the actuator and the nut **13** on it defines the starting position of the plunger.

2.2 Operation regimes of the actuator

The operation regimes of the actuator are two: on and off. They are realized in the following manners:
- When switching on the switched-off actuator (see Fig. 1 left), a current pulse I_{on} is delivered to field coil $C_1 \approx 4$. Now the ferromagnetic part **2** of the plunger starts to be pulled into it by force F_{m2on} (the pulsed current I_{on} should be switched off approximately at the moment when the ferromagnetic part is completely in the coil). As the connected permanent magnet **1** approaches the ferromagnetic lid of the shell **6**, it is attracted to it and, finally, the plunger gets into the position depicted in Fig. 1, right part.
- When switching off the switched-on actuator, we have to deliver an appropriately oriented pulse I_{off} to the field coil $C_2 \approx 5$ in order to demagnetize the permanent magnet **1**, which leads to a strong decrease of the force attracting it to the lid. At the same time, the same pulsed current I_{off} is also delivered to the field coil $C_1 \approx 4$. The ferromagnetic part of the plunger is again pulled into this field coil (now by force F_{m2off}). In this way, the actuator is switched off.

2.3 Materials of particular elements

The list of materials used for building of the actuator is given in Table 1. All these materials are available in practically every laboratory.

Table 1. Materials used for the actuator (see Fig. 1)

item	element	material	μ_r (-)
1	permanent magnet	Koerock 420 [4]	Fig. 2
2	ferromagnetic core	steel 12 040	Fig. 3
3	distance shell	nylon	1
4	coil C_1	Cu wire, Ø 1 mm	1
5	coil C_2	Cu wire, Ø 1 mm	1
6	shell	steel 12 040	Fig. 3
7	leading shell	nylon	1
8,9	dilatation spacers	brass	1
10	distance spacer	brass	1
11	connecting draw-bar	brass	1
12	distance pipe	brass	1
13	connecting nut	brass	1

The only exception is perhaps the element **1**, manufactured of a ferrite permanent magnet Koerock 420 [4]. Its demagnetization characteristic is depicted in Fig. 2. The magnet exhibits a very low electric conductivity in order to avoid generation of eddy currents in it during the processes of switching on and switching off, when the field coils carry currents I_{on} and I_{off}, respectively.

During the repeated demagnetization and magnetization of the permanent magnet it is only possible to make use of the straight part of its demagnetization characteristic, because only in this case the corresponding secondary hysteresis loops transform into straight lines, i.e., the magnet is not deteriorated energetically. The acceptable working interval of magnet Koerock 420 ranges (see Fig. 2, the dashed line) within the interval $B \in (0.178, 0.678)$ T.

The ferromagnetic shell **6** of the actuator and ferromagnetic element **2** of the plunger are manufactured of material with the lowest possible magnetic resistance that must also be cheap and easily machinable. We selected a low-alloyed carbon steel CSN 12 040 whose magnetization characteristic is shown in Fig. 3.

3. MATHEMATICAL MODEL

The general equation describing the distribution of electromagnetic field in the actuator reads [5]

$$\mathrm{curl}\left(\frac{1}{\mu}\mathrm{curl}\,A - H_c\right) = J \, , \tag{1}$$

where A denotes the magnetic vector potential, symbol μ stands for magnetic permeability, J is the field current density (only in the field coils) and H_c denotes the coercive force (only in the domain of permanent magnets). In the cylindrical coordinates both field current density J and magnetic vector potential A have only one nonzero component J_φ and A_φ in the circumferential direction.
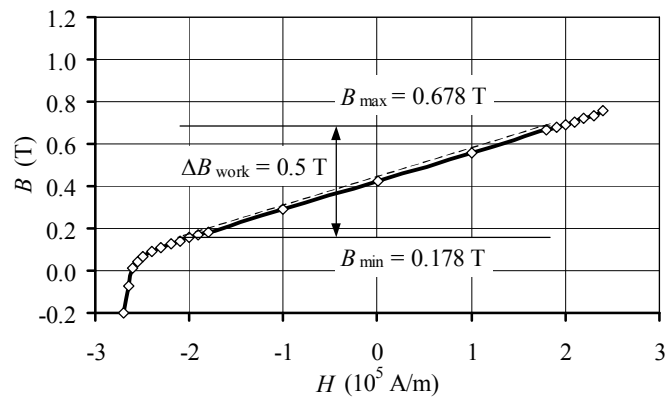

Fig. 2. Demagnetization curve and operation interval of magnet Koerock 420 [4]
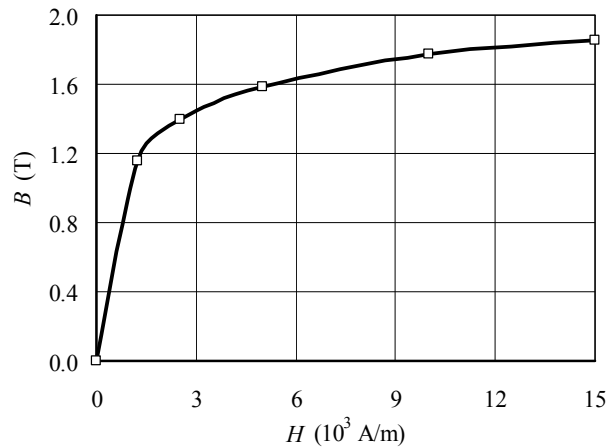
Fig. 3. Nonlinear magnetization $B(H)$ characteristic of carbon steel CSN 12 040

The boundary conditions along the axis of the arrangement and along the boundary of the investigated domain (axial cut of the device) are of the Dirichlet type ($A_\varphi = 0$). This artificial boundary may be (with a negligible error) represented by the external surface of the actuator.

The general vector of the magnetic force $\boldsymbol{F}_{\mathrm{m}}$ acting on ferromagnetic elements of the actuator is given [6] by the integral

$$\boldsymbol{F}_{\mathrm{m}} = \frac{1}{2} \oiint_S \big(\boldsymbol{H}(\boldsymbol{n} \cdot \boldsymbol{B}) + \boldsymbol{B}(\boldsymbol{n} \cdot \boldsymbol{H}) - \boldsymbol{n}(\boldsymbol{H} \cdot \boldsymbol{B}) \big) \, \mathrm{d}S, \qquad (2)$$

where $\boldsymbol{B}$ and $\boldsymbol{H}$ are the field vector, $\boldsymbol{n}$ denotes the unit outward normal and the integration is carried out along the whole surface S of both ferromagnetic parts. The force $\boldsymbol{F}_{\mathrm{m}}$ is formed by the following partial forces (all of them are supposed to have only one component in the axial direction):

- F_{m1} - force acting (see Fig. 1) on the permanent magnet **1** in the direction z_{on} during both processes of switching on and switching off. The permanent magnet is always attracted to the flat lid of the ferromagnetic shell **6**.

- F_{m2on} - force acting on the ferromagnetic element **2** in the direction z_{on} (see Fig. 1) in the process of switching on (the element is pulled into the field coil $\mathrm{C}_1 \approx \mathbf{4}$ regardless the orientation of the pulsed current I_{on} provided it is switched off in time).

- F_{m2off} - force acting on the ferromagnetic element **2** in the direction z_{off} (see Fig. 1) in the process of switching off (the element is pulled into the field coil $\mathrm{C}_1 \approx \mathbf{4}$ regardless the orientation of the pulsed current I_{off} provided it is switched off in time).

4. COMPUTER MODEL

The mathematical model of the actuator (equations (1) and (2) was solved as a nonlinear 2D problem in the cylindrical coordinates (r, z) using the FEM-based code QuickField 6 [6]. The goal of the computations was to obtain (as fast as possible) all necessary information, particularly the force conditions in the actuator in both operation regimes (switching on and switching off).

Carefully was checked the convergence of the solution on the density of the discretization mesh. The relevant data providing a good idea about the accuracy of the solution are listed in Table 2.

5. RESULTS AND THEIR DISCUSSION

The computer model described in the previous section allowed obtaining all required results, mainly of the quantitative character. One of the main results is that in the process of switching off both current pulses $I_{\mathrm{off}}(\mathrm{C}_1)$ and $I_{\mathrm{off}}(\mathrm{C}_2)$ must be oriented equally, and must appropriately demagnetize the permanent magnet **1**. Other results follow.

Table 2. Convergence of the results ($I_{on} = 0$, $z_{on} = 40$ mm)

parameters of mesh		results	
number of nodes (-)	spacing (mm)	$B_{1,avrg}$ (T)	F_{m1on} (N)
9254	1.0/2.0/10.0	0.357	52.067
35839	0.5/1.0/5.0	0.357	53.731
81489	0.25/0.5/2.5	0.357	54.887
251147	0.125/0.25/1.25	0.357	55.227

Figure 4 shows the influence of the demagnetization current $I_{off}(C_2)$ on the situation in the permanent magnet **1**. As the average value $B_{1,avrg}$ of magnetic flux density in it decreases, there also decreases the force F_{m1} acting in the direction z_{on}. But as we are limited by the straight part of the demagnetization characteristic (see Fig. 2), the maximum acceptable value of the demagnetization current $I_{off}(C_2) = -16$ A for $z_{off} = 0$ mm. For this value $B_{1,avrg} = 0.183$ T and $F_{m1} \approx 20$ N. And this force must be exceeded by the force F_{m2off}, by which the ferromagnetic element **2** is (using the same current $I_{off}(C_1) = -16$ A) pulled into field coil C_1.
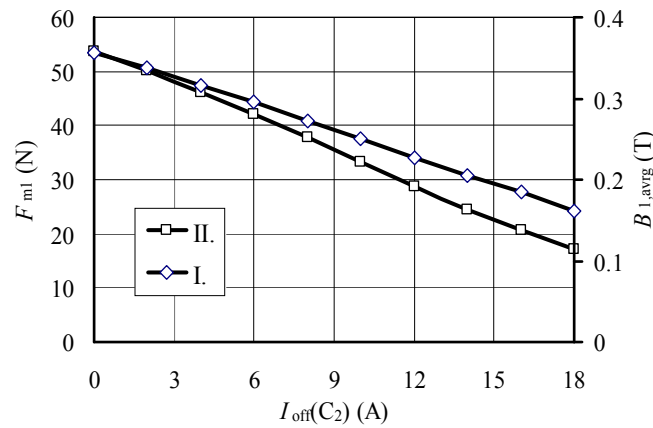

Fig. 4. Dependence of two important characteristics on current $I_{off}(C_2)$: I– F_{m1}, II– $B_{1,avrg}$

Figure 5 shows the static characteristic of the permanent magnet **1** in the switching-on regime, i.e., the dependence of force F_{m1} acting on the magnet on its

position z_{on} in the actuator ($z_{on} \in \langle 0, 40 \rangle$ mm). Another depicted curve is the corresponding average magnetic flux density $B_{1,avrg}$ in the magnet. It is obvious that at the beginning of the process the force F_{m1} is very low and starts increasing only at a half of its way to the ferromagnetic lid. There it reaches its maximum value $F_{m1,max} \approx 54$ N. Thus, this is the maximum attractive force that can be generated without external source of energy. On the other hand, the average value $B_{1,avrg}$ of magnetic flux density in permanent magnet **1** is practically independent of the position z_{on}; it slightly increases only when the magnet approaches the lid. This is caused by a mild homogenization of magnetic field in this position – a part of force lines entry practically perpendicularly the lid.
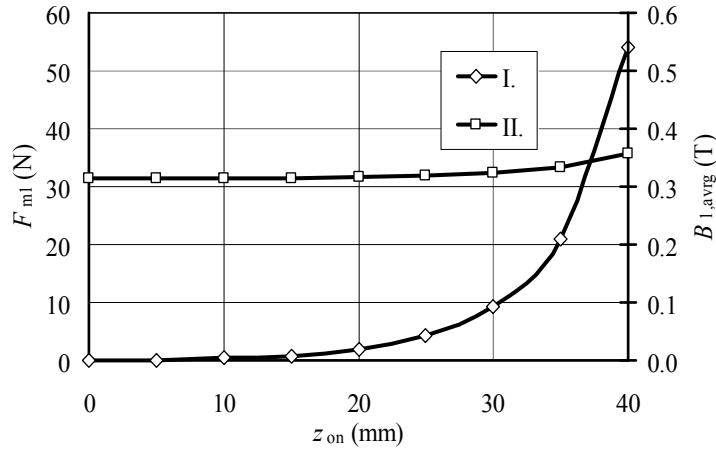

Fig. 5. Static characteristic of the permanent magnet **1** in the switching-on regime
$I_{on}(C_1) = I_{on}(C_2) = 0$ (I– F_{m1} , II– $B_{1,avrg}$)

Figure 6 depicts the resultant static characteristic of the whole actuator within the range $z_{on} \in \langle 0, 20 \rangle$ mm. This range corresponds to the position of ferromagnetic part **2** of the plunger in field coil $C_1 \approx \mathbf{4}$, where we obtain $F_{mres\,on} = F_{m1} + F_{m2on}$ (both forces F_{m1} and F_{m2on} being dependent on z_{on} and pulsed current I_{on}. In the remaining interval $z_{on} \in \langle 20, 40 \rangle$ mm there holds $F_{mres\,on} = F_{m1}$ where F_{m1} only depends on z_{on} – see Fig. 5. Here the pulsed current I_{on} has to be switched off, otherwise the ferromagnetic part **2** would be pulled again into the coil $C_1 \approx \mathbf{4}$. The local maximum in line II visible near the point $z_{on} = 2$ mm shows the place of the highest force F_{m2on} acting on the ferromagnetic part **2** of the plunger.
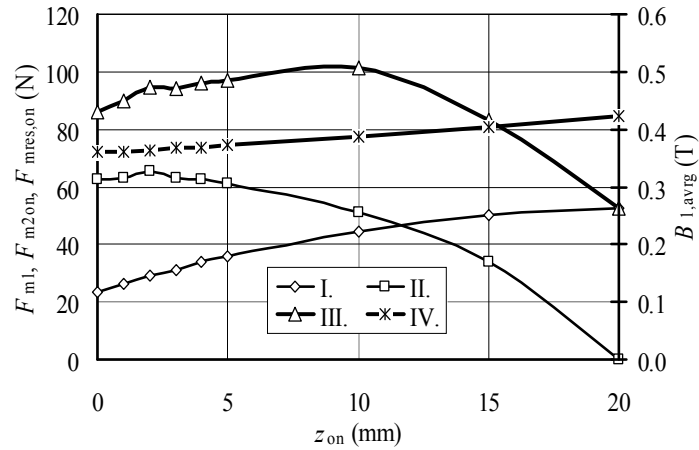
Fig. 6. Static characteristic of the whole actuator in the switching-on regime $I_{on}(C_1) = I_{on}(C_2) = 16$ A
(I– F_{m1} , II– F_{m2on} , III– $F_{mres\,on}$, IV– $B_{1,avrg}$)

Finally, Fig. 7 contains the resultant switch-off characteristic of the whole device, again within the range $z_{off} \in \langle 0, 20 \rangle$ mm corresponding to the position of ferromagnetic part **2** of the plunger inside the field coil C_1. Here the resultant force is $F_{mres\,off} = F_{m1} + F_{m2off}$. Now both forces on the right-hand side depend on z_{off} and pulsed current I_{off}. In the remaining interval $z_{off} \in \langle 20, 40 \rangle$ mm there holds $F_{mres\,off} = F_{m1}$ where F_{m1} only depends on $z_{off} = 40 - z_{on}$. Here the pulsed current I_{off} has to be switched off. Further movement of the plunger is realized by inertia or by means of a draw spring (which, however, is not present in Fig. 1).
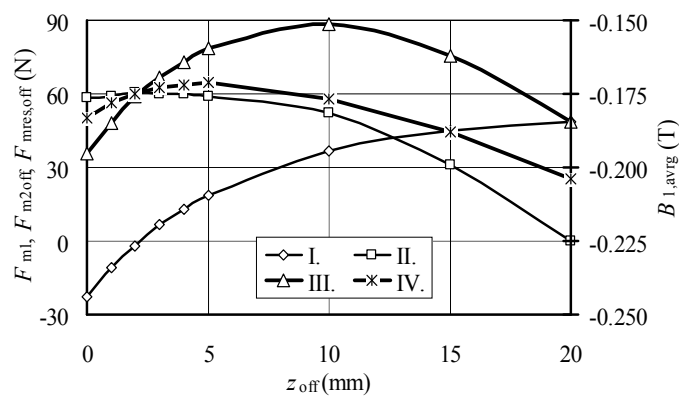

Fig. 7. Static characteristic of the whole actuator in the switching-off regime
$I_{on}(C_1) = I_{on}(C_2) = -16$ A (I– F_{m1} , II– F_{m2off} , III– $F_{mres\,off}$, IV– $B_{1,avrg}$)

At this place, it is necessary to remark that the permanent magnet is influenced by forces produced by both ferromagnetic material and external magnetic field in its neighborhood. That is why the force F_{m1} changes its sign within the interval $z_{off} \in \langle 0, 20 \rangle$ mm, see line I in Fig. 7. At the beginning, for small values of z_{off} the permanent magnet **1** is attracted to the lid of the ferromagnetic shell **6**. With respect to the direction of vector z_{off} (see the right part of Fig. 1) the force F_{m1} is oriented negatively. But for higher values of z_{off} the permanent magnet **1** is more strongly attracted to the field generated by the field coil $C_1 \approx \mathbf{4}$ that carries pulsed current I_{off}. Now, the force F_{m1} is positive with respect to vector z_{off}. At the moment when the permanent magnet reaches $z_{off} = 20$ mm and the pulsed current I_{off} vanishes, the force F_{m1} drops from the value about 50 N (Fig. 7, line I) to value -2 N oriented against z_{off}, see Fig. 5. This means that the permanent magnet is again attracted to the lid of ferromagnetic shell **6**, but due to a longer distance this force is already small. In case of still growing $z_{off} = 40 - z_{on}$, the force $F_{m1} \to 0$.

6. CONCLUSION

The proposed actuator is able to realize the basic steady-states (switch-on and switch-off regimes) without any delivery of external energy. The transients (processes of switching on and switching off) are controlled by means of short external pulsed currents. These can be obtained, for example, using appropriate electric circuits containing sufficiently strong capacitors. Due to these advantages, the actuator could be very prospective in a number of technical applications.

ACKNOWLEDGMENT

REFERENCES

[1]   Janocha H., Actuators, Basics & Applications – Springer, New York, 2004.
[2]   Brauer J. R., Magnetic Actuators and Sensors – Wiley, New York, 2006.
[3]   Bush-Vishniac I. J., Electromagnetic Sensors and Actuators – Springer, Berlin, 1998.
[4]   Koerox magnets, http://www.kolektor.si/resources/files/doc/magneti/KoeroxI.pdf.
[5]   Furlani E. P., Permanent Magnet and Electromechanical Devices – Academic Press, New York, 2001.
[6]   QuickField, www.quickfield.com.