Pulsed Actuator with Combined Plunger Made of Carbon Steel and Permanent Magnet

Ivo Doležel*, David Pánek, and Bohuš Ulrych****

Abstract – A special pulsed electromagnetic actuator is presented whose plunger consists of two parts made of carbon steel and permanent magnet, respectively. The actuator exhibits a high holding force and small consumption of energy. The movement of the plunger is controlled by short current pulses. The static characteristics and other operation properties of the device are modeled numerically.

Keywords: Pulsed actuator, Permanent magnet, Combined magnetic circuit, Demagnetization characteristic, Finite element method.

1. Introduction

Electromagnetic actuators (see, for example [1], [2] and [3]) represent important elements of various mechatronic systems. They are used in a wide spectrum of industrial branches such as machinery, transport, chemical and food technologies, and also in numerous robotic systems, for instance in biomedicine engineering.

One of disadvantages of classical electromagnetic actuators is the fact that they require delivery of electric energy (electric current) for the full time of their active operation. A long operation time may result in a high consumption of electric energy and, consequently, in local overheating of the system.

This disadvantage is removed by the use of combined electromagnetic actuators whose switching on and off processes are initiated by short electric pulses, but whose arbitrarily long operation regimes are secured by a permanent magnet, i.e., without delivery of any external energy and without any danger of overheating. One actuator of this type is discussed in this paper. First, its arrangement is described together with material properties of its structural parts. Then, its mathematical and computer models are presented. They allow 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 extent of the paper, attention is only paid to the static situation in the actuator, because users are mainly interested in the total forces generated by the device than in the time of the switch-on or switch-off process.

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2. Formulation of the Problem

2.1 Structural Arrangement of the Actuator

The arrangement of the considered combined actuator for the switch-on and switch-off operation regimes is shown in Fig. 1.

The basic parts of this actuator (whose structure may practically be considered axisymmetric) are the plunger consisting of a permanent magnet 1 and ferromagnetic element 2. These two parts are connected mechanically by a nonmagnetic drag-bar 11 and equipped with nonmagnetic elements 3, 12 and 13. The plunger is placed inside the ferromagnetic shell 6 and its axial movement is fixed by a nonmagnetic slotted leading shell 7. The axial slotting of shell 6 eliminates the hydraulic resistances during the movement of the plunger inside it.

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 coils $C_1 \approx \mathbf{4}$ and $C_2 \approx \mathbf{5}$ carrying pulsed currents I_{on} (switching on) or I_{off} (switching off). The above coils are fixed by nonmagnetic distance spacers 8, 9 and 10. The drag-bar 11 transfers the generated force outside the actuator.

2.2 Working Regime of the Actuator

The operation regimes of the actuator are realized in the f ollowing manners:

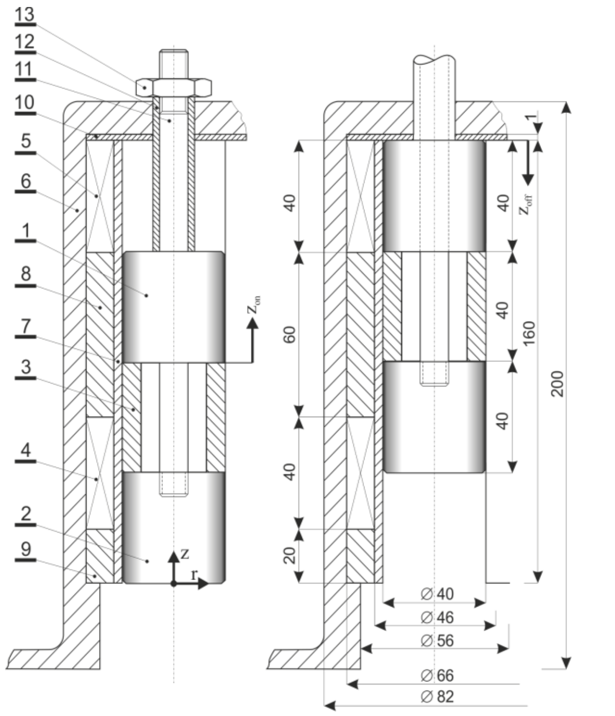

Fig. 1. Arrangement of the considered actuator, dimensions given in millimeters (switch-off left, switch-on right) 1–permanent magnet, **2**–ferromagnetic element,**3**–nonmagnetic distance shell, **4**–coil controlling element **2**, **5**–coil controlling magnet **1**, **6**–ferromagnetic shell of 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

- When switching on the switched-off actuator (Fig. 1 left), a current pulse I_{on} is delivered to field coil $C_1 \approx \mathbf{4}$. Now the ferromagnetic part 2 of the plunger starts to be pulled into it by force $\boldsymbol{F}_{m2on}$ (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 $C_2 \approx \mathbf{5}$ 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 pulsed current I_{off} is also delivered to the field coil $C_1 \approx \mathbf{4}$. The ferromagnetic part of the plunger is again pulled into this field coil (now by force $\boldsymbol{F}_{m2off}$). In this way, the actuator is switched off.

2.3 Materials Used for the Actuator

The list of materials used for building of the actuator is given in Tab. 1.

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

item	element	material	μ_r (-)
1	permanent magnet	Koerox 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 demagnetization characteristic of ferrite permanent magnet Koerox 420 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 initiated by pulsed currents I_{on} and I_{off}.

During its repeated demagnetization and magnetization 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 continues keeping its properties. The acceptable working interval ranges (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 made of 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], [6]

$$\operatorname{curl}\left(\frac{1}{\mu}\operatorname{curl}\boldsymbol{A}-\boldsymbol{H}_\mathrm{c}\right)=\boldsymbol{J}\,, \qquad (1)$$

where $\boldsymbol{A}$ denotes the magnetic vector potential, symbol μ stands for magnetic permeability, $\boldsymbol{J}$ is the field curren t density (only in the field coils) and $\boldsymbol{H}_\mathrm{c}$ denotes the coerc ive force (only in the domain of permanent magnets).

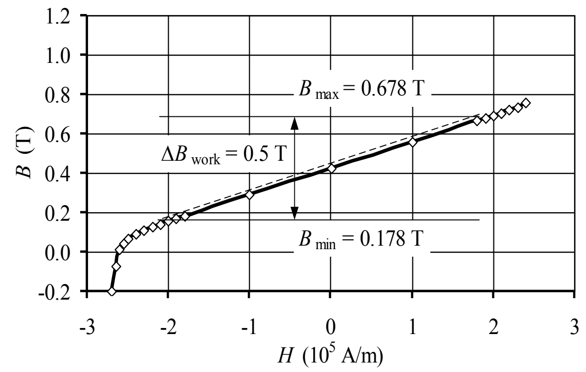

Fig. 2. Demagnetization curve and operation interval of magnet Koerox 420 [4]

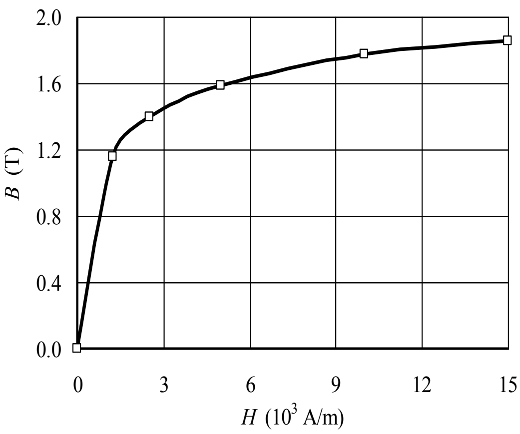

Fig. 3. Nonlinear magnetization $B(H)$ characteristic carbon steel CSN 12 040

The boundary conditions along the axis of the arrangement and along the boundary of the investigated domain are of the Dirichlet type ($\boldsymbol{A}=\boldsymbol{0}$). 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

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

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 more or less 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 device (equations (1) and (2) was solved as a nonlinear 2D problem in the cylindrical coordinates (r,z) using the FEM-based code QuickField 6 [7]. 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 about the accuracy of the solution are listed in Tab. 2.

For illustration, Fig. 4 shows the distribution of magnetic fields in the permanent magnet **1** in the regime of switching off for position $z_\mathrm{off}=0$ for various values of current I_off. All these figures provide a good qualitative idea about the situation in the magnet. Symbol $B_\mathrm{1,avrg}$ denotes the average value of magnetic flux density in the magnet 1.

Table. 2: Convergence of the results

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

5. Results and their Discussion

The computer model allowed obtaining all required results of both qualitative and quantitative characters.

5.1 Qualitative Information

This information directly follows from the analysis of ma gnetic fields in the device. For example:

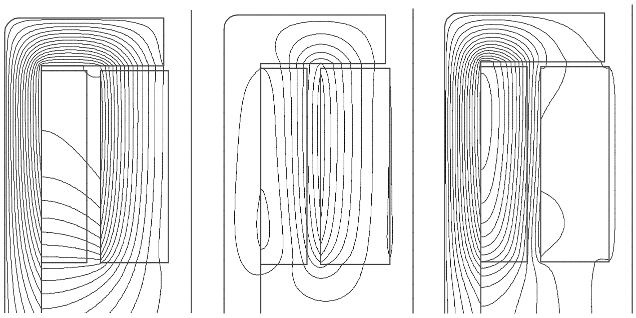

Fig. 4. Magnetic field (force lines) in the permanent magnet at the beginning of the switching-off process

Left: $z_{\mathrm{off}} = 0$, $I_{\mathrm{off}}(\mathrm{C}_2) = 0\,\mathrm{A}$, $B_{1,\mathrm{avrg}} = 0.357\,\mathrm{T}$

Middle: $z_{\mathrm{off}} = 0$, $I_{\mathrm{off}}(\mathrm{C}_2) = 16\,\mathrm{A}$, $B_{1,\mathrm{avrg}} = 0.183\,\mathrm{T}$

Right: $z_{\mathrm{off}} = 0$, $I_{\mathrm{off}}(\mathrm{C}_2) = -27.5\,\mathrm{A}$, $B_{1,\mathrm{avrg}} = -0.005\,\mathrm{T}$

- By comparing of particular fields in Fig. 4 we can see the influence of the switching-off current $I_{\mathrm{off}}(\mathrm{C}_2)$ producing a field that is oppositely oriented with respect to the original field of the permanent magnet **1**. If this current is not too high (middle parts of Fig. 4), magnetic field in the permanent magnet **1** is reduced, but its character remains the same (the force lines at the same scaling are not so dense, but their appearance is similar as in Fig. 4, left part). In this case we can speak about the possibility of a reversible change of magnetic field in the magnet, when the changes are realized in the straight part of its demagnetization characteristic (see Fig. 2). On the other hand, Fig. 4, right part, shows a full degradation of magnetic field in the magnet produced by high field current $I_{\mathrm{off}}(\mathrm{C}_2)$. The force lines in it practically vanish. Now the change becomes irreversible and by a mere reduction of this current the permanent magnet cannot return to the original state.
- Figure 5 shows the influence of the mutual orientation of the switching-off pulsed current $I_{\mathrm{off}}(\mathrm{C}_1)$ generating the switching-off force $\boldsymbol{F}_{\mathrm{m1off}}$ and switching-off demagnetizing pulsed current $I_{\mathrm{off}}(\mathrm{C}_2)$ on the resultant demagnetization of the permanent magnet **1** required for the switch-off process. If $I_{\mathrm{off}}(\mathrm{C}_2)$ causes partial demagnetization (reduction of internal magnetic field) of the permanent magnet **1** and $I_{\mathrm{off}}(\mathrm{C}_1)$ is oriented in the same way, then magnetic field produced by the coil C_1 is oriented oppositely with respect to the resultant field in the permanent magnet, see Fig. 5, left part. The fields do not practically affect one another. But when the currents $I_{\mathrm{off}}(\mathrm{C}_1)$ and $I_{\mathrm{off}}(\mathrm{C}_2)$ are oriented oppositely, the field produced by the coil C_1 and resultant field in the permanent magnet are oriented in the same manner. In this way, the field in the permanent magnet is slightly enlarged, which, however, is quite undesirable for the process of switching off. Immediately we can draw a qualitative conclusion (that, however, can easily be confirmed also quantitatively), 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 demagnetize the permanent magnet **1**.
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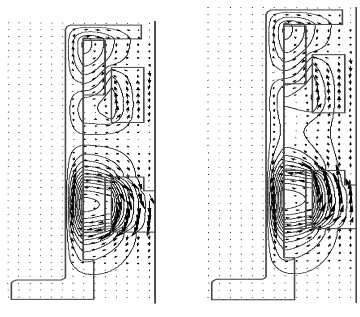

Fig. 5. Mutual influence of magnetic fields in the actuator in the regime of switching off

Left: $z_{off} = 20\,\text{mm}$, $I_{off}(C_1) = -16\,\text{A}$, $I_{off}(C_2) = -16\,\text{A}$
Right: $z_{off} = 20\,\text{mm}$, $I_{off}(C_1) = 16\,\text{A}$, $I_{off}(C_2) = -16\,\text{A}$

5.2 Quantitative Information

Such information can be obtained by an appropriate processing of the results. For example:

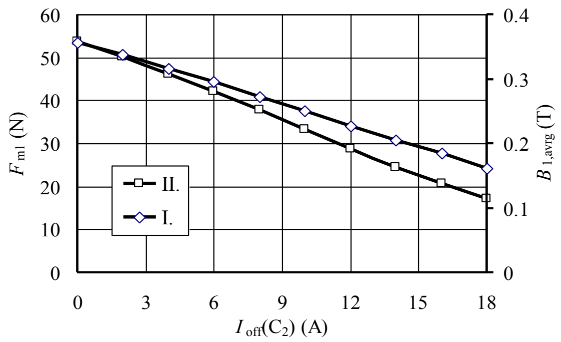

Fig. 6. Dependence of two important characteristics on current $I_{off}(C_2)$: I– F_{m1}, II– $B_{1,avrg}$

- Figure 6 shows the influence of the demagnetization current $I_{off}(C_2)$ on 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} pulling the ferromagnetic element **2** into field coil C_1.

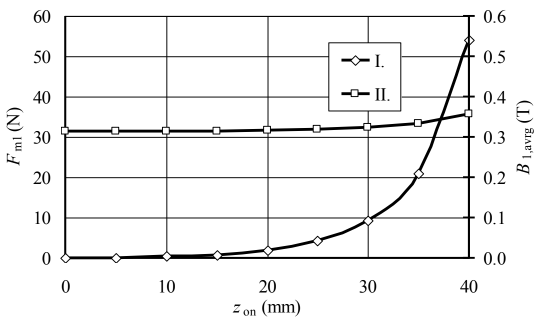

Fig. 7. Static characteristic of the permanent magnet **1** in the switching-on regime $I_{on}(C_1) = I_{on}(C_2) = 0$
I– F_{m1}, II– $B_{1,avrg}$

- Figure 7 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 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 any external source of energy. On the other hand, the average value $B_{1,avrg}$ of magnetic flux density in the 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 the lid practically perpendicularly (see Fig. 4, left part).
- Figure 8 depicts the resultant static characteristic of the whole actuator within the range $z_{on} \in \langle 0, 20 \rangle$ mm. This range corresponds with the position of ferromagnetic part **2** of the plunger in the 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. 7. 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 $z_{on} = 2\,\text{mm}$ shows the place of the highest force F_{m2on} acting on the ferromagnetic part **2** of the plunger.

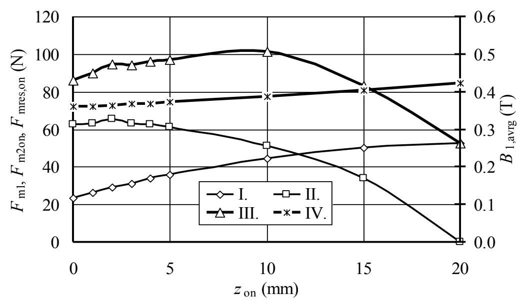

Fig. 8. Static characteristic of the whole actuator in the switching-on regime $I_{on}(C_1) = I_{on}(C_2) = 16$ A
I– F_{m1}, II– F_{m2on}, III– $F_{mres\,on}$, IV– $B_{1,avrg}$

- Finally, Fig. 9 contains the resultant switch-off characteristic of the whole device, again within the range $z_{\text{off}} \in \langle 0, 20 \rangle$ mm corresponding to the position of ferromagnetic part **2** of the plunger in the field coil C_1. Here the resultant force is $F_{\text{mres off}} = F_{\text{m1}} + F_{\text{m2off}}$. Now both forces on the right-hand side depend on z_{off} and pulsed current I_{off}. In the remaining interval $z_{\text{off}} \in \langle 20, 40 \rangle$ mm there holds $F_{\text{mres off}} = F_{\text{m1}}$ where F_{m1} only depends on $z_{\text{off}} = 40 - z_{\text{on}}$ – see Fig. 7. Here the pulsed current I_{off} has to be switched off, otherwise the ferromagnetic part **2** would be pulled again into the coil $C_1 \approx \mathbf{4}$. Further movement of the plunger is realized by inertia or by means o a draw spring (which, however, is not present in Fig. 1).

Here, 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 $z_{\text{off}} \in \langle 0, 20 \rangle$ mm, see line I in Fig. 9. 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 introduced coordinate system (direction of vector $\mathbf{z}_{\text{off}}$, 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 $\mathbf{z}_{\text{off}}$. At the moment when the permanent magnet reaches $z_{\text{off}} = 20$ mm and the pulsed current I_{off} vanishes, the force F_{m1} drops from the value about 50 N (Fig. 9, line I) to value -2 N oriented against the direction $\mathbf{z}_{\text{off}}$, see Fig. 7. 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 distance $z_{\text{off}} = 40 - z_{\text{on}}$ (in other words reduction of z_{on}, see Fig. 7), the force $F_{\text{m1}} \to 0$.

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 realized 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 will be very prospective in a number of technical applications.

Next work in the field will be aimed at building and experimental verification of the device.

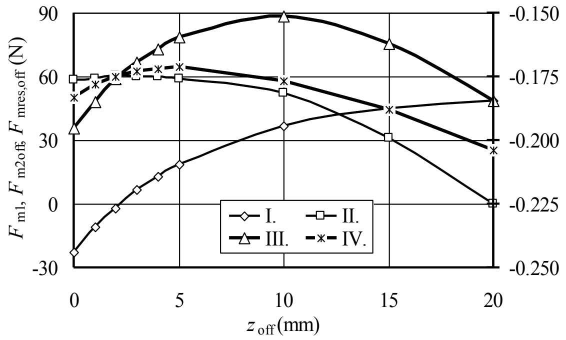

Fig. 9. Static characteristic of the whole actuator in the switching-off regime $I_{\text{on}}(C_1) = I_{\text{on}}(C_2) = -16$ A

I– F_{m1}, II– F_{m2off}, III– $F_{\text{mres off}}$, IV– $B_{1,\text{avrg}}$

Acknowledgements

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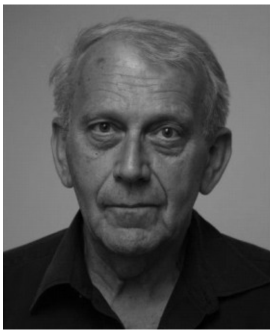

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