ANALYSIS OF AN ELECTROMAGNETIC ACTUATOR
WITH PERMANENT MAGNET

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Summary The paper deals with an electromagnetic actuator with permanent magnet. Starting from solution of its mathematical model we determined its basic operation parameters and characteristics. The theoretical analysis is illustrated on two typical examples whose results are discussed.

1. INTRODUCTION

Electromechanical actuators (power elements, electromechanical converters – for more details see, for example, [1], [2]) are devices that convert effects of electric currents on mechanical, force effect. They are widely used in various industrial and transport applications and in technological processes of automated production systems. The function of an actuator may be based on various physical principles. Frequently used are particularly:

- *Ferromagnetic actuators* – see, for instance, [3] – that employ magnetic force of an electromagnet and provide relatively high forces at shifts up to about 20 mm.

- *Linear electromagnetic actuators* – see, for example, [4] – working on the principle of a three-phase electromotor that have relatively high lift but their shifts are rather small.

- *Thermoelastic actuators* – see, for instance [5] – using thermal dilatability of metals during their heating or unequal dilatability of two various metals that are mechanically connected and electrically heated. These actuators produce extremely high forces, but their shifts are of the order of only tenth of mm.

- In association with development of production of permanent magnets, particularly on the basis of NdFeB with relatively high values of both coercive force H_c and remanence B_r, very prospective seem to *be DC electromagnetic actuators with permanent magnets*. Unlike the above types these devices are characterized by relatively high force and practically unlimited shift and also low volume and mass.

A principal scheme of the actuator with permanent magnet is depicted in Fig. 1. Its cylindrical coil **1** carries direct current of value I_{ext}. The coil is placed in magnetic field produced by a ring-shaped permanent magnet **2** magnetized in the radial direction. Magnetic flux then closes its path in magnetic circuit **3** manufactured from magnetically soft material. The coil is then affected by the Lorentz F_L in the axis of the arrangement. Its direction, however, depends on the direction of current I_{ext} and orientation of the permanent magnet.
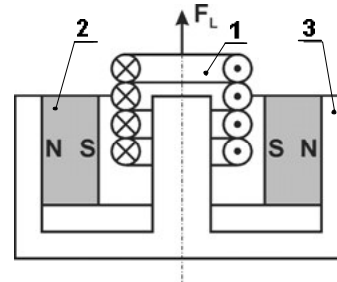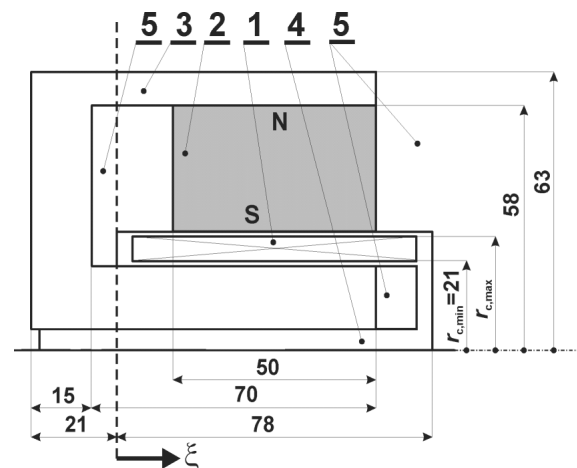

*Fig.1. Principal scheme of a DC electromagnetic actuator with permanent magnet: **1** – cylindrical field coil, **2** – permanent magnet, **3** – cylindrical magnetic circuit*

The aim of the paper is to evaluate the basic arrangement of the actuator with permanent magnet and determine its most important properties, particularly the force effects.

2. FORMULATION OF THE PROBLEM

Considered are two basic cylindrical arrangements of a DC electromagnetic actuator with permanent magnet depicted in Figs. 2a, 2b. In both cases coil **1** of the actuator consisting of N_z turns carries DC current of value I_{ext} with corresponding density J_{ext}. The coil is placed in a nonmagnetic leading shell **4** that transfers the force F_L on an external body out of the actuator. Now the situation in both arrangements is somewhat different and we can say that.
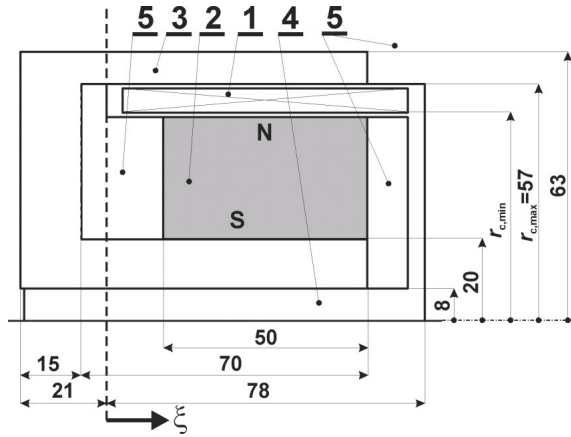
Fig. 2a,b. Basic cylindrical arrangements of a DC electromagnetic actuator with permanent magnet: 1 – cylindrical field coil, 2 – permanent magnet, 3 – cylindrical magnetic circuit, 4 – nonmagnetic leading shell, 5 - air

- "a" (Fig. 2a): Coil **1** with shell **4** moves in the air gap between the internal surface of the ring-shaped permanent magnet **2** and central cylindrical part of magnetic circuit **3** (its volume is smaller, but it is placed in the space of stronger magnetic field).
- "b" (Fig. 2b): Coil **1** with shell **4** moves in the air gap between the external surface of the ring-shaped permanent magnet **2** and internal cylindrical part of magnetic circuit **3** (its volume is bigger, but it is placed in the space of weaker magnetic field).

   The actuator is in both cases designed for an unidirectional acting of force F_{L} in direction z. The change of orientation of current I_{ext} leads, of course, to the change of orientation of F_{L}.

   The main goal of the work was

- to evaluate, which of the two arrangements "a" and "b" is more advantageous from the viewpoint of force F_{L},
- to determine the optimum radii $r_{\mathrm{c,min}}$ and $r_{\mathrm{c,max}}$ (compare Figs. 2a, 2b) of coil 1, again from the viewpoint of force F_{L},
- to find the static characteristics of both arrangements of the considered actuator, i.e. the dependence of force $F_{\mathrm{L}}(\varsigma)$ where ς is the shift of coil **1** with respect to unmovable magnetic circuit **3** (compare again Figs. 2a, 2b) for the given values of field current densities J_{ext}.

   Answers to these questions can be found in paragraph 5.2.

3.   MATHEMATICAL MODEL OF THE PROBLEM

   The mathematical model written in cylindrical coordinate system r, t, z is for both investigated arrangements practically the same. That is why only variant "a"

3.1.   Definition area of the problem

   The definition area consists of five subdomains $\Omega_1 - \Omega_5$, as depicted in Fig. 3 (compare also Fig. 2a). The whole area is bounded by a fictitious boundary ABCD.
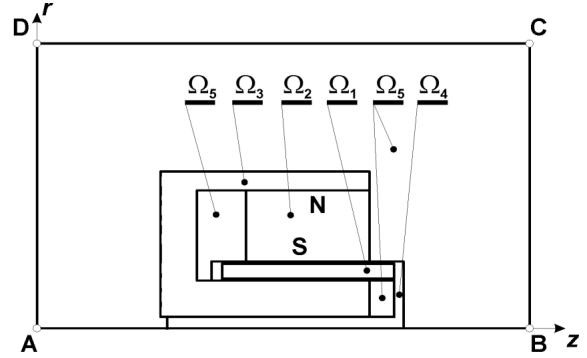

Fig. 3. Definition area of electromagnetic field – arrangement "a"

Here

Ω_1 represents the cross-section of coil **1** characterized by current density J_{ext} and magnetic permeability μ_0.

Ω_2 is the cross-section of the ring of permanent magnet **2** characterized by coercive force H_{c} and remanence B_{r}, or by permeability $\mu = |B_{\mathrm{r}}| / |H_{\mathrm{c}}|$ and orientation of the magnet with respect to coordinate system r, t, z.

Ω_3 represents the cross-section of the cylindrical magnetic circuit **3** characterized by nonlinear dependence $B(H)$.

Ω_4 is the cross-section of the nonmagnetic leading shell 4 of coil 1 characterized by permeability μ_0.

Ω_5 denotes air of permeability μ_0.

   The numerical values of physical parameters of particular subdomains are listed in Tab. 1.

Table 1: Basic physical data of particular materials occurring in the arrangement

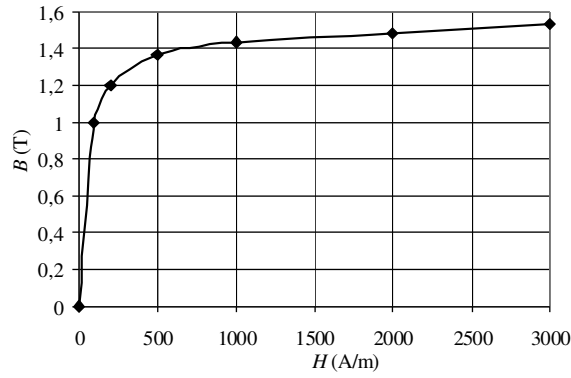| part	material	parameter and its value
coil **1**	Cu wire	diameter $d = 1\,\mathrm{mm}$ turns $N_z = 420$ current density $J_{\mathrm{ext}} = 2.5, 5, 7.5$ A/mm²
perm. mag. **2**	RECOMA 28 see [10]	coercive force $H_{\mathrm{c}} = 720$ kA/m remanence $B_{\mathrm{r}} = 1070$ mT permeability $\mu_R = 1.05$
magn. circuit **3**	steel 11 370 see [9]	magnetization curve see Fig. 4
leading shell **4**	Kevlar see [11]	permeability $\mu_{\mathrm{r}} = 1$

Fig. 4. Nonlinear magnetization characteristic $B(H)$
of steel 11 370

3.2. Differential equations of the problem

The differential equations in particular domains $\Omega_1 - \Omega_5$ read (see, for example, [6], [7] and [8]):

$$\Omega_1: \ \text{curl}\,\text{curl}\,A = \mu_0 J_{\text{ext}}, \tag{1}$$

$$\Omega_2: \ \text{curl}\left(\frac{1}{\mu}\text{curl}\,A - H_{\text{c}}\right) = 0, \tag{2}$$

$$\Omega_3: \ \text{curl}\left(\frac{1}{\mu}\text{curl}\,A\right) = 0, \tag{3}$$

$$\Omega_4: \ \text{curl}\,\text{curl}\,A = 0, \tag{4}$$

$$\Omega_5: \ \text{curl}\,\text{curl}\,A = 0. \tag{5}$$

Current density J_{ext} as well as vector potential A has one only nonzero tangential component, so that the corresponding vectors may be expressed as

$$J_{\text{ext}} = \mathbf{r}_0 0 + \mathbf{t}_0 J_{\text{ext}} + \mathbf{z}_0 0,$$

$$A = \mathbf{r}_0 0 + \mathbf{t}_0 A_t(r,z) + \mathbf{z}_0 0.$$

The Lorentz force acting on coil **1** carrying current J_{ext} that is placed in magnetic field $B(r,z)$ is given by relation

$$F_{\text{L}} = \int_{V_1}(J_{\text{ext}} \times B)\,\mathrm{d}V \tag{6}$$

where V_1 is the volume of coil **1**.

3.3. Boundary conditions

The boundary conditions providing unambiguous solution of equations (1)–(5) are – with respect to antisymmetry of magnetic field along axis AB and continuity of vector of magnetic flux density $B(r,z)$ at points A, B, C, D of the fictitious boundary (see Fig. 3) – expressed in the form

$$rA_t(r,z) = 0. \tag{7}$$

4. COMPUTER MODEL OF THE TASK, ACHIEVED ACCURACY OF RESULTS

The mathematical model presented in the previous paragraph was solved by the FEM-based professional code QuickField [12]. Particular attention was paid to the geometrical convergence of the solution. In order to achieve the accuracy of the Lorentz force F_{L} at the level of three nonzero valid digits it was necessary to use a mesh containing 80000–150000 elements, which depends on particular shift ς of coil **1** (see Fig. 2a,b).

5. ILLUSTRATIVE EXAMPLE

5.1. Input data

We considered two versions of axisymmetric actuator with permanent magnet depicted in Figs. 2a,b. Given are all dimensions of both arrangements – compare Fig. 2a,b and physical parameters of all components (Tab. 1).

It is necessary to carry out a set of test calculations that would provide the answers to questions formulated in paragraph 2.

5.2. Input data

The evaluation which of both arrangements "a" and "b" is more advantageous from the viewpoint of force F_{L} and determination of the optimum radii $r_{\text{c,min}}$ or $r_{\text{c,max}}$ (compare Figs. 2a,b) of coil **1** (again from the viewpoint of force F_{L}) may be carried out from Figs. 5a,b and Tab. 2.
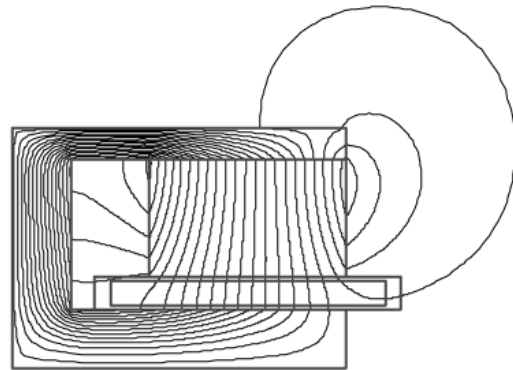

Fig. 5a. Force lines in arrangement "a"
($J_{\text{ext}} = 5\,A/mm2$, $r_{\text{c,max}} = 27\,mm$, $\varsigma = 0$)
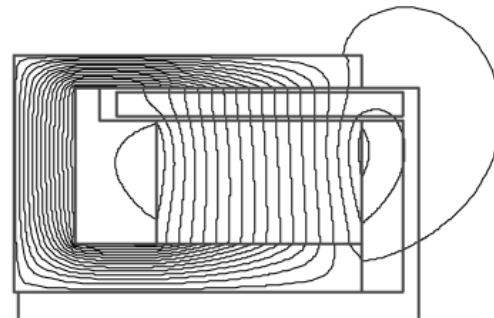
Fig. 5b. Force lines in arrangement "b"
($J_{\text{ext}} = 5\,A/mm2$, $r_{\text{c,max}} = 51\,mm$, $\varsigma = 0$)

*Table 2. Influence of the arrangement of coil **1** on the Lorentz force F_L ($J_{ext} = 5\,A/mm2,\ \varsigma = 0$)*

arrangement "a"		
$r_{c,min}$ (mm)	$r_{c,max}$ (mm)	F_L (N)
21	27	122.2
	30	163.3
	33	193.2
	36	**206.9**
	39	206.2
	42	188.7
arrangement "b"		
$r_{c,min}$ (mm)	$r_{c,max}$ (mm)	F_L (N)
51	57	138.6
48		182.8
45		209.0
42		**218.8**
39		209.5
36		184.0

Comparison of Figs. 5a,b shows that in both cases we can see partial leakage of magnetic field in the right part of the actuator, particularly in the area of higher radii. Nevertheless, in case of arrangement "b" the coil shifts just to this space, ς grows (compare Figs. 2b and 5b) so that we can suppose that even this leakage field may affect growth of force F_L. This conclusion is also confirmed by data in Tab. 2 showing that at the same thickness of the coil $r_{c,max} - r_{c,min}$ and current density J_{ext} the force F_L in the case "b" is higher. This is caused by the fact that in case of arrangement "b" the coil conductor is longer than in case "a". Tab. 2 may also be used for finding optimum radii $r_{c,min}$ and $r_{c,max}$ for both arrangements of the actuator.

The static characteristics of both arrangements of the actuator (i.e. functions $F_L(\varsigma)$ where ς is the shift of coil **1** with respect to the unmovable magnetic circuit **3**, see Figs. 2a,b) for given values of current densities J_{ext} are depicted in Figs. 6a,b.
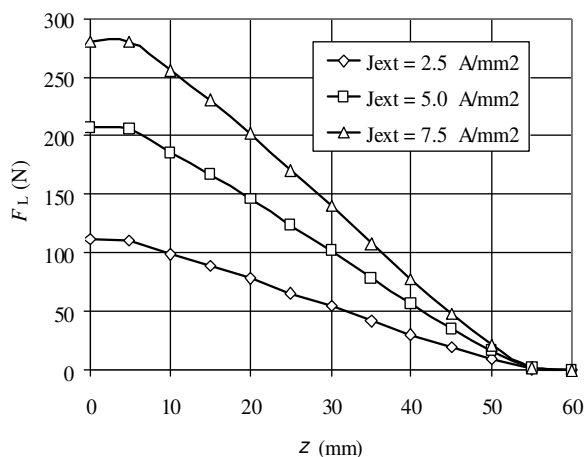

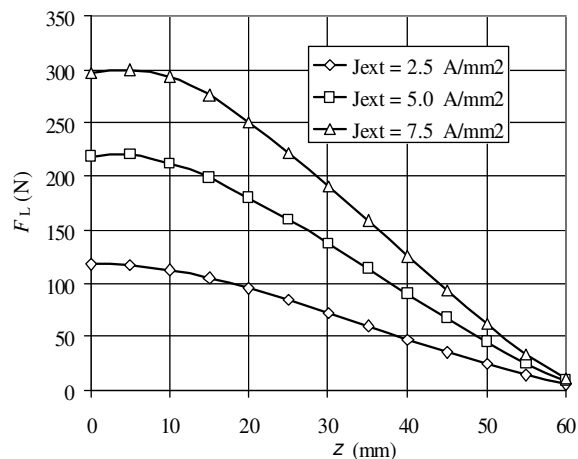*Fig. 6a: Static characteristic of the actuator of type "a" for($r_{c,max} = 36\,mm,\ N_z = 1050$)*

Fig. 6b: Static characteristic of the actuator of type "b" for($r_{c,max} = 42\,mm,\ N_z = 1050$)

The characteristics in Figs. 6a, b show that
- the considered type of electromagnetic actuator with permanent magnet produces relatively high forces at quite acceptable values of field current densities J_{ext} ,
- in accordance with the above facts, the arrangement of type "b" provides higher values of forces $F_L(\varsigma)$ even for greater shifts ς ,
- the dependence of force $F_L(\varsigma)$ on field current density J_{ext} is somewhat nonlinear, which is in accordance with the existence of nonlinear characteristic $B(H)$ of the cylindrical ferromagnetic circuit **3**,
- In both considered arrangements force $F_L(\varsigma)$ strongly depends on shift ς , its flat part is rather small. This is due to relatively small length of permanent magnet 2 (50 mm, compare Figs. 2a,b). Increase of this length (the length of the coil remaining the same) would evidently lead to longer flat part of the curve $F_L(\varsigma)$, because the field coil would be for a long time in uniform magnetic field.

6. CONCLUSION

The computations show that an electromagnetic actuator with permanent magnet represents a prospective type of device providing relatively high forces even for considerable shifts. The device works with currents of acceptable densities and its dimensions are small.

Further research in the domain should particularly be aimed at
- possibilities of obtaining flatter static characteristic $F_L(\varsigma)$ (which is a frequent demand in many practical applications) by means of suitable ratio of dimensions of the permanent magnet and field coil,

- increase of force $F_L(\varsigma)$ by using a suitable combination of several permanent magnets (such as the Halbach array, see, for example, [13]).

Acknowledgement

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