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Actuator with Ferromagnetic Plunger Working in Ferrofluidic Liquid

***Abstract**. An electromagnetic actuator with a plunger moving in a ferrofluidic liquid is suggested and modeled. The paper analyses its principal operation characteristics.*

***Streszczenie.** Zaproponowano nowy siłownik (aktuator) z popychaczem poruszającym się w cieczy typu ferrofluid. W artykule opisano główne cechy tego urządzenia. (**Siłownik w ferromagnetycznym popychaczem poruszającym się w cieczy typu ferrofluid**)*

Keywords: Electromagnetic actuator, ferrofluidic liquid, magnetic field, operation characteristics.
Słowa kluczowe: siłownik elektromagnetyczny, ferrofluid.

Introduction

Nowadays, ferrofluid liquids belong to prospective operation media in numerous industrial and laboratory applications. They are (see, for example, [1–3]) usually formed as colloidal solutions of very fine ferromagnetic particles in sufficiently viscous liquids. Higher viscosity of these liquids ensures their relatively good spatial and temporal homogeneity. Some of their physical parameters (permeability and viscosity) then strongly depend on external magnetic field.

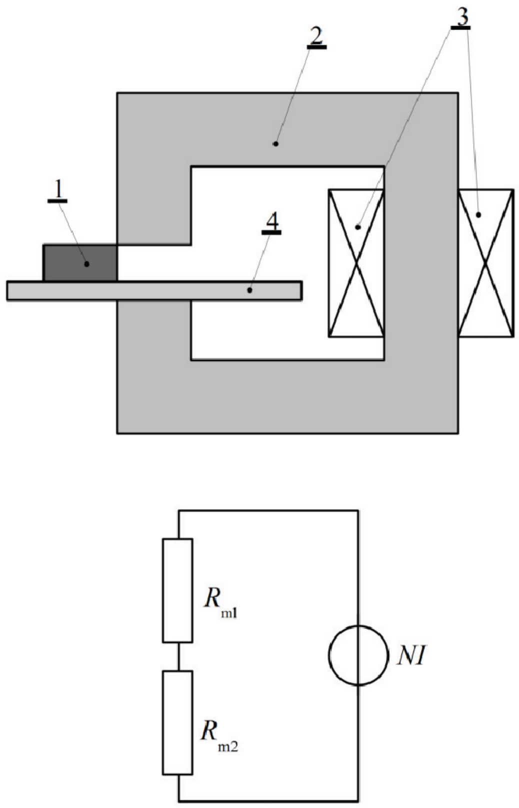

Fig. 1. Simple electromechanical transducer and its equivalent magnetic circuit; 1 - movable part, 2 - magnetic circuit, 3 - winding, 4 - gap between movable and static part filled with air or ferrofluidic liquid

One of the prospective technical applications working with them is represented by classical electromagnetic actuators [4–5] whose working space is filled with such ferrofluidic liquid. Their total magnetic resistance is lower and the required magnetic flux density may be achieved with lower field current. Therefore, their operation regimes exhibit better parameters than similar devices with air, which is also demonstrated in the presented paper.

Force enhancement basic principle

The magnetic force enhancement principle resulting from the use of ferrofluid will be demonstrated. Let us suppose a simple electromechanical transducer represented by Fig. 1.

The magnetic circuit made of ferromagnetic material is excited with coil carrying DC current. Movable body made of the same ferromagnetic material is placed between the poles of the magnetic circuit. An air gap is required between the movable body and poles of the magnetic circuit to enable movement. This body will move to the balanced position, where the resultant magnetic field energy is minimal. Such device can be modelled with the use of magnetic circuit theory.

The total magnetic flux flowing through the magnetic circuit of the transducer is given by the total current exciting the coil and the magnetic reluctance of the circuit:

(1) $$\Phi = \frac{NI}{R_m} = \frac{NI}{R_{m1} + R_{m2}},$$

where R_{m1} and R_{m2} represent the magnetic reluctances of the ferromagnetic materials and gap:

(2) $$R_{m1} = \frac{l_1}{\mu_1 S}, \quad R_{m2} = \frac{l_2}{\mu_2 S} = f\left(\frac{1}{\mu_2}\right),$$

where l_1 and l_2 represent mean lengths of magnetic force lines in the magnetic circuit and in the gap. Finally, symbol S stands for the cross-section of the magnetic circuit and gap.

The resultant static magnetic force acting on the movable body in the x direction can be achieved, for example, from the total energy of the magnetic field:

(3) $$F_x = \frac{dW_m}{dx}$$

where the energy of the magnetic field W_m can be determined for example from the formula

(4) $$W_m = \Phi I.$$

It is obvious that the magnitude of the magnetic flux (and also the magnitude of the acting force) depends, among other parameters, on the reluctance of the air gap. If this gap is filled with the ferrofluid with relative permeability $\mu_r > 1$, the magnetic reluctance of the circuit decreases and acting forces increase. The relative permeability in the linear part of magnetization characteristics of ferrofluids currently at the disposal is in range μ_r = 1.2~5 (a method for simple industrial measurement of magnetic fluids permeability with measured values of permeability of several magnetic fluids was proposed in [3]). The use of a ferrofluid, thus, offers increasing of the force theoretically up to several times.

Actuator with ferrofluidic liquid

The principal arrangement of an electromagnetic actuator working with a ferrofluid is depicted in Fig. 2.

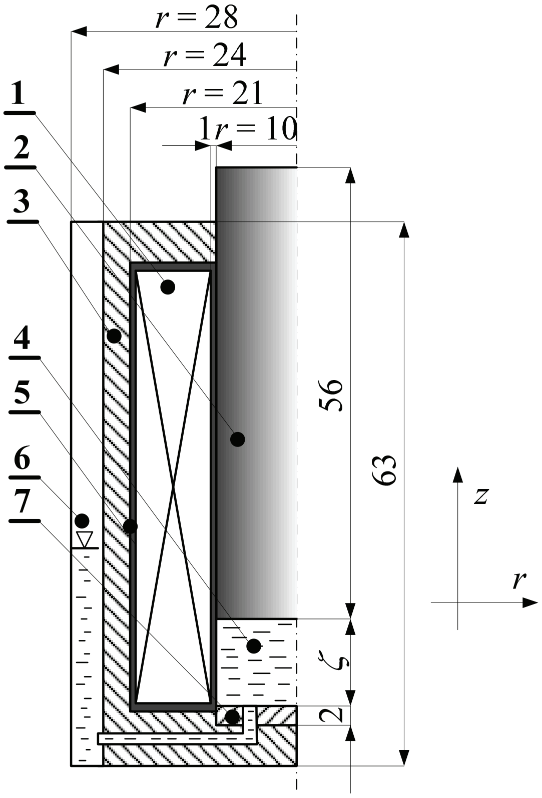

Fig. 2. The considered actuator (dimensions in mm)
1–field coil, 2–ferromagnetic plunger, 3–ferromagnetic shell, 4–ferrofluid with permeability $\mu_{r,4}$, 5–insulation of field coil, 6–tank with ferrofluid, 7–spacer

Its basic elements are the ferromagnetic plunger 2 inserted in ferromagnetic shell 3, and the direct current carrying field coil 1 with insulation 5. The working space of the device is filled in with a ferrofluid 4 that (when the plunger moves) flows from or to the tank 6. Above the level of ferrofluid the tank contains a suitable gas under pressure that ensures the reverse flow of ferrofluid to the working space of the actuator. The lowest position of the plunger 2 is on the nonferromagnetic spacer 7.

When the field coil carries direct current $\boldsymbol{I}_{\mathrm{ext}}$, this current produces magnetic field $\boldsymbol{B}$ that pulls the plunger by force $\boldsymbol{F}_{\mathrm{m}}$ into the coil. If this force is higher than the sum of various resistances (friction, hydrodynamic resistance, external force), the plunger moves. If the field current is switched off, the plunger can return to its initial position by a force exerted, for example, by a return spring (that is not depicted in Fig. 1) or by an overpressure in the ferrofluid tank.

While the forces exerted by the device are higher than in the case of air medium, its dynamic characteristic is slower because a much higher resistance of the working medium.

Mathematical model

Magnetic field in the system can be described by the equation [6]

(5) $$\mathrm{curl}\left(\frac{1}{\mu}\mathrm{curl}\boldsymbol{A}\right) = \boldsymbol{J}_{ext},$$

where $\boldsymbol{A}$ denotes the magnetic vector potential $\boldsymbol{A}$, μ is the magnetic permeability and $\boldsymbol{J}_{\mathrm{ext}}$ stands for the value of density of the field current $\boldsymbol{I}_{\mathrm{ext}}$. Equations describing the magnetic field in individual components can be easily acquired using (1).

At any position of the plunger 2 the magnetic force $\boldsymbol{F}_{\mathrm{m}}$ acting on it is given by the formula [6]

(6) $$\boldsymbol{F}_{\mathrm{m}} = \frac{1}{2}\oint_{S_1}\left[\boldsymbol{H}(\boldsymbol{n}\cdot\boldsymbol{B}) + \boldsymbol{B}(\boldsymbol{n}\cdot\boldsymbol{H} - \boldsymbol{n}(\boldsymbol{H}\cdot\boldsymbol{B})\right]dS,$$

where $\boldsymbol{H}$ and $\boldsymbol{B}$ are vectors of the magnetic field ($\boldsymbol{B} = \mathrm{curl}\,\boldsymbol{A}$) and $\boldsymbol{n}$ denotes the unit vector of the outward normal to the surface of the plunger. The integration is performed over the complete surface S_2 of the plunger pos. 2 in Fig. 2.

As the arrangement can be considered (with a small error) axisymmetric, the vectors $\boldsymbol{J}_{\mathrm{ext}}$ and $\boldsymbol{A}$ have only one nonzero component in the tangential direction, field vectors $\boldsymbol{H}$ and $\boldsymbol{B}$ two components in the radial and axial directions and magnetic force $\boldsymbol{F}_{\mathrm{m}}$ one component in the axial direction.

Numerical solution and discussion of results

The numerical solution was carried out by a FEM-based code QuickField 5.0 [7]. We respected the nonlinear permeability of carbon steel 12 040 (Fig. 3) used for the plunger and shell, while (due to the lack of data) the permeability of ferrofluid was considered constant (generally, however, the permeability is anisotropic and nonlinear, $\mu_r = \mu_r(x, y, z, \boldsymbol{B})$). Ferrofluids with different permeabilities were used, even fictitious ferrofluids with permeability $\mu_{r,4} > 5$ to get overview of their influence on the static characteristics of the device.

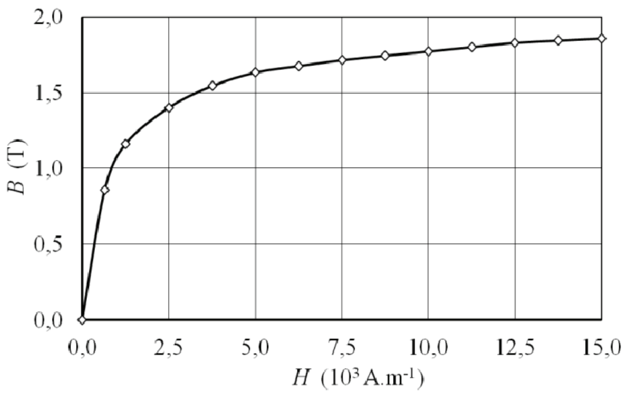

Fig. 3. Magnetization characteristic of steel 12040 (for T_0 = 20 °C)

Other parameters: the coil wound by a copper conductor of circular cross section and diameter d = 1 mm has N = 500 turns, coefficient of filling being k = 0.785. Carefully was checked the convergence of solution (an illustration is given in Table 1).

Table 1. Convergence of solution – computation of magnetic force $|\boldsymbol{F}_\mathrm{m}|$ (N) acting on the plunger for various permeabilities of ferroliquid (J_ext =10^6 A/m^2)

Number of nodes	μ_r = 1	μ_r = 10	μ_r = 50
4×10^3	11.91	18.53	26.24
16×10^3	12.47	18.98	26.47
47×10^3	12.70	18.96	26.29
187×10^3	12.70	18.74	25.99

The number of the results abounds. First we will show two results of qualitative character represented by the distributions of magnetic fields in the device when the working medium is air and when the working medium is ferrofluid. The maps of magnetic field for current density $\boldsymbol{J}_\mathrm{ext}$ = 10^6 A/m^2 are shown in Fig. 4.

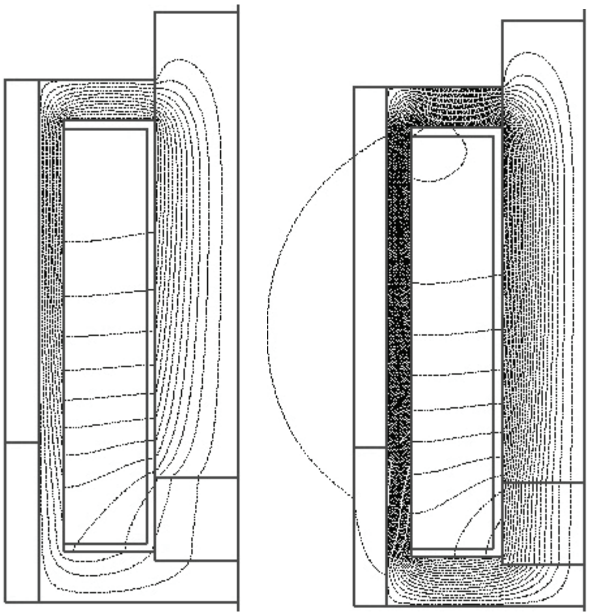

Fig. 4. Distribution of magnetic field in the system when the working medium is air ($\mu_{\mathrm{r},4}$ = 1, left) and ferrofluid ($\mu_{\mathrm{r},4}$ = 10, right), field current density $\boldsymbol{J}_\mathrm{ext}$ =10^6 A/m^2

It is obvious that for $\mu_{\mathrm{r},4}$ = 10 the field is stronger, which results in higher magnetic force $|\boldsymbol{F}_\mathrm{m}|$ (this also follows from Tab. 1). On the other hand, oversaturation of the magnetic shell is still low, so that that the leakage magnetic flux is also low. Fig. 5 shows an example of the static characteristics of the actuator as functions of the permeability of the working medium.

It is clear that the presence of ferrofluid leads to a growth of the magnetic force $\boldsymbol{F}_\mathrm{m}$ acting on the plunger. Moreover, the value of its permeability affects not only this force itself, but even the shape of the corresponding curve. With higher values of $\mu_{\mathrm{r},4}$ the characteristic becomes flatter, while the increase of the force is visible mainly at greater distances of the plunger from the spacer.

Conclusion

It can be concluded that utilization of ferrofluids in electromagnetic actuators affects qualitatively and quantitatively their static characteristics. This fact must be properly considered when designing electromechanical devices featuring the ferrofluid.

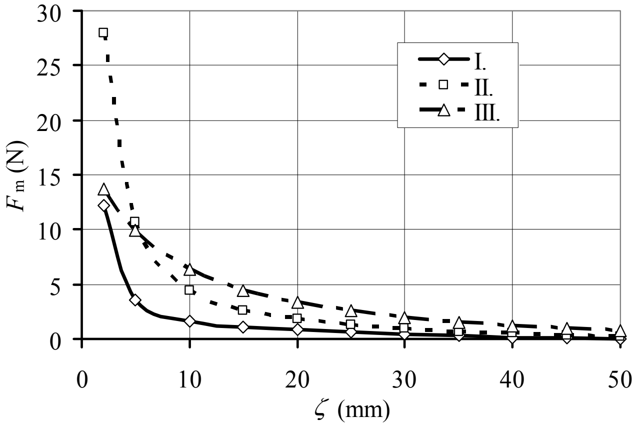

Fig. 5. Static characteristics of the actuator
I.– $\mu_{\mathrm{r},4}$ = 1, II.– $\mu_{\mathrm{r},4}$ = 10, III.– $\mu_{\mathrm{r},4}$ = 50

Development of new types of ferrofluids with different relative permeabilities can be expected in the future due to intensive research in the field of nanotechnology nowadays. Such fluids can offer even more interesting magnetic force enhancements. Our future work will be aimed at the evaluation of the influence of permeability and viscosity of ferrofluids on the dynamic characteristics of such devices. All results obtained from the numerical analysis, however, should be validated by experiments.

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