Actuator with Ferromagnetic Plunger Working in Ferrofluidic Liquid

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

Keywords: **Electromagnetic actuator, ferrofluidic liquid, magnetic field, operation characteristics.**

I. 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 its relatively good spatial and temporal homogeneity. Some of their physical parameters (permeability and viscosity) then strongly depend on external magnetic field.

One of prospective technical applications working with them are classical electromagnetic actuators [4–5] whose working space is filled with such 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.

II. FORMULATION OF THE PROBLEM

The principal arrangement of an electromagnetic actuator working with a ferrofluid is depicted in Fig. 1.

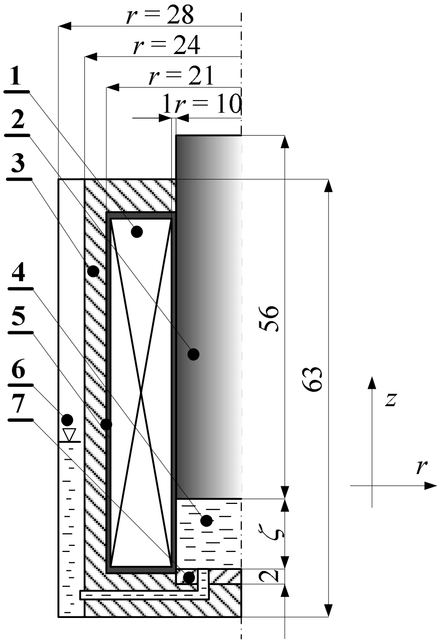

Fig. 1. The considered actuator (dimensions in mm)
1–field coil, **2**–ferromagnetic plunger, **3**–ferromagnetic shell, **4**–ferrofluid, **5**–insulation, **6**–tank with ferrofluid, **7**–spacer

Its basic elements are the ferromagnetic plunger **2** inserted in ferromagnetic shell **3** and 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 I_{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 pressure in the ferrofluid tank.

III. MATHEMATICAL MODEL

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

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

where $\boldsymbol{A}$ denotes the magnetic vector potential, μ is the magnetic permeability $\boldsymbol{J}_{\mathrm{ext}}$ stands for the value of density of the field current I_{ext}.

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

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

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.

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.

IV. NUMERICAL SOLUTION AND DISCUSSION OF RESULTS

The numerical solution was carried by a FEM-based code QuickField 5.0 [7]. We respected nonlinear permeability of carbon steel 12 040 used for the plunger and shell, while (due to the lack of data) the permeability of ferrofluid was considered constant. 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 $\kappa = 0.785$. Carefully was checked the convergence of solution (an illustration is given in Tab. 1).

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

number of nodes	$\mu_\mathrm{r} = 1$	$\mu_\mathrm{r} = 2$	$\mu_\mathrm{r} = 5$
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 is high. 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 for field current density $J_\mathrm{ext} = 10^6$ A/m^2 are shown in Fig. 2.

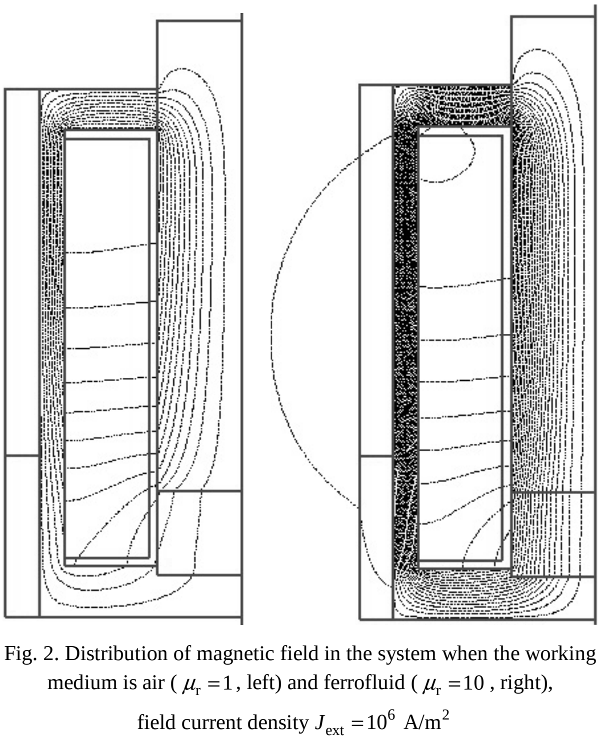

Fig. 2. Distribution of magnetic field in the system when the working medium is air ($\mu_\mathrm{r} = 1$, left) and ferrofluid ($\mu_\mathrm{r} = 10$, right), field current density $J_\mathrm{ext} = 10^6$ A/m^2

It is obvious that for $\mu_\mathrm{r} = 10$ 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. Figure 3 shows an example of the static characteristics of the actuator as functions of the permeability of the working medium.

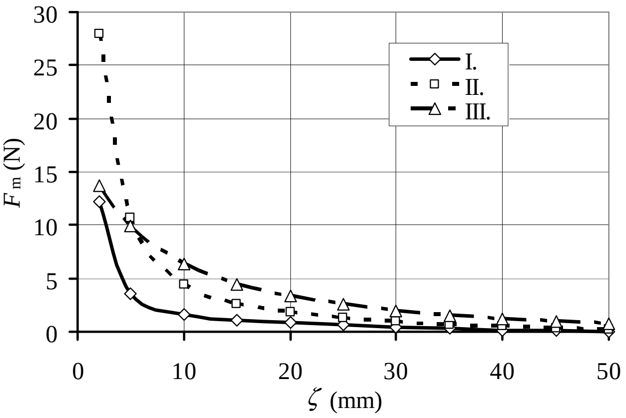

Fig. 3. Static characteristics of the actuator I– $\mu_\mathrm{r} = 1$, II– $\mu_\mathrm{r} = 10$, III– $\mu_\mathrm{r} = 50$

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 μ_r the characteristic becomes flatter, while the increase of the force is visible mainly at grater distances of the plunger from the spacer.

V. CONCLUSION

It can be concluded that utilization of ferrofluids in electromagnetic actuators affects qualitatively and quantitatively their static characteristics. The 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.

VI. ACKNOWLEDGEMENTS

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