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ELECTROMECHANICAL SYSTEMS WITH FERROFLUID FILLED GAP

Summary. This paper deals with the possibility of improving the output characteristics of an electromechanical actuator by filling the air gap with ferromagnetic liquid. The enhancement assumption is theoretically derived, testing device is built and its static and dynamic characteristics are measured to confirm the theory.

Keywords: Air gap elimination, electromechanical actuator, ferrofluid

UKŁADY ELEKTROMECHANICZNE ZE SZCZELINĄ POWIETRZNĄ WYPEŁNIONĄ CIECZĄ MAGNETYCZNĄ

Streszczenie. W artykule omówiono możliwość polepszenia charakterystyki zewnętrznej elektromechanicznego siłownika poprzez wypełnienie szczeliny powietrznej cieczą magnetyczną. Koncepcję opracowano na drodze przemyśleń teoretycznych, zbudowano model fizyczny do prób i zmierzono jego charakterystyki statyczne i dynamiczne dla potwierdzenia słuszności teorii.

Słowa kluczowe: likwidacja szczeliny powietrznej, elektromechaniczny siłownik, ciecz magnetyczna

1. INTRODUCTION

Modern electrical and mechanical engineering industry often uses electromechanical converters in their products, these converters are called transducers, or actuators. Designers have a wide range of transducers at their disposal nowadays, with various static and dynamic properties based on different physical principles. Common requirements imposed on all transducers are, among other things, a low weight, small dimensions and high performance. The mechanical force of a transducer is usually caused by direct or alternating magnetic field acting on the moving part. This part consists of an iron armature, or coil powered by the electric current. The armature, resp. the coil is a part of the magnetic circuit that can perform motion - linear or rotary. This represents a mechanical output of a transducer. The magnitude of this force depends on the magnetic induction; it obviously increases with the decrease of the reluctance of the passing magnetic flux. The main idea of the new transducer lies in the fact that the air gap needed in the magnetic circuit is replaced with the magnetic fluid which possesses ferromagnetic properties, namely relative permeability $\mu_r > 1$, while enabling movement of the movable part.

Ferrofluids are colloid suspensions of ferromagnetic nanoparticles in a carrier liquid, most often oil. Depending on particular composition, these fluids represent a liquid ferromagnetic material with relative permeability in range $\mu_r = 1{\sim}5$. Nowadays, ferrofluids are used or are planned to be used in several technical and even medical applications. Several works [1,2] are aimed at the use of ferrofluids in air gaps of electromechanical devices to improve the characteristics of the device. This paper contributes to this field of research.

2. THEORETICAL BACKGROUND AND MOTIVATION

Presence of a ferromagnetic liquid in the air gap of an electromechanical device improves its magnetic circuit while still enabling the movement of the device. Let us demonstrate this improvement on the electromechanical actuator represented by the Fig. 1:

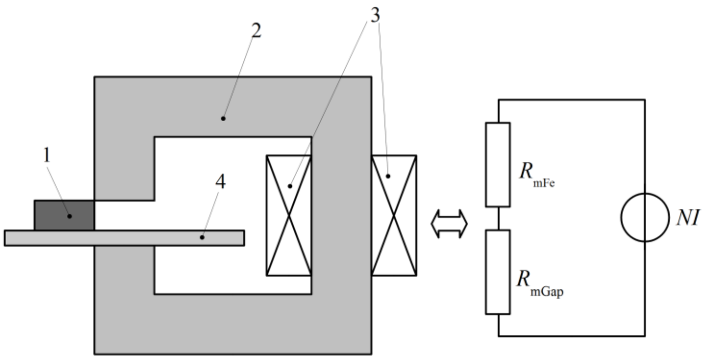

Fig. 1. Simple electromechanical actuator and its equivalent magnetic circuit: 1 - movable part, 2 -magnetic circuit, 3 - winding, 4 - air gap between movable and static part
Rys. 1. Prosty elektromechaniczny siłownik i jego schemat zastępczy magnetyczny: 1 - część ruchoma, 2 - obwód magnetyczny, 3 - uzwojenie, 4 - szczelina powietrzna między częścią ruchomą i nieruchomą

The magnetic circuit made of ferromagnetic material is excited with coil with 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 such position, that resulting magnetic field energy is minimal. Such device can be modeled 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:

$$\Phi = \frac{NI}{R_\mathrm{m}} = \frac{NI}{R_\mathrm{m1} + R_\mathrm{m2}} = \frac{NI}{\frac{l_1}{\mu_1 S} + \frac{l_2}{\mu_2 S}} \tag{1}$$

and the mechanical force in the horizontal direction acting on the movable part of the device can be computed for example from the energy of the magnetic field

$$F_x = \frac{\mathrm{d}W_m}{\mathrm{d}x} = \frac{\mathrm{d}(\Phi I)}{\mathrm{d}x}\,. \tag{2}$$

Clearly, the higher is the permeability of the medium filling the air gap, the higher are the forces acting on the movable body. Nevertheless, practical experiments based on filling the air gaps of electromechanical systems with ferrofluids did not confirm this theory [2]. Explanation can be given with the use of more sophisticated model.

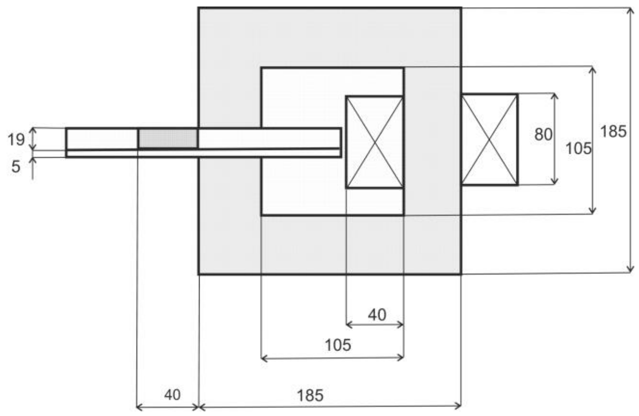

Fig. 2. Dimensions of numerically simulated electromechanical actuator, in mm
Rys. 2. Rozmiary siłownika zasymulowanego numerycznie, w mm

The magnetic circuit is excited in such a way, that value of magnetic induction in its gap is not higher than $\boldsymbol{B}$ = 0.6 T, the current density in the coils is $\boldsymbol{J} = 5\cdot10^6$ A/m^2. Both used iron and ferrofluid are not saturated, the relative permeability of iron is supposed μ_r = 1000. According to the arrangement of the device, two-dimensional model of the problem can be used. The definition area is chosen, border conditions are implemented and the equation for the magnetic vector potential $\boldsymbol{A}$ is solved:

$$\mathrm{curl}\frac{1}{\mu}\mathrm{curl}\boldsymbol{A} = \boldsymbol{J}\,. \tag{3}$$

The magnetic field induction can be determined from its definition. The magnetic force $\boldsymbol{F}_\mathrm{m}$ acting on the movable body can be determined form the change of magnetic field energy.

$$\boldsymbol{B} = \mathrm{curl}\boldsymbol{A}, \quad W_\mathrm{m} = \int_V \Big(\int_0^B \boldsymbol{H}\mathrm{d}\boldsymbol{B}\Big)\mathrm{d}V, \quad \boldsymbol{F}_{\mathrm{m}x} = -\frac{\mathrm{d}W_\mathrm{m}}{\mathrm{d}x}\,, \tag{4}$$

The horizontal component of the magnetic force $\boldsymbol{F}_x$ is the object of our interest, this force causes movement of the device. The function of this force depending on the displacement of the core from its stabile position is the static force characteristics $F_x(l)$.

Software Agros2D based on Hermes2D [3] mathematical library developed by our department with users' scripts in python language was used to solve the static force characteristics. The convergence of the solution depending on the definition area, number of nodes and polynomial order of used elements was observed.

Several types of ferrofluids with different relative permeabilities are considered, even the influence of ferrofluids with higher permeabilities than μ_r = 5 in theoretical case that new types of ferrofluids are developed in the future. Results can be seen in Fig. 3. Depending on the permeability of the used ferrofluid, increases in the force characteristics can be seen.

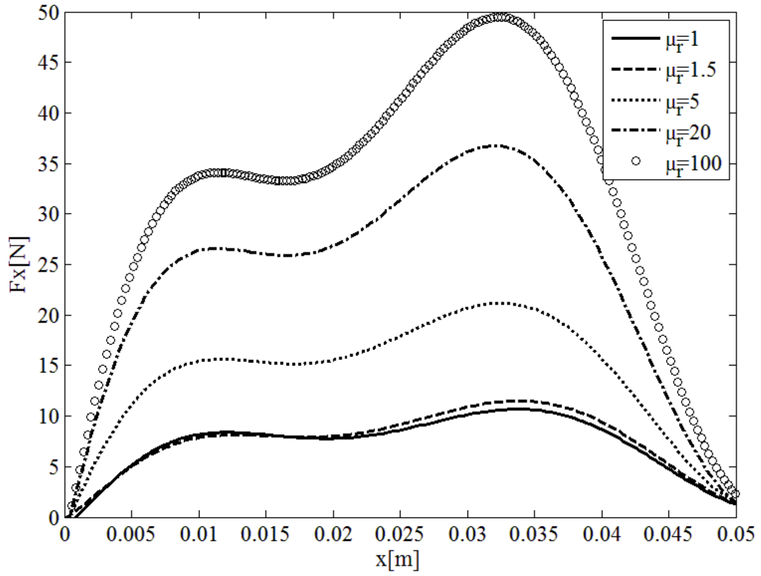

Fig. 3. Simulated static characteristics of the horizontal force for ferrofluids with different permeabilities, air gap filled with ferrofluid

Rys. 3. Zasymulowane charakterystyki statyczne siły poziomej dla cieczy magnetycznych o różnych przenikalnościach, szczelina powietrzna wypełniona cieczą magnetyczną

The increase in static magnetic forces itself does not mean that the resulting output characteristics of the electromechanical actuator are always improved. Operation of an electromechanical machine or actuator is generally dynamical phenomenon and dynamical quantities must be taken into account. Most important dynamical quantity influencing the operation of the ferrofluid filled actuator is the dynamical viscosity of the used liquid. Clearly, the presence of the liquid in the device causes mechanical viscous losses, as the movable part of the actuator moves in the viscous liquid. Overall dynamics of the device can be solved as transient phenomena described by the set of differential equations [4]. Because both magnetic field and temperature influence the ferrofluid, resulting task is coupled problem.

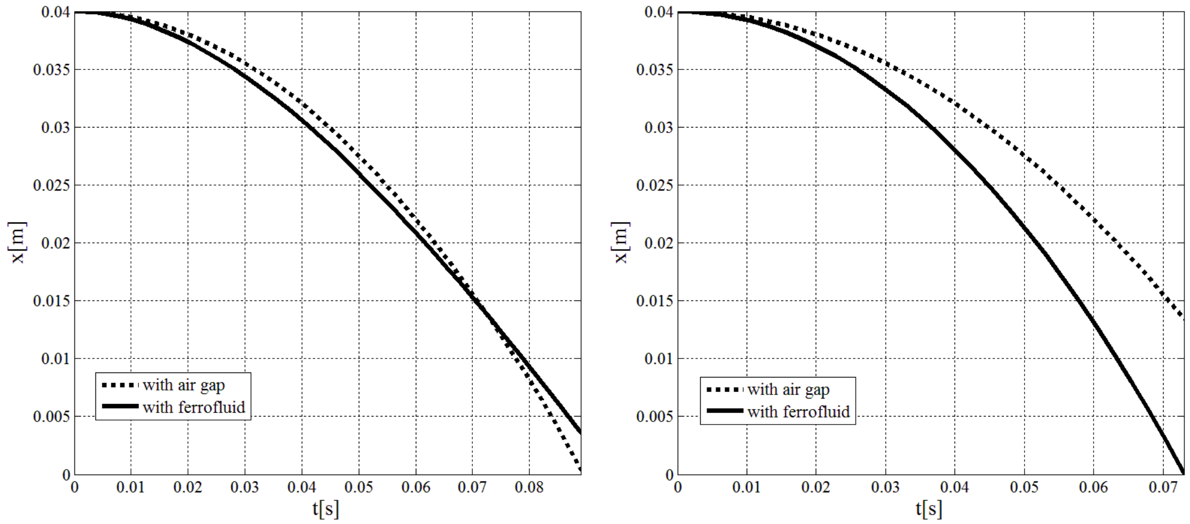

Fig. 4. Examples of simulated dynamic characteristics - position of the movable part of the actuator in time. Left - high viscous ferrofluid; right - low viscous ferrofluid in the air gap
Rys. 4. Przykłady zasymulowanych charakterystyk dynamicznych - położenie ruchomej części siłownika w funkcji czasu. Po lewej - ciecz magnetyczna o dużej lepkości, po prawej - ciecz magnetyczna o małej lepkości w szczelinie powietrznej

3. EXPERIMENTAL VERIFICATION

Experimental linear electromechanical actuator was built and its static and dynamic characteristics with and without the air gap filled with ferrofluid were measured and compared.

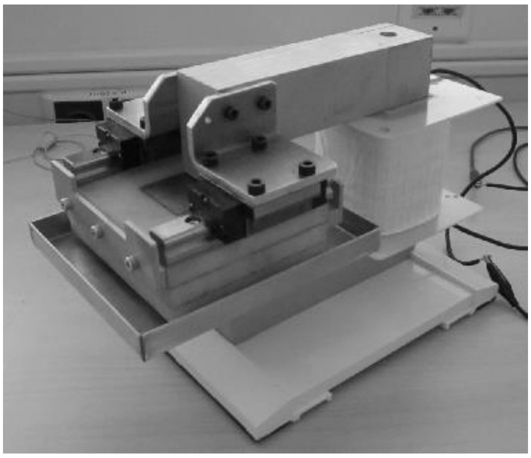

Fig. 5. Experimental linear electromechanical actuator
Rys. 5. Testowy elektromechaniczny liniowy siłownik

Working principle of this actuator can be seen in the next figure - if the winding is powered, forces between poles of magnetic circuit are generated and the movable body of the actuator moves to the zero position between poles.

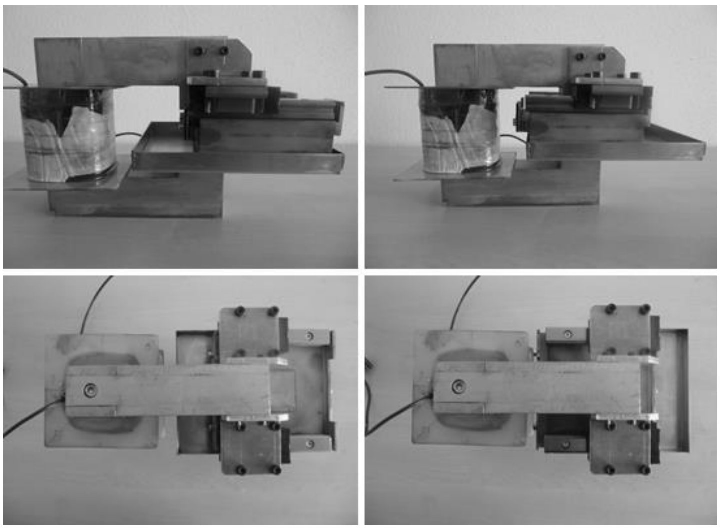

Fig. 6. Working principle of the experimental actuator - movable body placed in both maximal positions - maximal displacement and zero position
Rys. 6. Zasada działania doświadczalnego siłownika - część ruchoma w dwóch pozycjach krańcowych - przesunięcie maksymalne i pozycja spoczynkowa

Static characteristics of the force on the movable body in the horizontal direction $F(x)$ were measured by Newtonmeter Omega while the movable part was fixed in the measured position.

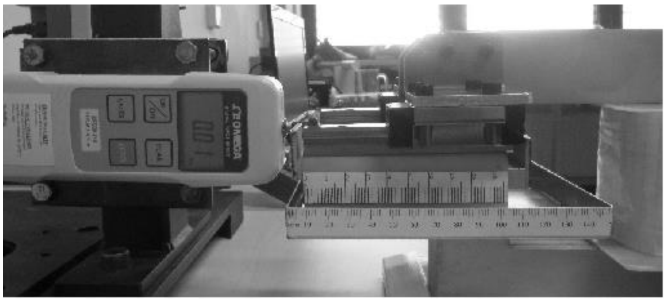

Fig.7. Apparatus for measuring the static force characteristics of the actuator
Rys. 7. Aparatura pomiarowa do pomiaru charakterystyk siły statycznej siłownika

Static characteristics with and without filling the air gap with the ferrofluid and for different values of current powering the winding were measured.

Ferrofluid Ferrotec EFH-1 with relative permeability μ_r = 1.789 in the linear part of the magnetization characteristics (a method for measurement the permeability of magnetic fluids was proposed by authors in [5]) was used to fill the air gap of the device. Force amplification was expected to be stronger if a ferrofluid with higher permeability is used.

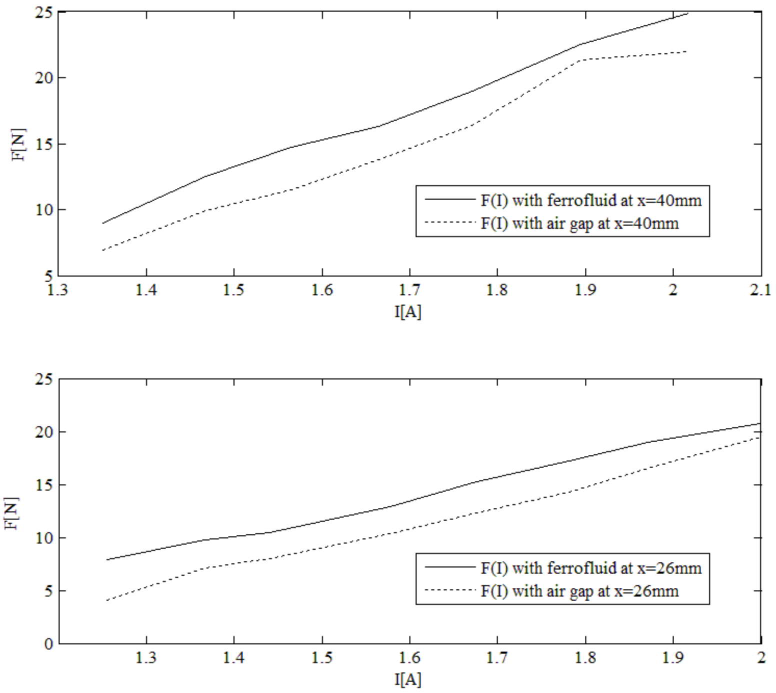

Fig. 8. Measured horizontal static forces with and without ferrofluid filled air gap at different positions of the movable body of the actuator

Rys. 8. Zmierzone poziome siły statyczne dla szczeliny powietrznej wypełnionej i niewypełnionej cieczą magnetyczną, dla różnych położeń ruchomej części siłownika

The overall performance of the device is described by its dynamical characteristics, which means function $x(t)$ as a position of the movable part vs.time. Even though the static characteristic improves with the use of ferrofluid, mechanical viscous losses that occur during the movement of the movable part in the ferrofluid may worsen the dynamics of the actuator.

Measurement of the dynamic characteristics of the electromechanical actuator was a difficult task because of high speeds of the transient phenomena, in order of tenths and even hundredths of seconds. Maximal sampling frequency of deflection meters available at our department is $f = 0.25\ s^{-1}$. From this reason the dynamics of the actuator were measured optically with the use of high-speed camera. Example of the results of one measurement can be seen in the Fig. 9.

Software Avidemux 2.6 software was used for processing obtained photos. Additional correction was needed because of optical distortion depending on the positioning of the camera and the actual position of the movable body of the actuator. The correction is simple, with knowledge of the current layout of camera, goniometrical functions were used to compute the real position $x(t)$. Examples of resulting dynamical characteristics of the device can be seen in Fig. 10.

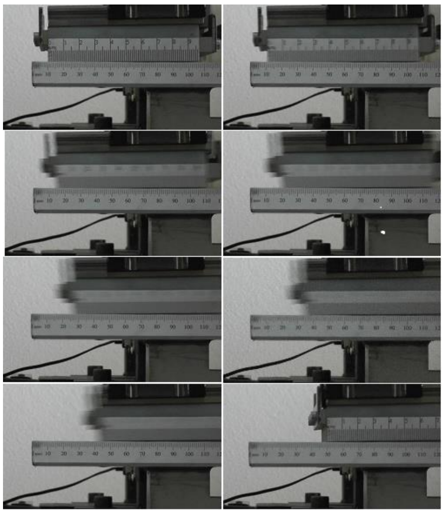

Fig. 9. Example of the results of high-speed camera measurement of the dynamic characteristics of the actuator

Rys. 9. Przykład wyników pomiaru charakterystyk dynamicznych siłownika przy użyciu aparatu o dużej prędkości robienia zdjęć (high-speed camera)

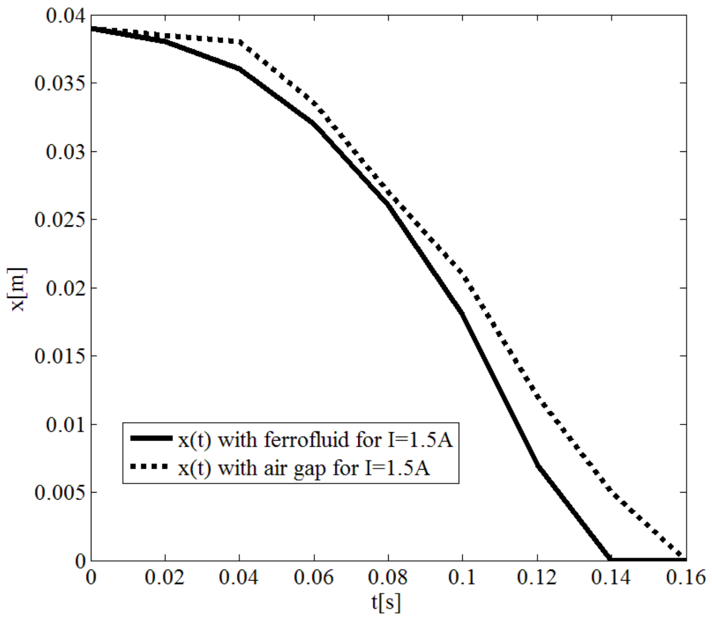

Fig. 10. Example of measured dynamical characteristics of the experimental linear electromechanical actuator; winding powered with DC I=1.5A in the steady state

Rys. 10. Przykład zmierzonych charakterystyk dynamicznych doświadczalnego liniowego elektromechanicznego siłownika; uzwojenie zasilone prądem stałym 1,5 A w stanie ustalonym

Resulting dynamic characteristics show the overall positive effect of filling the air gap with ferrofluid. Shorter duration of the dynamical phenomena when the air gap is filled with ferrofluid means that the gain in magnetic forces is stronger than the negative effect of viscous losses emerging during the movement of the body in the liquid. However, this improvement is most likely not generally valid and depends on the viscosity of the used fluid.

4. CONCLUSION

Both experimental and simulation results confirm the improvement of output of investigated linear electromechanical actuator with the use of ferrofluid in the air gap. The improvement of the force outputs of the actuator increases with the magnetic permeability of the used ferrofluid while the dynamics worsens with the rise of the fluid's viscosity due to viscous losses. In high-speed devices, highly permeable ferrofluids with as low viscosity as possible are required. These requirements may be met in near future according to current boom in nanotechnologies. Our future research will be aimed at possibilities of improvement of other types of electromechanical systems and even rotating electrical machines.

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