Ferrofluid Force Enhancement of Electromechanical Actuator

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***Abstract*—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; force enhancement

I. INTRODUCTION

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 μ_r = 1~5. Nowadays, ferrofluids are used or are planned to be used in several technical and even medical applications. Several works [1,2] are aimed on 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.

II. 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:

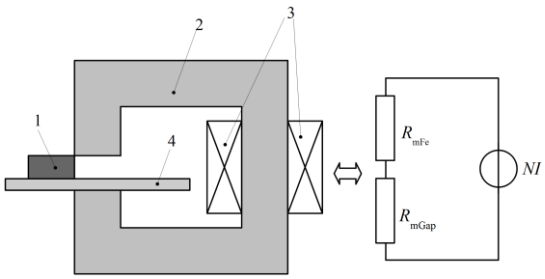

FIG.1.: SIMPLE ELECTROMECHANICAL ACTUATOR AND ITS EQUIVALENT MAGNETIC CIRCUIT;1 - MOVABLE PART, 2 -MAGNETIC CIRCUIT, 3 - WINDING, 4 - AIR GAP BETWEEN MOVABLE AND STATIC PART

Using the magnetic circuit theory, the total magnetic flux can be computed as

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

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. During our previous research (see work [2] for details), a geometrical condition of the force enhancement was formulated. The ferrofluid must be present only in the space between the movable and static part of the device, if the whole area is filled, the resulting mechanical forces are reduced. Significant gradient of permeabilities must be present in the force direction to ensure improvement of the device. This conclusion is in accordance with Korteweg-Helmholtz theory defining the density of magnetic forces [3]:

$$\boldsymbol{f}_m = \boldsymbol{J} \times \boldsymbol{B} - \frac{1}{2}\boldsymbol{H}^2 \mathrm{grad}\mu. \tag{3}$$

Static characteristics of the force [4] in the horizontal direction of one such actuator were numerically simulated with the use of FEM software Agros2D [5] and the resulting function $F(x)$ can be seen in Fig.2

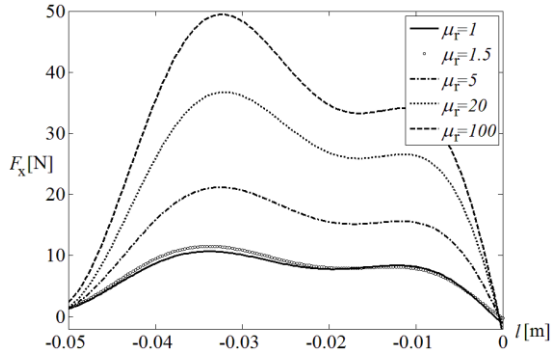

FIG.2.: STATIC CHARACTERISTICS OF THE HORIZONTAL FORCE OF ELECTROMECHANICAL ACTUATOR FOR FERROFLUIDS WITH DIFFERENT PERMEABILITIES

III. 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.

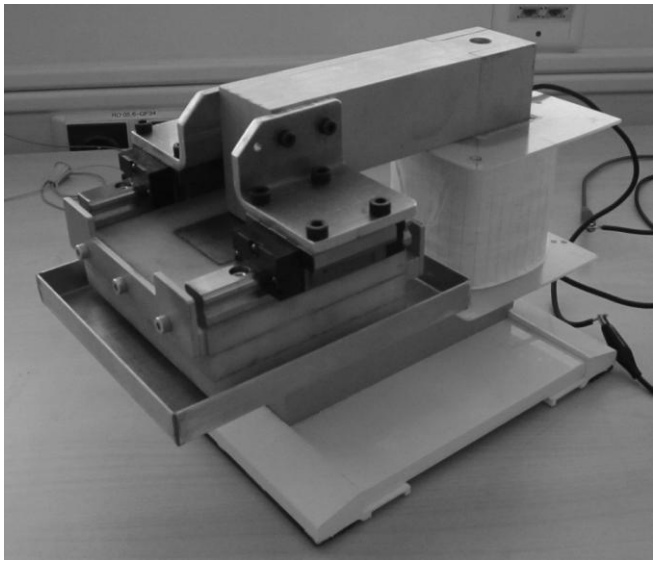

FIG.3.: EXPERIMENTAL LINEAR ELECTROMECHANICAL ACTUATOR

Linear movement of the device was realized by the use of linear bearings. The validity of geometrical condition stated by (3) was guaranteed by placing the movable part of the actuator into the block of a nonmagnetic material.

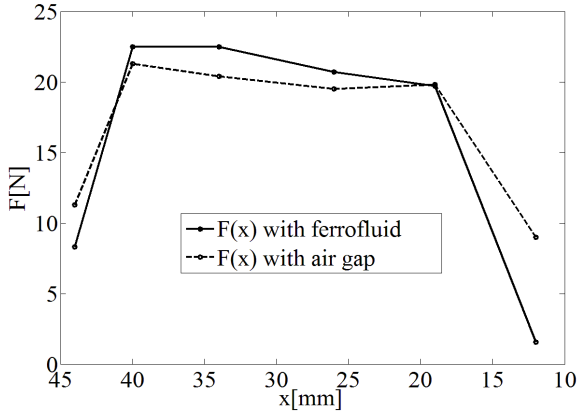

FIG.4.:MEASURED STATIC CHARACTERISTICS OF THE EXPERIMENTAL LINEAR ELECTROMECHANICAL ACTUATOR

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 author in [6]) to fill the air gap of the device. Amplification of the static forces is visible, although it is not present on the whole measured interval. Weakening near the zero position was caused by accumulating of ferrofluid in the area during the long time static measurement, the ferrofluid supports the movable body and weakens the resulting force.

Dynamic characteristics of the device was measured optically with high speed camera. The resulting phenomena is faster with the use of ferrofluid. Overall, it can be stated that the gain in mechanical forces is higher than mechanical viscous losses caused by the movement of the body in the ferrofluid.

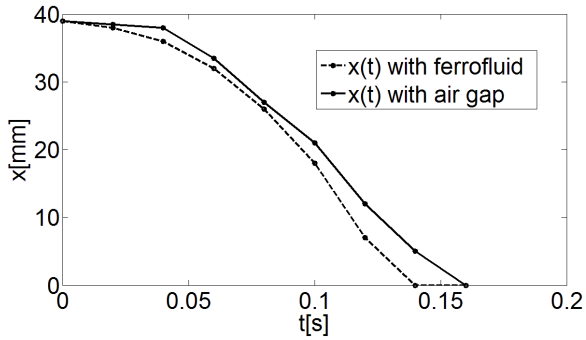

FIG.3.: MEASURED DYNAMIC CHARACTERISTICS OF THE EXPERIMENTAL LINEAR ELECTROMECHANICAL ACTUATOR

IV. Conclusion

The possibility of improving the characteristics of the electromechanical actuators by filling the air gap with ferromagnetic liquid was theoretically derived and a geometrical condition of force enhancement was stated. Results of measurements of an experimental electro-mechanical actuator confirm the correctness of our project. Future research should be aimed on the possible use of ferrofluids in air gaps of different types of electro-mechanical actuators and even electrical machines.

Acknowledgment

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