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INVESTIGATIONS ON OUTPUT DISPLACEMENT OF A FERROFLUID BASED MAGNETIC ACTUATOR

BY

ALEXANDRU ARCIRE[*] and RADU OLARU

“Gheorghe Asachi” Technical University of Iaşi
Faculty of Electrical Engineering

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Abstract. The purpose of this paper is to investigate the output displacement of a linear actuator with a non-magnetic body levitated in a ferrofluid pre-magnetized by permanent magnets and the means and possibilities to enhance its displacement characteristic linearity. Numerical simulations led to a good understanding of the processes acting inside this type of actuator and led to elaboration of a more accurate prototype model. The experimental setup allowed measurements to be effectuated on the actuator prototype which are in a good agreement with theoretical and simulation results. Doubling the number of permanent magnets and adding magnetic rings led to increasing the output displacement and improvement of the displacement *vs*. current characteristic linearity.

Key words: displacement output; ferrofluid; magnetic actuator; permanent magnets.

1. Introduction

Magnetic actuators have important advantages with respect to conventional mechanical drives: simplicity, flexibility and reliability. Most of the magnetic field driven actuators can be classified as electromagnetic, electrodynamic, magnetostrictive, magnetorheologic and ferrofluidic (magneto-fluidic). While the first three mentioned actuators have been known for a long

[*]Corresponding author: *e-mail*: arcire_alexandru@yahoo.com

time and are widely used, the ones of the latter two groups gained importance only in the last years.

A ferrofluid or magnetic fluid is a colloidal suspension of small (10 nm, typically) magnetite particles in a carrier liquid. In a non-uniform field the whole fluid responds as a homogeneous magnetic liquid which moves to the region of highest flux. Based on this effect, some actuators use a non-magnetic body immersed in the ferrofluid, its motion being controlled by an exterior applied magnetic field. The first type of actuator that uses this principle was described by Olaru *et al.*, (2000). A non-magnetic disc, immersed in a ferrofluid and placed near a coil with a magnetic core, can be moved in horizontal direction when a current passes through the coil, thus transmitting a force and a displacement by means of a rod articulated with an elastic thread. The actuator can be with simple action (one magnetic inductor) or with double action (differential, with two inductors). A double action actuator was tested as a current to pressure transducer in an electro-pneumatic converter (Olaru *et al.*, 2010). This principle can be used in controlling the vertical motion of a non-magnetic body. Lee *et al.*, (2009, 2011) have studied the position feedback control of such an actuator. A stable position control of the cylindrical non-magnetic body was obtained in a limited displacement region, inside the two coils supplied with currents that create magnetic fluxes in opposition. The principal drawbacks of the actuator are: stable levitation is obtained for large currents, between 50% and 100% of the current range and the drive force is very small.

Vertical positioning systems using different actuator configurations with a non-magnetic body levitating in a ferrofluid are described by Uhlmann *et al.* (2003, 2004, 2007). Several prototypes of precision positioning systems were developed and investigated, the influence on velocity and accuracy of positioning being discussed. Such a large scale prototype with optimized magnetic field, using a coil with a ferromagnetic core, a field former (ferromagnetic cylinder) and a ferrofluid with cobalt particles, was able to position loads of up to one kilogram, on small distances of 2…3 mm.

Sudo *et al.*, (2012), have examined the driving characteristics of a micro reciprocating magnetic fluid actuator and the dynamic behavior of magnetic fluid surface at higher frequencies of external alternating field, while Cheng Hu *et al.*, (2013), have studied the relationship between first order buoyancy force and displacement of a non-magnetic body under different relative permeability of ferrofluid, and the relationship between first order buoyancy force and the relative permeability of ferrofluid.

A new idea applied for the actuator with non-magnetic body levitated in ferrofluid consists of the use of two opposed permanent magnets to create a powerful magnetic field gradient in a ferrofluid that contains a non-magnetic body, whose motion is rigorously and stably controlled by the current in the coil (Olaru *et al.*, 2012). In this way larger drive forces can be generated for the same actuator size, than in the case of ferrofluid actuators presented in literature and described above. At the same time an increase in actuator efficiency and in the linearity of the transfer characteristics, current to force and current to displacement, is obtained. Olaru *et al*., (2012, 2013), have conducted numerical analysis of the structure, geometrical and material parameters and also experimental measurements in order to investigate the possibilities of increasing the magnetic force produced by the actuator. In this paper an experimental study concerning the current to displacement characteristics of an actuator similar to that used in a previous paper (Arcire *et al*., 2012) is performed.

2. Basic Principle of the Actuator

The principle of the double effect actuator, described in previous papers (2011, 2013), that use a non-magnetic body immersed in a ferrofluid differentially pre-magnetized by two magnets, is illustrated in Fig. 1.

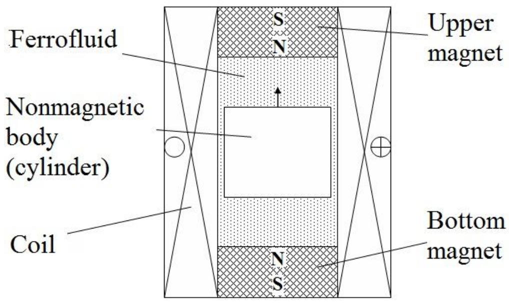

Fig. 1 – Working principle of the actuator.

In a first approximation, the magnetic levitation force may be expressed by the relation

$$F = F_1 - F_2 = 2\mu_0 \chi A H_M H_i, \tag{1}$$

where: H_I is the magnetic field produced by the coil which adds up with the enter pre-existent magnetic field of the two magnets, $H_M = H_{M1} - H_{M2}$, A – the circular surface area of non-magnetic body and χ – the ferrofluid susceptibility that is assumed to be constant.

Since the magnetic field produced by the coil is of the form $H_I = k_I I$, where, k_I , [m^{-1}], is a coefficient that depends on the geometry of the coil and the number of coil windings, the final expression for the magnetic force on the non-magnetic body placed at equal distances from the two magnets is:

$$F = 2\mu_0 k_I A M_M I, \tag{2}$$

where $M_M = \chi H_M$.

Although eqs. (1) and (2) may not be used to calculate accurately the value of the magnetic force, they have the advantage of simplicity in expression and interpretation, mentioning the main quantities and how they are involved in generating the force.

It may be concluded that, according to relation (2), the force produced by the actuator represented in Fig. 1, is directly proportional with the coil current, with the circular disc area and with the initial ferrofluid magnetization. In addition, the force is proportional to the susceptibility of the ferrofluid (see eq. (1)).

Although the magnetic field generated at any point by one magnet has a non-linear dependence *vs*. the distance point – magnet, a linear dependence can be assumed for small displacements, Δz, of the non-magnetic body due to the differential effect of the two magnets on the resultant field, so that $\Delta H_M = k_z \Delta z =$ $= H_I$, where k_z is a constant.

3. Study of the Magnetic Field Inside the Actuator

As demonstrated by Arcire *et al*., (2012), the use of magnetic material enhances the actuator's output displacement so in order to optimize it we have studied in detail the magnetic field formed by the four magnets (mounted in pairs of two at a distance of 22 mm). Also it is investigated the influence of doubling number of magnets in comparison with the model used in the mentioned paper which had only two pre-magnetizing permanent magnets.

The actuator model used in simulations, having four pre-magnetization ring magnets, is shown in Fig. 2.

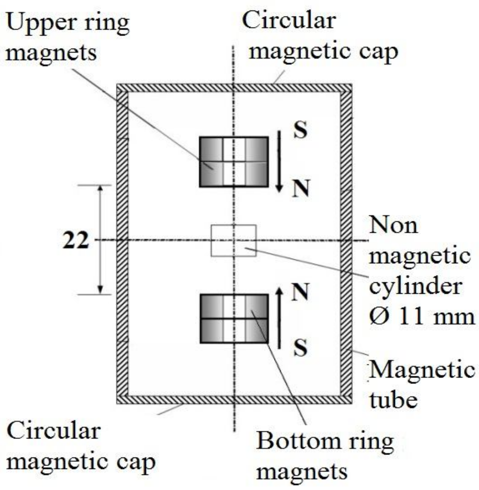

Fig. 2 – Actuator model with four magnets used in simulations.

Based on simulations conducted in Comsol Multiphysics 3.5 software we've investigated the influence of using magnetic material with respect to the magnetic field generated by the ring-shaped permanent magnets. The plot has attached on the left side a colour intensity bar, blue on the bottom of the scale being the smallest value and red on top being the biggest value of the magnetic field.

The stationary magnetic 2-D field with axial symmetry, determined with COMSOL 3.5, is based on the finite element method. The Magnetic Fields interface from the AC/DC module in COMSOL solves the differential eq. with partial derivatives

$$\nabla \times \left(\mu_0^{-1} \mu_r^{-1} \mathbf{B} \right) - \sigma \mathbf{v} \times \mathbf{B} = \mathbf{J}_e, \tag{3}$$

where $\mathbf{B} = \nabla \times \mathbf{A}$ is the magnetic flux density, $\mathbf{A}$ – the magnetic potential vector and $\mathbf{J}_e$ – the externally generated current density. The mesh consisted of approximately 10,500 elements with 22,000 nodes (degrees of freedom).

As the plot shows (Fig. 3), the maximum values of the magnetic field (1.65 T), data values provided by COMSOL is obtained by the configuration in Fig. 3. The presence of the magnetic rings on the permanent magnet acts as a magnetic field concentrator recording the highest values in the proximity of the outer edge of the rings. The use of magnetic case acts as a magnetic shield, enhancing the effect generated by the presence of magnetic rings and also has a role of mechanical protection.

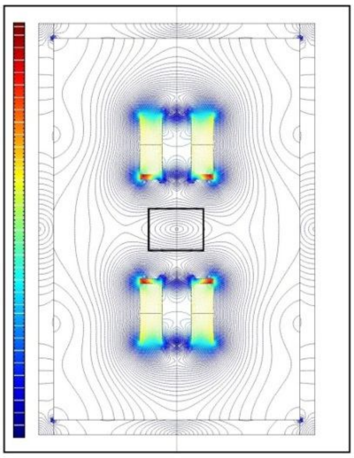

Fig. 3 – Contour view of magnetic field distribution of magnets with 1 mm magnetic ring placed on container and a magnetic case of 3 mm thickness.

Using the same software it has been simulated the axial distribution characteristic of the magnetic field, $H(z)$, in air using two or four enter pre-magnetization magnets, respectively, for a distance between magnets $z_0 =$ $= 22$ mm, with and without a magnetic field generated by the coil (Figs. 4 and 5).

In this case we use the Azimuthal Induction Currents module in COMSOL that solves the differential eq. with partial derivatives

$$\nabla \times \left(\mu^{-1} \nabla \times \mathbf{A}\right) = J_{\phi}^{(e)} \mathbf{e}_{\phi}, \tag{4}$$

where $\mathbf{A} = A_{\phi}\mathbf{e}_{\phi}$ is the magnetic potential vector, that has only a tangential component, and $J_{\phi}^{(e)}$ is the applied current density (non-zero in the coil). Second order Lagrange elements were used. The mesh consisted of approximately 6,200 elements with 38,000 nodes (degrees of freedom). The parametric solver was used in simulations that implied a scalar parameter variation (such as current or magnetic susceptibility).

Because of the ring-shaped magnets the maximum magnetic field is attained at a distance of about 4 mm from the magnet end. At the same time, increasing the number of pre-magnetization magnets leads to the increase of the magnetic field gradient in the linear zone of the curve $H(z)$. The magnetic field is maximum on the magnets surface, at a distance $r = (D + d)/4$ from the device axis, where D and d are the outer and inner diameter of the ring magnets, respectively.

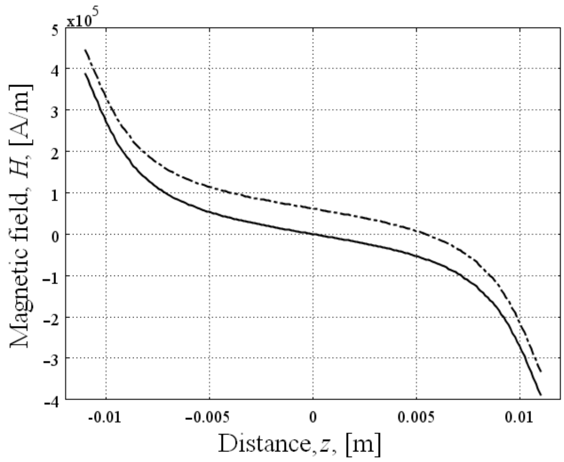

Fig. 4 – Distribution of the magnetic field along an axis parallel to the central axis at r = 5.25 mm, configuration with two pre-magnetization magnets (z between –0.011 m and +0.011 m, I = 0 solid line, I = 2 A dash-dot line).

In order to verify the results of the simulation, the magnetic field generated by the coil, H_I, and magnets, H_M, were measured separately with a Lakeshore Gaussmeter model 410 using the axial probe.

Fig. 6 shows the magnetic field generated by the magnets along an axis parallel to the central axis at r = 5.25 mm where the field is maximum on the magnet faces for the distance between magnets of z_0 = 22 mm, while Fig. 7 shows the axial distribution of the magnetic field generated by the coil of 1,750 windings of Copper Ø 0.55 mm for a current of 1 A and 2 A, respectively.

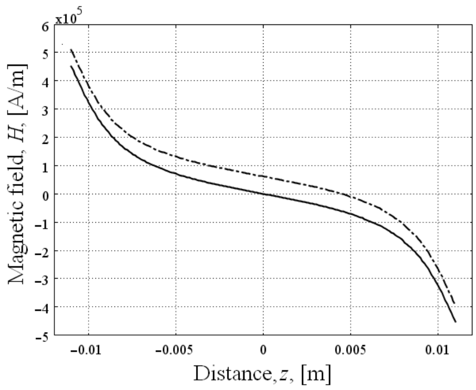

Fig. 5 – Distribution of the magnetic field along an axis parallel to the central axis at r = 5.25 mm, configuration with four pre-magnetization magnets (z between –0.011 m and +0.011 m, I = 0 solid line, I = 2 A dash-dot line).

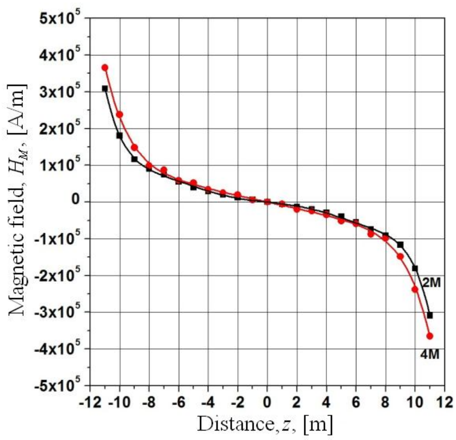

Fig. 6 – Magnetic field, H_M, along an axis parallel to the central axis at r = 5.25 mm, for two (2M) and four (4M) pre-magnetization magnets.

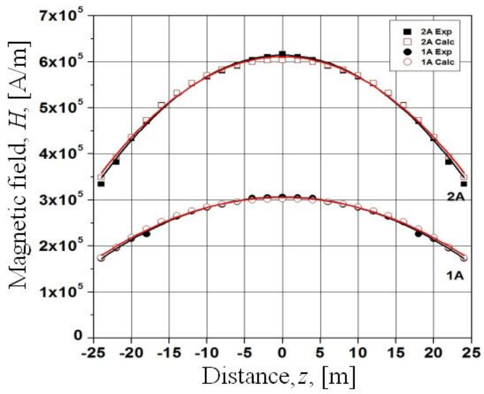

Fig. 7 – Axial distribution of the coil magnetic field, H_I, for a current of 1 A and 2 A.

Although the values of the magnetic field generated by the coil was measured axially and the field generated by the magnets was measured along an axis parallel to the central axis at r = 5.25 mm, it can be seen that the shape of the curve and the resulting field values measured experimentally by adding together magnetic fields H_M and H_I (Figs. 6 and 7) are close to the results obtained by simulation (Figs. 4 and 5), so it is considered that the experimental (Fig. 8) and simulation results are in good agreement.

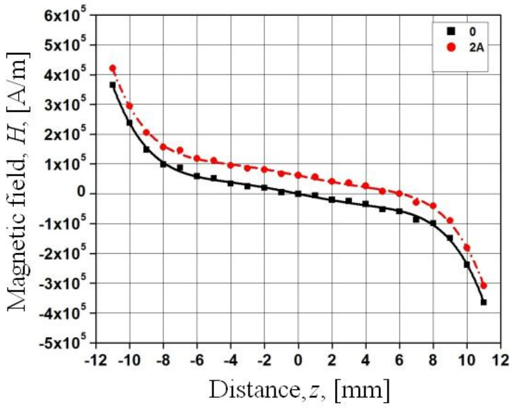

Fig. 8 – Distribution of the resulting magnetic field (H_M + H_I) in configuration with four pre-magnetization magnets (z between –0.011 m and +0.011 m) for a current of 2 A.

4. Analysis of the Actuator's Displacement Characteristics

The actuator schematic with a non-magnetic disc levitated in a ferrofluid pre-magnetized by four permanent magnets is illustrated in Fig. 9. The four ring-shaped permanent magnets mounted in pairs of two, with poles of the same name face to face, are fixed inside the coil casing (frame). In the space between the two magnets a container is disposed which houses a ferrofluid and a non-magnetic cylinder or disc. The actuator force and the disc displacement are transmitted outside by means of a rod. The prototype contains a coil with 1,750 windings of Copper Ø0.55 mm. The non-magnetic cylinder, made of a polyamide material, has a diameter of 11 mm and a height of 8 mm. The top and bottom ring magnets in Fig. 9 are two pairs of Nd-Fe-B, type R-15-06-06-N magnets (www.supermagnete.de), with the characteristics Ø15/6 mm, H = 6 mm, remanent flux density B_r = 1.3 T. The ferrofluid used (Art. FER-02, P196, www.supermagnete.de) is made with hydrocarbons similar to those found in motor oil. The initial magnetic susceptibility was measured experimentally, χ_i = = 1.2, giving an initial magnetic relative permeability, μ_{ri} = 2.2, respectively.

Based on the configuration in Fig. 9, experimental results emphasize that doubling the number of magnets (4M), for the same non-magnetic mobile body of 8 mm height and Ø11 mm diameter, improves the linearity of the actuator's displacement characteristics and also increases the stroke of the actuator with almost 20% (Fig. 10).

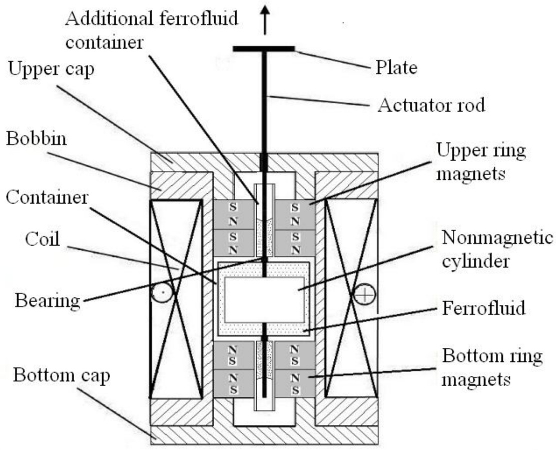

Fig. 9 – Basic actuator configuration with nonmagnetic body immersed in a ferrofluid container.

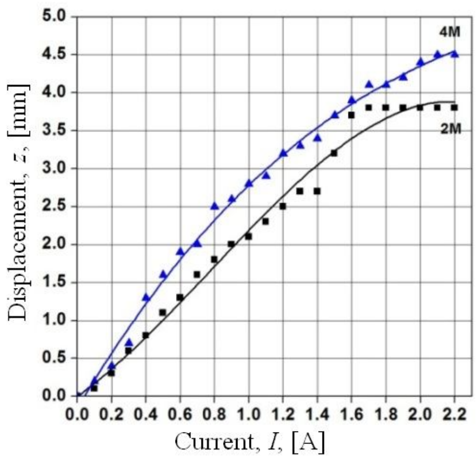

Fig. 10 – Displacement *vs.* current characteristic for two (2M) and four (4M) pre-magnetizing magnets.

In the experimental procedure it was investigated the effect of using five different heights of the movable non-magnetic cylinder, z_c = 6, 8, 10, 12 and 14 mm (with the same diameter of 11 mm), in two different configurations of the actuator (with magnetic case and with magnetic rings) on the displacement *vs.* current characteristic.

Fig. 11 shows an experimental comparison study of the non-magnetic body displacement regarding the basic actuator assembly with two pairs of permanent magnets disposed at 22 mm distance (mounted on each ends of the ferrofluid recipient) and using a magnetic case. When is used a magnetic case of 3 mm thickness the increase of the current to displacement slope is maximum 5%, but maintains for each nonmagnetic body a good linearity of the displacement characteristic (Fig. 11).

In Fig. 12 we use the same basic configuration as in Fig. 9 but in combination with a pair of two magnetic rings of 1 mm thick mounted inside the actuator on each magnet, in the space between the magnets and recipient.

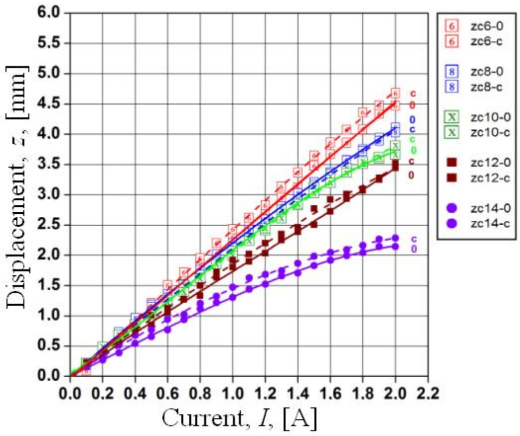

Fig. 11 – Displacement *vs.* current characteristic with (c) or without (0) magnetic case of 3 mm thickness.

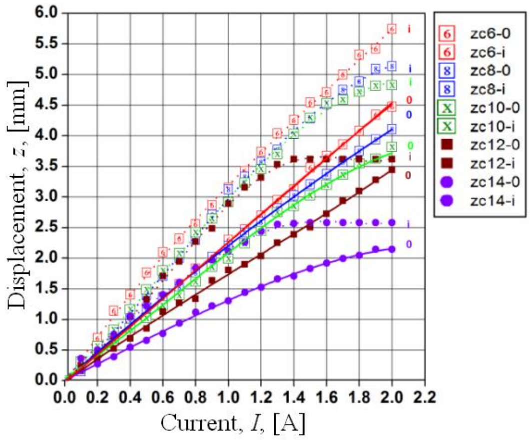

Fig. 12 – Displacement *vs.* current characteristic with (i) or without (0) magnetic rings of 1 mm thickness for different heights of the non-magnetic body.

Analysing the displacement characteristic for the configuration with magnetic rings in Fig. 12 pinpoints clearly that the maximum stroke was greatly enhanced (about 20% more) when comparing to the basic actuator configuration and maintaining a good linearity. In comparison to the values obtained with magnetic case, the ones obtained with magnetic rings are about 15% much higher (Fig. 13).

For the mobile non-magnetic body of 6 mm height the maximum stroke increases from 4.5 to 5.7 mm and for the 8 mm height body increases from 4,1 to 5.1 mm, approximately 20% (Fig. 12). All these results are in good agreement with the simulations, that comes to sustain the results obtained in Fig. 3, which indicated that an increase in displacement will certainly be obtained in the configuration with magnetic rings.

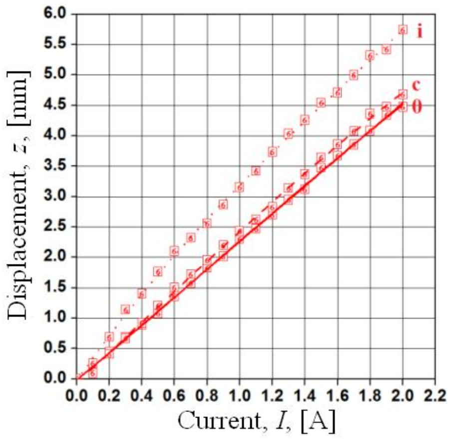

Fig. 13 – Displacement *vs.* current characteristic for the 8 mm height non-magnetic movable body with magnetic case (c) and magnetic rings (i).

In both configurations adding a magnetic material (magnetic rings or magnetic case) improves the range of the actuator output displacement for the same current fed through the coil while maintaining a very good linearity. From the five different heights of the non-magnetic body cases studied, the best displacement linearity and maximum stroke is obtained by the non-magnetic mobile body of 6 mm height with magnetic rings of 1 mm thickness.

5. Conclusions

In this paper an actuator with ferrofluid pre-magnetized by permanent magnets was studied focusing on optimizing the actuator's output displacement and the linearity of the displacement *vs*. current characteristic. Evaluation through simulation and experiment of the magnetic field acting inside this type of actuator led to an increased understanding of the complex processes that takes place in the interior of the actuator which resulted in designing a more accurate actuator having the highest slope of the current *vs*. displacement characteristic.

Doubling the number of magnets led to an increase of the actuator output displacement and an enhanced linearity of the current *vs*. displacement characteristic. The use of magnetic material in different configurations (magnetic rings and magnetic case) increases the actuator's output displacement and maintains a good linearity of the displacement characteristic.

Although the use of magnetic material in the form of magnetic case of 3 mm thickness increases the maximum stroke with about 5%, the use of magnetic rings mounted on the interior face of the permanent magnets significantly enhance the output displacement of the actuator (with about 20%) while maintains a good linearity of the actuator displacement characteristic.

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INVESTIGAŢII PRIVIND DEPLASAREA OBŢINUTĂ LA IEŞIREA UNUI ACTUATOR MAGNETIC BAZAT PE FEROFLUID

(Rezumat)

Scopul acestui articol îl constituie studiul deplasării obţinute la ieşirea unui actuator liniar cu corp nemagnetic levitat în ferofluid premagnetizat cu magneţi permanenţi şi posibilităţile de a îmbunătăţi liniaritatea caracteristicii deplasare–curent. Simulările realizate au condus la o bună înţelegere a proceselor ce au loc în interiorul actuatorului şi la elaborarea unui prototip îmbunătăţit. Aranjamentul experimental a permis obţinerea de rezultate experimentale care sunt în bună concordanţă cu rezultatele simulărilor. Dublarea numărului de magneţi permanenţi şi introducerea de inele feromagnetice în configuraţia actuatorului au condus la creşterea cursei maxime şi îmbunătăţirea liniarităţii caracteristicii deplasare-curent.