NEW LINEAR ACTUATOR WITH FERROFLUID AND PERMANENT MAGNETS

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In this paper an actuator with a new magnetic configuration having a nonmagnetic cylinder (or disc) in a ferrofluid differentially pre-magnetized by permanent magnets is studied by simulation and experiment. This prototype shows superior performance compared to an actuator with basic magnetic configuration. The new actuator exerts a force approximately three times higher than the basic actuator. In addition, the transfer characteristics, current versus displacement and force, have a better linearity.

1. INTRODUCTION

Ferrofluids or magnetic fluids are suspensions of magnetic particles of a few nanometers (a diameter of approximately 10 nm) stabilized by surfactants in carrier liquids. This combination of fluidic and magnetic properties of the ferrofluid is exploited in a wide range of applications [1–8].

If a magnetizable body is exposed to a magnetic field, a magnetic force is exerted on it. Therefore a non-magnetic body immersed in a ferrofluid, which is exposed to a magnetic field produced by an external source (magnet or electromagnet), is subjected to a magnetic pressure. As a direct consequence, a force, equal and opposite to the magnetic force acting on the volume of ferrofluid displaced by that body, results. This force can be used in the levitation of the nonmagnetic body, the effect being known as the first order bouncy magnetic force, or in generation of forces and displacements with actuators designed for this purpose. As presented in [9], since 2000, actuators based on this principle were proposed, both for small [10–12] as well as for large forces [13–14], so that a prototype was capable of positioning loads of up to 1 kg on small distances of 2–3 mm. Most of these applicators work only in vertical position and the control of levitation is difficult because the restoring force due to gravitation is not adequate enough for a stable levitation. For stable levitation of a buoyant body such that a negative
restoring force accompanies any small displacement from equilibrium, it is required that \( \delta H > 0 \), where \( \delta H \) is the variation of magnetic field in the direction of displacement [15]. This is possible if two magnetic fields of opposite directions are produced in the ferrofluid by coils or permanent magnets. The stabilization method with magnets is preferred because opposing magnets create a powerful magnetic field gradient in the ferrofluid that contains a nonmagnetic body, and therefore large forces can be generated.

We have previously formulated [16] the practical principle, to obtain a stable state in functioning of actuators that use a nonmagnetic body immersed in a ferrofluid. This principle states that a nonmagnetic body immersed in a ferrofluid can be stably positioned if a differential magnetization of the ferrofluid, in the direction of motion, is ensured. This magnetization is achieved by applying two opposite magnetic bias fields, produced by coils or permanent magnets.

In the following sections a new version of an actuator with nonmagnetic body immersed in a ferrofluid differentially magnetized by permanent magnets is described and studied by simulation and experiment.

2. WORKING PRINCIPLE OF THE ACTUATOR

The basic actuator [17], which is schematically illustrated in Fig. 1, is composed of two fixed ring-shaped permanent magnets, with poles set in repulsive position, disposed symmetrically on the top and bottom of the ferrofluid container. Magnetic counterforces, developed in the differentially magnetized ferrofluid, move the nonmagnetic cylinder (disc) in the middle position of the ferrofluid container. The magnetic field produced by a current through the coil will increase the magnetic field produced by one magnet and decrease with the same amount the magnetic field of the second magnet. Thus, the non-magnetic disc moves to a new position where the magnetic fields on the flat disc faces are equal in magnitude giving a null resulting force. The magnetic force \( F_m \) acting on the cylinder, set in the initial equilibrium position, for a given current \( I \) in the coil, can be estimated with one of the equivalent expressions [16]:

\[
F_m = 2\mu_0 \chi A H_M H_I, \quad F_m = 2\mu_0 k_I A M_M I \quad \text{or} \quad F_m = 2\mu_0 A M_M H_I, \tag{1}
\]

where \( \mu_0 \) is the magnetic permeability of vacuum, \( \chi \) is the magnetic susceptibility of the ferrofluid, \( A \) is the area of the cylinder circular surface, \( H_M \) and \( M_M \) are the magnetic field and magnetization produced by the two magnets near the circular nonmagnetic body surfaces, \( H_I = k_I I \) is the magnetic field produced by the coil and \( k_I \) [m\(^{-1}\)] is a coefficient that depends on the geometry and the number of windings in the coil.
The expression for the actuator transfer characteristic, displacement versus current, is:

\[ x = \frac{k_i}{k_z} = k I, \]  

(2)

where \( k_z [\text{A/m}^2] \) is a coefficient and \( k = \frac{k_i}{k_z} \) is the transfer factor.

Equation (2) suggests that the actuator has a linear response, which is of great importance in applications that require precision positioning.

Theoretical, simulation and experimental results show that the following techniques can be applied in order to increase the actuator force [17]:

- the increase in the number of magnets pairs or the length of the two magnets;
- the use of a ferrofluid with high magnetic susceptibility (as shown by the first equation in (1), eq. (1));
- the increase of the distance between the magnetization magnets and, at the same time, the rise in the height of the non-magnetic cylinder \( (z_b) \), for a maximum reduction of the distance between cylinder and magnets; maximizing the force in this way implies the reduction of the maximum displacement (stroke) of the device;
- usage of a ferromagnetic casing which ensures at the same time a mechanical protection and an electromagnetic shielding; the thickness and magnetic permeability of the shield do not have significant influence on the force;
- increasing the size of the non-magnetic cylinder radius also contributes to the growth of the actuator output force.
3. NEW ACTUATOR
WITH IMPROVED ELECTROMAGNETIC CONFIGURATION

A schematic model of the new actuator is illustrated in Fig. 2. The magnetic structure, with the ferrofluid container and the nonmagnetic cylinder at its center, consists of two ring magnets and three ferromagnetic parts (one shaped as a ring and two shaped as a disc) disposed around the ferrofluid container. In order to be efficient, the new structure, including the coil, must be shielded by a ferromagnetic casing. The main advantage of the new structure compared to the basic model is that it ensures an important increase of the magnetic flux and of the magnetic field, $H_I$, produced by the coil, thus increasing the resulting force produced by the actuator (see eq. (1), and (1)$$_3$).

3.1 ANALYSIS BY SIMULATION OF THE ACTUATOR

The actuator used in simulations (Fig. 2) has ring-shaped permanent magnets type R-27-16-05 [18], made of NdFeB, with remanent magnetic flux density $B_r=1.3$ T, having the outer diameter of 27 mm, the inner diameter 16 mm and the height 5 mm. The coil has 1750 copper wire windings, with a diameter of 0.55 mm. The nonlinear characteristic of the ferrofluid, type MH-UTR, experimentally determined, was taken into account during numerical computations.

Simulations have been conducted using COMSOL Multiphysics and aimed to determine the actuator geometrical parameters that give a maximum output force. Experimental tests showed that, for practical purposes, a 5 mm high ferromagnetic ring is enough to cancel the counterforce between the upper and the lower magnet, thus facilitating the structure assembling.

Preliminary simulations showed that a height larger than 5 mm of the magnetic ring and of the two circular magnetic discs does not lead to an increase of the resulting force. Consequently the same height, $h = 5$ mm, was chosen for all ferromagnetic pieces. The main problem remains the number of ring magnets that gives the maximum force in a convenient actuator geometry (height/diameter ratio). At the same time the optimal geometry must be in direct connection with the design specifications of the actuator and its specific applications. In both cases a flattened geometry must be avoided.

Figures 3–8 show the transfer characteristics magnetic force versus current, $F(I)$, for the actuator with 2, 4 and 6 magnets, in configurations with or without casing (shield). The number of coil wires is $N = 1750$ and the relative magnetic permeability of the inner ferromagnetic parts is $\mu_r = 200$. In order to compare the results, the same values of the maximum (theoretical) displacement of the nonmagnetic body in the ferrofluid were used, ± 6 mm and ± 3 mm, respectively, for each set of values of $z_b$. The dimensions of the magnetic structure (diameter and height) were modified in order to keep a constant $N$. 

Fig. 3 – $F(I)$ for actuator with 2 magnets, $z_h = 2$ mm.

Fig. 4 – $F(I)$ for actuator with 2 magnets, $z_h = 6$ mm.

Fig. 5 – $F(I)$ for actuator with 4 magnets, $z_h = 8$ mm.

Fig. 6 – $F(I)$ for actuator with 4 magnets, $z_h = 14$ mm.

Fig. 7 – $F(I)$ for actuator with 6 magnets, $z_h = 18$ mm.

Fig. 8 – $F(I)$ for actuator with 6 magnets, $z_h = 24$ mm.
Table 1 presents the values of the force for $I = 2\text{A}$, in the case of the actuator structure with 2, 4, and 6 magnets, for several values of the nonmagnetic body height, $z_b$, and for different casing permeabilities $\mu_C$. The force decreases for increasing number of magnets, due to the decrease of the coil field for the same number of wires, when the length/ diameter ratio of the coil increases.

The axial magnetic field distribution for the actuator with four magnets, without (Fig.9) and with magnetic casing (Fig.10), shows an important increase of the magnetic field produced by the coil $H_I$ ($I = 2\text{A}$) in the presence of the magnetic casing. For example, with a nonmagnetic cylinder 10 mm long, the magnetic field produced by the coil at $z = \pm 5\text{mm}$ is 70 kA/m for the unshielded actuator and rises up to 120 kA/m in the shielded case.

<table>
<thead>
<tr>
<th>Number of magnets</th>
<th>$\mu_C$</th>
<th>1</th>
<th>200</th>
<th>1</th>
<th>200</th>
<th>500</th>
<th>1</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z_b$ (mm)</td>
<td></td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>6</td>
<td>8</td>
<td>14</td>
<td>8</td>
</tr>
<tr>
<td>$F(N)$ $I = 2\text{A}$</td>
<td></td>
<td>0.12</td>
<td>0.25</td>
<td>0.24</td>
<td>0.66</td>
<td>0.24</td>
<td>0.28</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.49</td>
<td>0.58</td>
<td>0.25</td>
<td>0.4</td>
<td>0.25</td>
<td>0.4</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 9 – Magnetic field on the axis for the actuator with 4 magnets, without magnetic casing.

Fig. 10 – Magnetic field on the axis for the actuator with 4 magnets and magnetic casing.

3.2. EXPERIMENTAL RESULTS

The actuator and the experimental setup for displacement measurement are illustrated in Fig.11. Figure 12 presents the experimental current-displacement characteristic obtained by using a laser telemeter, type Bosch GLM 100c, for contactless measurement of displacement. The precision of the instrument is 0.1 mm
which is sufficient for this experiment. The values were introduced in the graphic program Origin v.8.6 that gives the plot of the transfer characteristic $z(I)$. The transfer characteristic current versus displacement, $z(I)$, exhibits a good linearity.

The analysis of the force, which is delivered by the actuator, was performed using a setup consisting of a 200g cell force and an electronic circuit for signal conditioning and amplification. Together with the interface program and the data acquisition board, the entire measuring device can have an accurate calibration, using standard weights for the force range implied in this application.

The dependance force as a function of current, $F(I)$ is presented in Fig. 13. A ferrofluid, type MF-UTR, with the saturation magnetization $M_s = 33$ kA/m and the initial magnetic susceptibility $\chi_m = 0.74$, was used. Increasing the height of the nonmagnetic body from 8 to 14 mm determines a 30% increase of the force, but the usage of ferromagnetic casing that completely encompasses the actuator, determines a rise of the force by over 50%, for both values of the nonmagnetic body heights.

In order to reveal the influence of the ferrofluid magnetic susceptibility, Fig.14 shows the characteristic $F(I)$ of the shielded actuator for three values of the initial susceptibility $\chi_m$: 0.74, 1.1 and 1.3, respectively, corresponding to the three types of ferrofluid (MF-UTR, EFH1 and FER-02) used in the laboratory experiments. The slope of the curves increases with the magnetic susceptibility and the height of the nonmagnetic body.
Fig. 13 – Force vs. current, $F(I)$, for actuator with ferrofluid MF-UTR, without and with magnetic casing, $z_h = 8$ and 14 mm.

Fig. 14 – Force vs. current, $F(I)$, for actuator with magnetic casing and 3 ferrofluids having different magnetic initial susceptibility: $\chi_i = 0.74$ (MF-UTR), $\chi_i = 1.1$ (EFH1) and $\chi_i = 1.3$ (FER-02).

4. CONCLUSIONS

An actuator with a nonmagnetic cylinder placed in a ferrofluid magnetized by permanent magnets with an imposed magnetic structure was proposed and analyzed by simulation and experimental measurements. The magnetic structure, that contains a cylinder with a ferrofluid and a nonmagnetic disc immersed in it, has a compact design, consisting of four ring magnets and three ferromagnetic pieces - one central ring and two circular discs. In order to be efficient the structure must be shielded with a ferromagnetic casing. The main advantage of the new structure, compared to the basic actuator model, is that, by using a lateral positioning of the ring magnets, an important increase of the magnetic flux and magnetic field is obtained in the working zone of the nonmagnetic mobile disc, thus increasing the force rendered by the actuator. The influence of the magnetic shield is more important compared to the basic actuator. Following the experimental testing and simulations in COMSOL it was found that the structure that maximizes the magnetic force and, at the same time, is not out of proportions, consists of $2 \times 2$ R-27-16-05 ring magnets, one central ferromagnetic ring and two circular ferromagnetic outer discs, all of these being 5 mm in height. The device must be encompassed by a 2 to 3 mm thick shield in close contact with the other components.

The results obtained by simulation and experiment show a significant increase of the generated force, almost three times larger than in the case of the basic actuator model. At the same time an improved linearity of the force-displacement characteristic is obtained.

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