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VERTICAL DISPLACEMENT ACTUATOR WITH NON-MAGNETIC BODY IMMERSED IN FERROFLUID

BY

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Abstract. A new type of actuator with a nonmagnetic body immersed in a ferrofluid is presented, its position being controlled by a command current in the surrounding coils. The actuator was theoretically and experimentally analysed, two different theoretical methods in determining the magnetic force being used, one based on analytical methods and the second one using a software simulation. Two different methods in feeding the coils are studied: without and with polarization current (using a differential command). The second one has led to a quasi-linear current displacement characteristic.

Key words: magnetic actuator; ferrofluid; magnetic force.

1. Introduction

A principle used for generating mechanical actions in ferrofluid devices consists in changing the position of a non-magnetic body immersed in the ferrofluid, when exposed to field gradient (Rosensweing, 1985). An application of the phenomenon is the micro-positioning system (Lee *et al.*, 2009; Uhlmann & Bayat, 2006). In such systems levitation occurs due to the combined action of an electromagnetically controlled field and gravity (Olaru *et al.*, 2000; 2011).

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This paper presents a study of a magnetic fluid actuator with a nonmagnetic body immersed in the ferrofluid.

2. Working Principle

The analysed actuator, presented in Fig. 1, produces mechanical displacements based on the phenomenon of magnetic levitation acting upon a non-magnetic body immersed in the ferrofluid. The non-magnetic body, having a cylindrical shape, is placed inside a container filled with ferrofluid so that, in the absence of any magnetic force, the body is subjected only to gravity and Archimedes force. Around the ferrofluid chamber two identical, ring shaped coils, are placed, which provide the magnetic field able to lift the non-magnetic body. By feeding the coil with a constant current, the magnetic field changes the steady-state of ferrofluid and thus generates a magnetic force, acting upon the nonmagnetic body (Lee *et al.*, 2009).

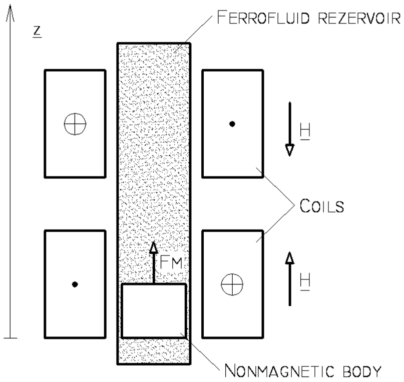

Fig. 1 – Principle model of the actuator with non-magnetic body immersed in the ferrofluid.

In order to determine this force the expression of the differential pressure in the ferrofluid subjected to an external magnetic field is used namely

$$\Delta p = m_0 \int_0^{H_{\max}} M \mathrm{d}H, \tag{1}$$

where: m_0 is the vacuum permeability, $\overline{M}$ – ferrofluid magnetization and $\overline{H}$ – the magnetic field strength with the maximum value $H_{\max}$.

Based on the expression of the pressure difference the magnetic force acting on the mobile element can be determined

$$F_M = A\Delta p \tag{2}$$

The ferrofluid magnetization, **M**, depends on the external magnetic field:

$$\mathbf{M} = c_i \mathbf{H}\,, \tag{3}$$

where c_i is the magnetic susceptibility of the ferrofluid.

Introducing relations (1) and (2) in (3) the magnetic force becomes

$$F_M = m_0 A c_i \int_{H_1}^{H_2} H \mathrm{d}H = \frac{m_0 A c_i}{2}\left(H_1^2 - H_2^2\right), \tag{4}$$

where H_1 and H_2 are the magnetic fields corresponding to the two sides of non-magnetic body.

Thus the resulting force, including gravity and Archimedes force is

$$F = \frac{m_0 A c_i}{2}\left(H_1^2 - H_2^2\right) - gV\left(r_b - r_f\right), \tag{5}$$

where: ρ_b and ρ_f are the non-magnetic body density and ferrofluid density, respectively, and g – the gravitational acceleration. As can be seen from the last relation, the body sinks when introduced into the ferrofluid if $\rho_b > \rho_f$, in the absence of any magnetic field. In the presence of an external magnetic field, the non-magnetic body can be positioned in a desired position by controlling $\nabla\mathbf{H}$, so that stable levitation conditions can be expressed by

$$F_m \geq \left(r_b - r_f\right)g = a\ . \tag{6}$$

3. Analytical and Simulated Determination of the Magnetic Force

For the analytical calculation of the magnetic force acting upon the nonmagnetic body relation (4) is used. Constructive parameters of the actuator used in calculations are: coil length, l = 20 mm, coil inner and outer radius, r_1 = 9 mm and r_2 = 25 mm, number of wires N = 900, distance between coils, d =10 mm, actuator height, H = 60 mm. The magnetic force was calculated analytic-cally along the z-axis. In Fig. 2 the force variation acting on non-magnetic body is presented; it was calculated for four values of current in the coil: 0.25, 0.5, 0.75 and 1 A, the coils being connected in series and carrying currents of opposite signs. On this chart the minimum force for vertical lift of the non-magnetic body was also drawn, a = 2.44 mN, calculated for the physical model data. Using the same relation utilized to determine the force, we can calculate the current value for which the condition of levitation is met, $F_m = a$, namely I_p = 0.26A. In Fig. 3 the dependence $F_m(z)$, obtained by software simulation (Petrescu *et al.*, 2011), is presented for several current values, $I = I_1 = I_2 = 0.25, 0.5, 0.75, 1$ A. As may be seen the dependence is always sinusoidal and the condition $F_m(z) = 0$ is obtained in exactly the same positions.

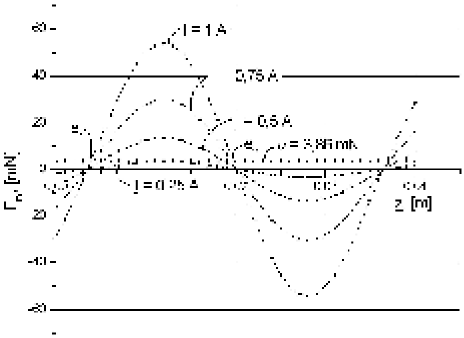

Fig. 2 – Magnetic force *vs*. displacement, analytically calculated, for several current steps.

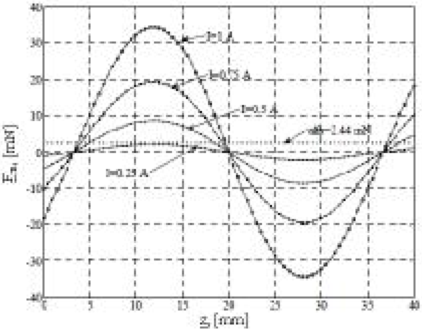

Fig. 3 – Software simulated force *vs*. displacement characteristic (Petrescu *et al.*, 2011).

As can be seen, the simulation confirmed the analytical determinations, the differences being due to simplifying assumptions adopted for ease of calculation. From these charts the useful force area, corresponding to $F_m > 0$, can be also delimitated, being between $z = 3$ mm and $z = 20$ mm. Inside this area there are two equilibrium points, corresponding to $F_m = a$, one on the rising slope (e_1) and one on the decreasing force area (e_2). In section e_1 there is an unstable equilibrium, the non-magnetic body reaching this point tends to move to the stable equilibrium point e_2. In contrast, in point e_2 the body is in a position of stable equilibrium, precise control of its position can be realized by proper control of currents in the coil.

4. Differential Actuator

Considering the expression of the magnetic force, given by (4), F_m varies according to the square current through the coils, and a non-linear force *vs*. current characteristic has been obtained (Fig. 4). In order to achieve a linear response to current command, maintaining the actual structure of the actuator, a new way of feeding the coils is proposed, by differential command current. From a polarization current, I_0, that runs through both windings initially, the inferior winding current is increased in the interval $[I_0, I_{\max}]$, while decreasing it through the upper one in the range $[I_0, 0]$.

In the case of differential command current the input parameter of the system is considered to be ΔI, the difference between the currents through the two coil windings, $\Delta I = I_1 - I_2$. This leads to a linear increase of the force exerted on the non-magnetic body relative to ΔI, facilitating a more precise control over it. In Fig. 4 the magnetic force *vs*. command current, determined analytically, is presented for three different cases: windings are fed with differential currents and the non-magnetic body is placed at z = 14 mm and respectively z = 20 mm from the origin; for comparison, the case when the windings are fed with opposite currents for z = 14 mm is also presented.

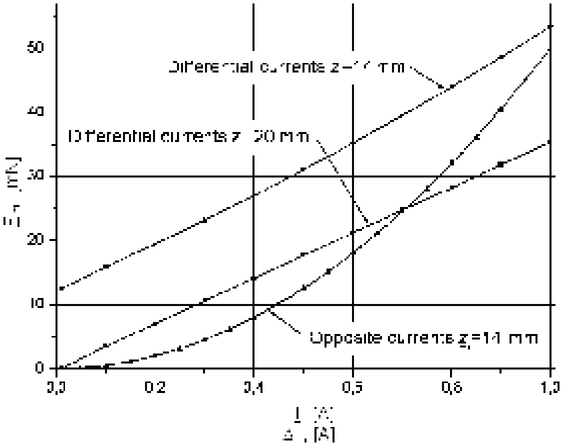

Fig. 4 – Magnetic force *vs*. command current, differential current, respectively.

5. Experimental Results

The actuator was supplied by a constant voltage source and measurements were made to determine the non-magnetic body movement depending on the command current value. Measurements were made in the range 0,…,1 A, for three initial positions of the non-magnetic body (z = 5, 10 and 15 mm), (Fig. 5). For z = 5 and 10 mm, when reaching the unstable equilibrium point e_1, the body is levitated upwards to the position of stable equilibrium e_2, thus precise control of its position can not be achieved. If the actuator is controlled in the decreasing magnetic force zone, $z \in$ [~12 mm, ~19 mm], the non-magnetic body position control can be achieved easily. The displacement *vs*. current characteristic for z = 15 mm, is approximately linear, however the actual movement of the body is limited to about 5 mm. To test the differential actuator the two windings of the coil where supplied separately. Considering the maximum coil current 1 A, I_0 = 0.5 A was chosen for the initial polarization current. According to the graph in Fig 4, the non-magnetic body was placed in the initial position z_i = 20 mm, corresponding to F_m = 0 N. Increasing the current through the lower winding, and decreasing it through the higher one, the body could be vertical levitated, the characteristic $z(\Delta I)$ showing a nearly linear increase (Fig. 6). The point of separation corresponds to a differential current of approx 0.2 A, point where the magnetic force equals a. In the interval 0.2…1 A the non-magnetic body was moved in upward direction along the *z*-axis, reaching a maximum displacement of about 22 mm. Unlike the method of supplying windings with opposite currents, when using the differential current command, an almost linear $z(\Delta I)$ characteristic is attained, improving body control, an extension on the non-magnetic body stable displacement zone being also achieved.

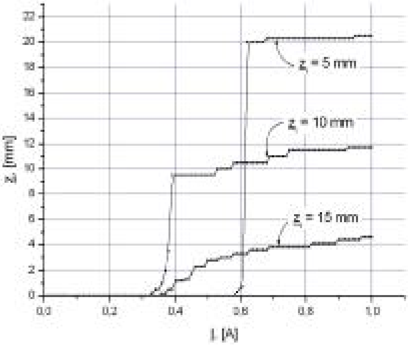

Fig. 5 – Measured $z(\Delta I)$ characteristic when windings are fed with opposite currents.

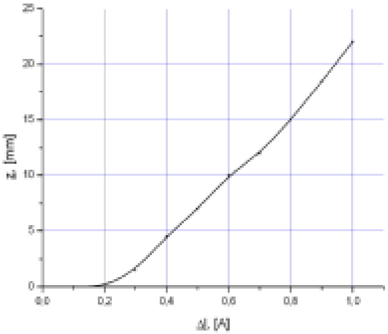

Fig. 6 – Quasi-linear $z(\Delta I)$ characteristic obtained by differential current command.

6. Conclusions

In this paper a vertical displacement actuator with non-magnetic body immersed in the ferrofluid, using both theoretical and experimental methods was analysed. The magnetic force expression was determined from the relation that defines the difference of pressure in a volume of ferrofluid subjected to an external magnetic field. Using simulation and experimental methods the accuracy of the developed magnetic force expression was demonstrated. The new method of feeding the coils, by differential current command, leads to a quasi-linear current *vs.* displacement characteristic, and also to an extended operation interval for the actuator.

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ACTUATOR PENTRU DEPLASĂRI PE VERTICALĂ CU CORP NEMAGNETIC CUFUNDAT ÎN FEROFLUID

(Rezumat)

Se prezintă un tip nou de actuator cu corp nemagnetic cufundat în ferrofluid, a cărui poziţie este controlată prin comanda curentului în bobinele plasate în spaţiul învecinat. Actuatorul a fost analizat, atât experimental cât şi practic, iar în cadrul lucrării sunt prezentate o serie de rezultate obţinute. În cadrul etapei experimentale au fost utilizate două metode de determinare a forţei magnetice ce acţionează asupra corpului nemagnetic; prima are la bază principii analitice de calcul, iar a doua utilizează un soft de simulare. Au fost studiate două metode de alimentare a bobinelor: cu şi fără curent de polarizare. A doua variantă a condus la o caracteristică deplasare–curent cvasi-liniară.