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A new type magnetofluidic actuator

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Abstract

A new type magnetofluidic actuator, based on the magnetic fluid free surface profile around a linear vertical electric current is presented in the paper. It consists of a nonmagnetic box with a horizontal separating wall with orifices, containing a magnetic fluid in the lower part, water in the higher part and an optical device in the lower part opposite to the commanding electric current wire. When the box is placed near a vertical electric wire, the magnetic fluid's free surface reaches its equilibrium profile in a time interval depending on orifice dimensions and allows the optical device to give a command signal. Advantages such as simplicity of design and construction, high reliability determined by inexistence of moving mechanical parts and large range of working electric current intensities are put into evidence.

Keywords: Magnetic fluid; Actuator; Vertical linear electric current

1. Introduction

The special magnetic and fluidic properties of the magnetic fluids make them very useful in a large area of technical applications [1–5]. There is, however, a physical phenomenon, less exploited for technical applications.

If a magnetic fluid is placed near a vertical linear wire with an electric current, the magnetic forces determine its vertical movement towards the upper part of the wire, reaching an equilibrium free surface profile depending on electric current intensity and magnetic fluid characteristics [6,7]. The free surface profile was theoretically and experimentally studied in several particular cases in which theoretical expressions can be analytically approximated. A more general study, for real cases, must use numerical approximation methods, using computer-aided design, and is the subject of this paper.

2. Theoretical aspects

Let us consider a vertical linear electric conductor (1) passing through the symmetry centre of a cylindrical nonmagnetic vessel (2) containing a magnetic fluid (3), as can be seen in Fig. 1. A horizontal profile of the magnetic fluid free surface (4) is obtained. If an electric current with intensity I passes through the wire, the magnetic field gradient around the wire generates a magnetic force on the magnetic fluid and a new profile of the magnetic fluid free surface (5) is obtained in the equilibrium state.

The profile equation as a function of electric current intensity and magnetic fluid characteristics was determined starting from Bernoulli equation and has the expression

$$\Delta z(I,r,r_0) = z(I,r) - z(I,r_0) = \frac{\mu_0}{\rho_{\mathrm{MF}} g}\int_{H(I,r_0)}^{H(I,r)} M_{\mathrm{MF}}(I,r)\,\mathrm{d}H(I,r), \quad (1)$$

where μ_0 is the vacuum permeability, g is gravitational acceleration and ρ_{MF} is magnetic fluid density. The magnetic fluid magnetization is given, for low concentrated magnetic fluids, by

$$M_{\mathrm{MF}}(I,r) = \varepsilon_{\mathrm{M}} M_{\mathrm{S}}\left[\sum_{n=1}^{N} p_n\left(\coth\frac{\mu_0 M_{\mathrm{S}} V_{M_n} H(I,r)}{kT} - \frac{kT}{\mu_0 M_{\mathrm{S}} V_{M_n} H(I,r)}\right)\right]\frac{1}{\sum_{n=1}^{N} p_n V_{M_n}}, \quad (2)$$

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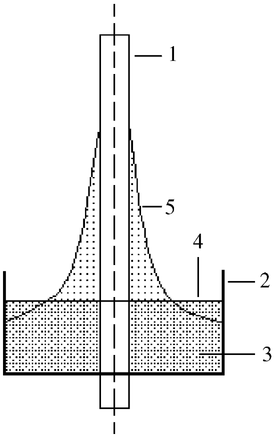

Fig. 1. Magnetic fluid's free surface profile around a vertical linear electric current.

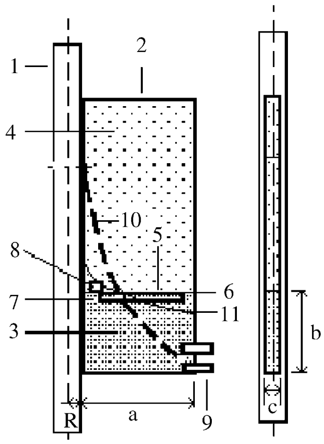

Fig. 2. A schematic diagram of the actuator.

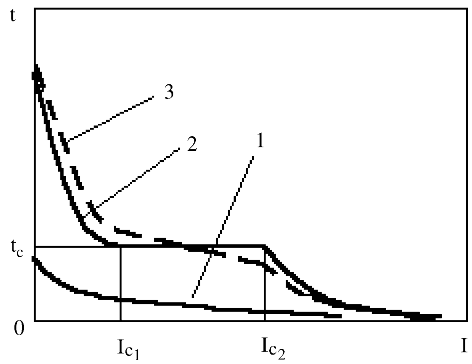

Fig. 3. Characteristics of the actuator.

where ε_M is the volume fraction of the magnetic phase, M_S is the saturation magnetization of the particles, p_n is the population number ratio of the particles having the magnetic volume V_{M_n}, k is the Boltzmann constant and T is the absolute temperature. The magnetic field intensity around the electric conductor is $H(I,r) = \mu_0 I/(2\pi r)$.

3. Working principle and discussions

A schematic diagram of the magnetofluidic actuator is presented in Fig. 2. Near the electric conductor wire (1) is attached to the actuator, consisting of a nonmagnetic box (2) which contains the magnetic fluid (3) and water (4). The wall (5), separating the water and the magnetic fluid nonmiscible with water, have the orifices (6) and (7) with the flexible valve (8). The optical device (9) gives a command electric signal only if the magnetic fluid leaves its active zone, it means if the magnetic fluid has its equilibrium free surface with the profile (10) in the presence of the electric current with intensity I. The orifice (6) allows the water to go down in the bottom part of the box, whereas the orifice (7) allows the magnetic fluid to go up in the top part of the box. For a given value of the electric current intensity, the flow of the magnetic fluid through the hole (7) is determined by the magnetic force and by the viscous one. Therefore, nonequilibrium (intermediate) magnetic fluid free surface profiles of type (11) appear, and then an equilibrium profile (10) is obtained after a time t, which is the actuator action (command) time. At high intensity electric currents, the flexible valve (8) increases its passing section under the influence of viscous and magnetic forces determined by the magnetic fluid flow, allowing a faster passing of the magnetic fluid through the orifice (7).

Fig. 3 shows the actuator characteristic $t = t(I)$, which means the dependence of the acting time on the electric current intensity.

Curve 1 describes the time for the equilibrium in the absence of the wall (5) and is determined only by magnetic fluid and water inertia. The simplest magnetofluidic actuator cannot contain the wall (5) but also has a simple characteristic of type 1.

Curve 2 describes the ideal characteristic of an actuator. At low electric current intensity, a long acting time is required. With the increase in the electric current intensity, a decreasing acting time is required. Between two critical electric current intensities I_{c1} and I_{c2}, a critical value of the acting time t_c must be obtained. For electric current intensities higher than I_{c2}, lower acting times, rapidly decreasing, are required.

For the proposed actuator, a characteristic (curve 3) very close to the ideal one was obtained, using a magnetic fluid based on magnetite particles coated with oleic acid and dispersed in kerosene, having $\rho_{MF} = 1050\,\mathrm{kg/m^3}$ and $\varepsilon_M = 2.66\,\mathrm{vol\%}$.

The actuator's characteristics (nonmagnetic box dimensions, critical values of electric current intensity and acting time) were determined by computer-aided solving of Eq. (1) in which ρ_{MF} was replaced by $\rho_{MF}-\rho_{water}$, completed with expression (2). The nonmagnetic box dimensions were determined from the condition that its bottom volume delimited by the wall $V_0 = abc$ equals the volume calculated with the equilibrium profile:

$$V = -c \int_{r_0}^{r} \Delta z(I, r, r_0)\,\mathrm{d}r \qquad (3)$$

with $r_0 = R + a$ and $r = R$.

The acting time was also determined by numerical methods, taking into account the magnetic fluid flow through the orifice (7) under the action of gravitational, magnetic and viscous forces. For simplicity, the orifice (6) was large enough to neglect the viscous force acting on water.

4. Conclusions

The actuator based on magnetic fluid free surface profile around a vertical linear electric current is very simple, easy to be designed both theoretically (using numerical methods) and experimentally (trying different magnetic fluids and physical dimensions of the constructive parts). It has a high reliability because it does not contain moving mechanical parts and its characteristic is very close to an ideal one asked for by technical applications. The command signal is a typical electric one, allowing a simple and easy connection to a computer system.

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