ELSEVIER

Sensors and Actuators A 94 (2001) 161–164

SENSORS AND ACTUATORS A PHYSICAL

www.elsevier.com/locate/sna

Computer aided design of a high electric current magnetofluidic sensor

Constantin Dan Buioca*, Vasile Iusan, Aurora Stanci

Physics Department, University of Petrosani, 20 University Street, 2675 Petrosani, Romania

Received 30 March 2000; received in revised form 20 July 2001; accepted 25 July 2001

Abstract

A new type of high electric current sensor based on the correlation between the electric current intensity and the shape of the free surface of a magnetic fluid around a vertical linear conducting wire is presented. The basic hydrostatic and magnetostatic equations describing the sensor behavior are deduced and solved in real cases in order to allow the design of a new type of sensor, taking into account the electric current intensity range, magnetic fluid characteristics and sensor physical dimensions. Important advantages of the new sensor, such as the zero resistance, the absence of moving mechanical parts, no limitation of the electric current intensity range, the use for ac and dc measurements without modifications and without direct intervention on the electric circuit, are put into evidence. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Computer aided design; High electric current; Magnetic fluid; Sensor

1. Introduction

The measurement of the electric current intensity is still a scientific research subject, especially for extreme. The main disadvantages of the existing sensors for high or very high electric currents are [1]: the complexity of construction, the high costs, and the presence of moving mechanical parts.

Magnetic fluids are ultrastable colloidal dispersions of ferry- or ferro-magnetic monodomenic particles in a carrier liquid. The combination of fluid and magnetic properties has made them very useful in a large area of sensors, including electric current sensors [2–7]. There is a physical phenomenon characteristic to the magnetic fluids, not exploited in technical applications but directly related to the electric current. If we have a magnetic fluid in a vessel surrounding a linear vertical electric conductor then, the shape of the free surface of the magnetic fluid depends on the electric current intensity in the wire and the magnetic fluid characteristics [8,9]. The paper presents the basic equations describing this phenomenon, and the way in which it can be used in the design of a new type of high electric current sensor.

2. Theoretical bases of the sensor

Let us consider a linear vertical electric conductor (1) passing through the symmetry center of a cylindrical non-magnetic 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. Let us determine the profile equation as a function of electric current intensity and magnetic fluid characteristics.The equation of Bernoulli for the equilibrium state (magnetic fluid velocity equal to zero) is [9]

$$p + \rho_{\mathrm{MF}} g z - \mu_0 \int_0^H M_{\mathrm{MF}}\, \mathrm{d}H = \text{constant} \tag{1}$$

where p is the hydrostatic pressure, ρ_{MF} and M_{MF} the magnetic fluid density and magnetization, respectively, g the gravitational acceleration, H the magnetic field intensity and $z = z(r)$ is the magnetic fluid free surface height, which depends on the distance r to the symmetry axis of the wire.

In Eq. (1), the magnetic field intensity is given by the well-known formula

$$H = \frac{I}{2r} \tag{2}$$

---

*Corresponding author. Fax: +40-54-54-27-92.
E-mail address: buioca@upet.ro (C.D. Buioca).

0924-4247/01/$ – see front matter
PII: S0924-4247(01)00704-X

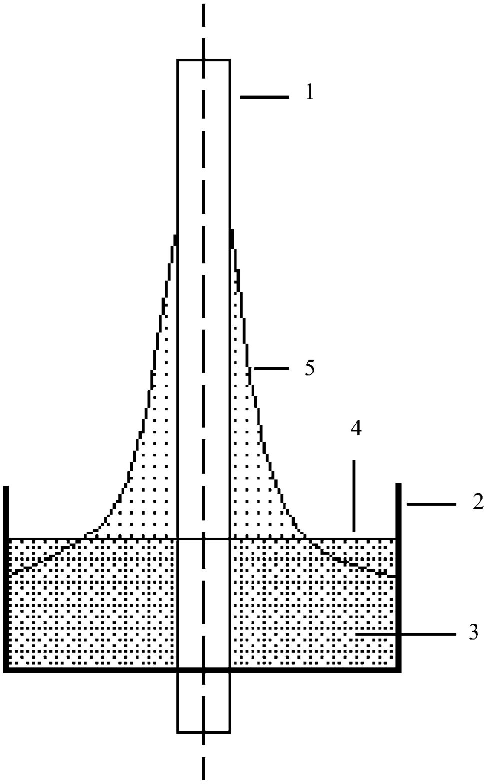

Fig. 1. The magnetic fluid profile around a vertical linear electric current.

and therefore,

$$dH = \frac{I}{2r^2}\,dr \qquad (3)$$

For usual magnetic fluids, the magnetic fluid magnetization depends on the magnetic field intensity according to Langevin type formula [10]

$$M_{MF}(H) = \varepsilon_M M_S \left[\sum_{n=1}^{N} p_n \left(\coth\frac{\mu_0 M_S V_{Mn} H}{kT} - \frac{kT}{\mu_0 M_S V_{Mn} H}\right)\right] \times \frac{1}{\sum_{n=1}^{N} p_n V_{Mn}} \qquad (4)$$

Here, we have considered that the particles can be classified in N classes, each characterized by the magnetic volume V_{Mn} and percent concentration p_n. The distribution function of the particles by their volumes, $p_n = f(V_{Mn})$, is usually determined with a good accuracy from magnetization curves measurements, using Charles method [9,10]. M_S is the saturation magnetization of the bulk material of the particles, ε_M the volume concentration of the magnetic phase in magnetic fluids, k is the Boltzmann constant and T is the absolute temperature.

Since expression (4) is rather complex, an analytical solving of the integrals containing this expression is not possible, and numerical solving methods are necessary. In the following equations, a general dependence $M_{MF}(r)$ will be used.

Considering Eq. (1) for two points of the magnetic fluid free surface placed at distances r and r_0, we obtain

$$p(r,z) + \rho_{MF} g z(r) - \mu_0 \int_0^{H(r)} M_{MF}(r)\,dH(r) = p(r_0,z) + \rho_{MF} g z(r_0) - \mu_0 \int_0^{H(r_0)} M_{MF}(r)\,dH(r) \qquad (5)$$

For all points of the magnetic fluid free surface, the static pressure is constant and therefore, Eq. (5) becomes

$$\Delta z(r,r_0) = z(r) - z(r_0) = \frac{\mu_0}{\rho_{MF} g} \int_{H(r_0)}^{H(r)} M_{MF}(r)\,dH(r) \qquad (6)$$

Eq. (6), with Eqs. (2)–(4), allow the determination of the magnetic fluid profile in real cases. A good agreement between theoretical and experimental data was obtained in particular cases of magnetic fluids, near or at long distance to the electric current wire [9]. For a rigorous determination of the profile, only numerical methods (using the computer) can be used.

A final remark on this section must be pointed. Experimental and theoretical results have shown that, if the magnetic fluid is surrounded only by the atmosphere, the maximum value of the difference $\Delta z(r,r_0)$ does not exceed a few millimetres, even for electric currents intensities of hundreds of amperes [8–11]. For practical applications, this is not enough, and that is why the magnetic fluid is introduced in the vessel with another liquid, non-miscible with it, with a lower density. Taking into account, the hydrostatic pressure of the liquid, the previous equations will be written in the same form, but replacing the magnetic fluid density with the difference $\rho_{MF} - \rho_L$, where, ρ_L is the liquid density.

3. Computer aided design of the sensor

The magnetic fluid free surface profile, described by relation (6) together with relations (2)–(4), was evaluate in the case of a real magnetic fluid based on magnetite particles coated with oleic acid and dispersed in kerosene, characterized by $\varepsilon_M = 0.02$, $M_S = 4.5 \times 10^5$ A/m, $\rho_{FM} = 1050$ kg/m^3, $T = 300$ K. The distribution function of the particles (considered spherical) versus their magnetic radius and the dependence of the magnetic fluid magnetization on the magnetic field intensity are presented in Fig. 2. The nonmiscible liquid was water.

The magnetic fluid free surface profile for two values of the electric current intensity (100 and 200 A) is presented in Fig. 3. Two important results must be pointed here. The first one is that no important variations of Δz with r, for distance r greater than 2 cm occur. This means that a larger dimension of the sensor on radial direction is not necessary. The second one is, that the values of Δz near the electric conductor surface (e.g. $r = 0.2$ cm) are about 10 and 20 cm, respectively. Taking into account, an acceptable precision of 1 mm

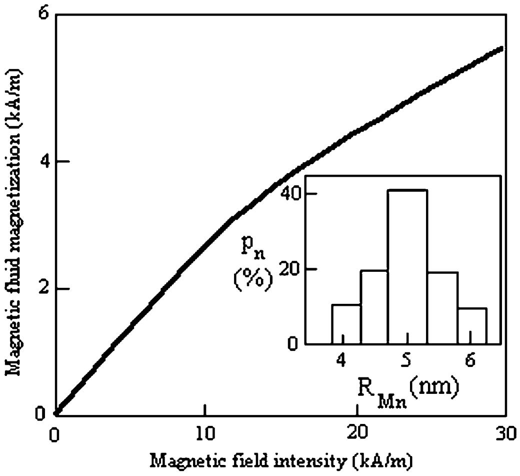

Fig. 2. The dependence of the magnetic fluid magnetization on the magnetic field intensity. The distribution function of the magnetic fluid particles by their magnetic radius is represented in the corner.

for Δz, a relative error of about 1% for the electric current can be easily obtained.

Fig. 4 presents the dependence of Δz as a function on the electric current intensity, near the electric conductor surface. A direct determination of this parameter allows the determination of the electric current intensity with a good precision.

Starting from the results presented above, a sensor for electric currents, schematically presented in Fig. 5, was conceived. Near the electric conductor wire (1) is attached the sensor, consisting of a nonmagnetic (glass made) parallelipipedic box (2), which contains the magnetic fluid (3), and water (4). The magnetic fluid free surface profiles in the absence and presence of the electric current in the wire are (5) and (6), respectively. The dimensions of the box (a, b, and c) depend on the maximum value of the electric current intensity. For example, in the analyzed case, $a = 2$ cm, $b = 20$ cm, and $c = 0.5$ cm.

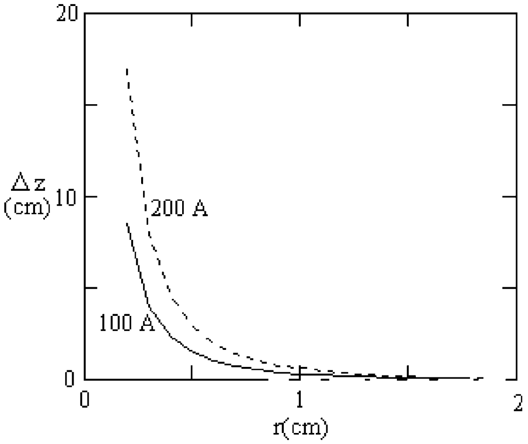

Fig. 3. The magnetic fluid profile around the vertical linear conductor, for two values of the electric current intensity.

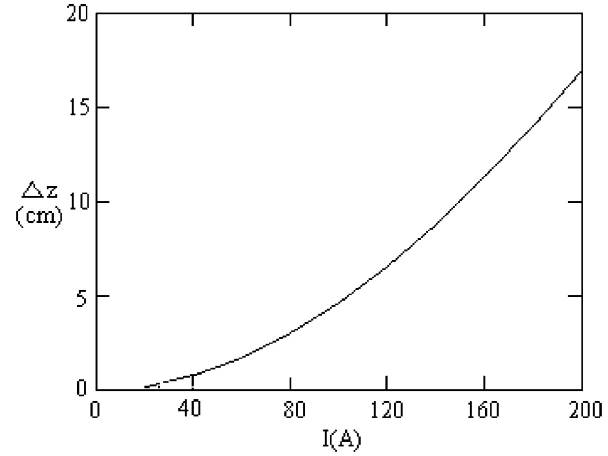

Fig. 4. The dependence of the co-ordinate difference Δz on the electric current intensity near the electric wire.

The magnetic fluid free surface height d in the absence of the electric current, is determined from the condition that the magnetic fluid volume $V_0 = acd$ exceeds the magnetic fluid volume calculated with the profile Eq. (6)

$$V = -c\int_{r_0}^{r} \Delta z(r)\,\mathrm{d}r \tag{7}$$

For practical reasons, we will determine the magnetic fluid free surface height ΔH near the conductor wire, measured with respect to the initial height (for $I = 0$)

$$\Delta H = \Delta z(r) - \frac{V}{ac} \tag{8}$$

Fig. 6 shows the dependence $\Delta H(I)$, which is similar to the dependence $\Delta z(I)$ in Fig. 4, but differing at high electric current intensities with several centimeters. The points represent our experimental results obtained by direct determination of H (using a millimeter scale and simple optical system) and I (using a claw type ampermeter). The interrupted line

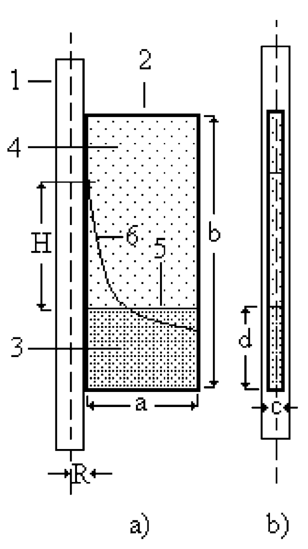

Fig. 5. The schematical diagram of the sensor.

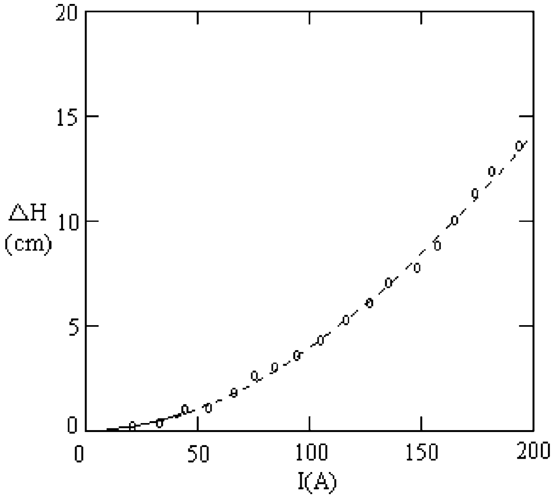

Fig. 6. The dependence of the height ΔH on electric current intensity.

represents the theoretically predicted results, using relations (2)–(8) and the previously mentioned values for magnetic fluid characteristics and box dimensions. A good agreement between experimental and theoretical results was obtained.

Relations (2)–(8) allow the determination of the physical dimensions of the sensor (constants a, b, c, d) and of the dependence $\Delta H(I)$, starting from the main characteristics of the magnetic fluid and maximum value of the electric current intensity.

The same dependence $\Delta H(I)$ is obtained in ac measurements, were I is in this case the effective value of the ac intensity, in a large range of ac frequency. This was explained starting from the particle orientation mechanism and magnetic fluid inertia [9]. For low frequencies (lower than a few kHz), the magnetic moments of the particles rotate in the magnetic field together with the particles, the rotation time from zero field to an instantaneous field value being about 10^{-6} s. The mean magnetic fluid magnetization is the same that those given by the effective value of the magnetic field intensity — calculated with relation (2) in which I is the effective value of the ac intensity. Because of the magnetic fluid inertia, its free surface profile will not oscillate with ac frequency, but will be an equilibrium one, the same obtained for a dc intensity value equal to the effective ac intensity one. Therefore, the dependence $\Delta H(I)$, once established for a given device, allows the determination of both instantaneous and effective value of electric current intensity in dc and ac measurements respectively.

4. Conclusions

The new type of high electric current magnetofluidic sensor allows a rapid determination of the electric current intensity by measuring the magnetic fluid free surface height near the electric conductor surface. It has some major advantages with respect to other electric current sensors: simplicity of construction, absence of mechanical moving parts, zero electric resistance, no limitation of the measurement range, usage without modifications for ac and dc measurements. The accuracy of the sensor depends on the accuracy in determining the magnetic fluid free surface height.

References

[1] P. Manolescu, Industrial electrical measurements, Technical Publishing House, Bucharest, 1966.
[2] R.I. Bailey, Lesser known applications of ferrofluids, JMMM 39 (1983) 178.
[3] I. Anton, I. De Sabata, L. Vekas, Application orientated researches on magnetic fluids, JMMM 85 (1990) 219.
[4] K. Raj, R. Moskowitz, Commercial applications of ferrofluids, JMMM 85 (1990) 233.
[5] I. De Sabata, N.C. Popa, I. Potencz, L. Vekas, Inductive transducers with magnetic fluids, in: A. D'Amico (Ed.), Proceedings of EUROSENSORS V, Vol. 2, Rome, Italy, 1991, Sens. Acuators A 32 (1992) 678.
[6] K. Nakatsuka, Trends of magnetic fluid applications in Japan, JMMM 122 (1993) 387.
[7] V.Z. Iusan, A.Gh. Stanci, Inertial magnetofluidic sensor, IEEE Trans. Mag. 30 (2) (1994) 1104.
[8] R. Olaru, C. Cotae, Magnetofluidic transducers and devices for measuring and control, BIT Publishing House, Iassy, Romania, 1997.
[9] E. Luca, Gh. Calugaru, R. Badescu, C. Cotae, V. Badescu, Ferrofluids and their applications in industry, Technical Publishing House, Bucharest, Romania, 1979.
[10] V.G. Bastovoi, M.S. Krokov, A.G. Reks, Magnetic fluids and powders — new technological materials. Scientific Problems and Applications, Minsk, 1991.
[11] V. Iusan, C.D. Buioca, Trends in magnetic fluids physics and applications, Annal. Univ. Petrosani Phys. 1 (1999) 117.

Biographies

Vasile Iusan Professor, PhD, physicist (PhD thesis presented in 1974), chief of Physics Department of the University of Petrosani, Romania; Field of interest: Physics and applications of magnetic fluids, sensors and transducers, magnetic separation, spectroscopy, applications of LASERS in industry.

Constantin Dan Buioca Lecturer, PhD, physicist (PhD thesis presented in 1999), Physics Department of the University of Petrosani, Romania; Field of interest: Physics and applications of magnetic fluids, magnetic separation, environmental physics, computational physics.

Aurora Stanci Lecturer, PhD, physicist (PhD thesis presented in 1999), Physics Department of the University of Petrosani, Romania; Field of interest: Physics and applications of magnetic fluids, sensors and transducers, magnetic separation, spectroscopy.