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COMMUNICATIONS

AN APPROACH TO MEASURMENT OF PERMEABILITY/PERMITTIVITY TENSOR OF FERROFLUIDS

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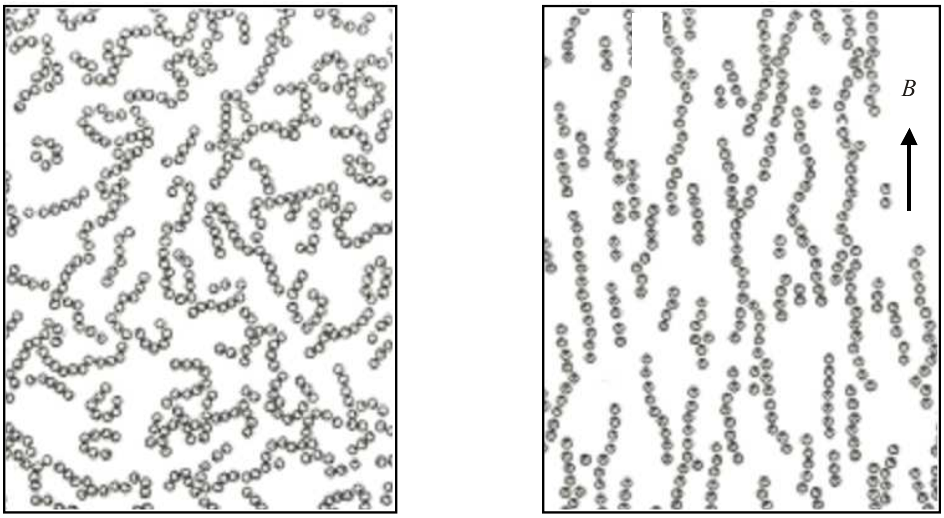
The magnetic field acting on the ferrofluids causes microstructural conversions that result in a change of their permeability. For this physical phenomenon is referred to as field induced magnetism (FIMA). An experimental method is described for ferrofluids in this state to examine their permeability tensor. Also an analogous phenomenon is described also when there is a change of the ferrofluids permittivity. We call it field induced dielectric anisotropy (FIDA). The contribution describes the method of measuring of the permittivity tensor. It can be expected that the FIMA and FIDA of ferrofluids will find interesting applications in designing of various sensors, in measurement technology, in mechatronic and in other areas of practice.

Keywords: ferrofluids, induced anisotropy, permeability (permittivity) tensor, frozen anisotropy

1 INTRODUCTION

Ferrofluids have been the subject of increased scientific interest for the last several years. The ferrofluid is a stable colloidal suspensions consisting of single-domain magnetic particles coated with a surfactant and immersed in a carrier fluid. Ferrofluids were first synthesized in 1964. Despite the relatively short existence of ferrofluids many significant advances have been achieved in this area. Effective methods of synthesis of ferrofluids heve been developed, significant effort has been devoted to the revelation of magneto-hydrodynamic properties of ferrofluids and to the formulation of mathematical models of ferrofluid-electrodynamics (generalized Maxwell's equations). These theoretical findings have been widely applied particularly in electrical engineering and bioengineering (see *eg* [1, 6, 8, 10]).



(a) (b)

Fig. 1. Microstructure of ferrofluids: (a) — without external magnetic field, (b) — with an external uniform magnetic field (after [3], [10])

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A dominant feature of ferrofluids is the magnetoviscous effect [9]. In engineering applications it is widely used, namely for controlled ferrohydrodynamic damper, ferrohydrodynamic sealing *etc* (see *eg* [6–8]). Ferrofluids, however, have other interesting properties, some of which still have not been explored sufficiently. In the present study we will examine the effect of an external magnetic field on the permeability and permittivity of ferrofluids. On the basis of experimental methods we demonstrate that these dependencies are greatly significant under the effect of a relatively weak external magnetic field. The authors of this work is convinced that these findings will be sources of various interesting applications.

2 INDUCED ANISOTROPY

Microstructure of the ferrofluids consists of a chain of dipolar nanoparticles, together with a surfactant, in a carrier liquid. In the absence of an external magnetic field, these chains are arranged randomly. External magnetic field causes the rotation of the chains into direction of the magnetic field (Fig. 1). This conversion of the microstructure of ferrofluids results in a change of its viscosity and can expect further changes of its physical properties. The question is whether these changes will be quantitatively significant. In the next phenomenological study we investigate the changes permeability and permittivity.

Direct observation of the microstructure of ferrofluids by electron microscopy, when simultaneously acting external magnetic field, is very difficult. The problem lies in the need to prevent interaction between the observed object (*ie* dipolar magnetic nanoparticles) including the external magnetic field and the magnetic lens of the electron microscope. for this purpose An electroncryo-microscope was used in [2] and the observed object was shaped as a thin layer. Microstructure observations of ferrofluids were not done because this information is not crucial for the studied phenomena.

2.1 Field induced magnetic anisotropy

From the above it is clear that without application of an external magnetic field the ferrofluid is (from macroscopic viewpoint) an isotropic medium (Fig. 1a), while after application of the external magnetic field becomes magnetically anisotropic medium (Fig. 1b). The physical phenomenon where the action of an external magnetic field leads to structural changes of ferrofluids and it becomes magnetically anisotropic medium, is called field induced magnetic anisotropy (FIMA). Magnetic anisotropy thus occurs as a response of ferrofluids to the external magnetic field. FIMA depends on the intensity of external magnetic fields. In the maximal stage of FIMA occur in such an external magnetic fields, in which perfectly ordered chains arrise.

The magnetic field distribution is such as to minimise its energy. The easy axes of the anisotropic medium, in the state of FIMA, are curvilinear and identical the vector lines of magnetic field $\boldsymbol{B}$. The direction of vector $\boldsymbol{B}$ determines the local orientation of the easy axis. Only in a magnetic field whose vector $\boldsymbol{B}$ has only one component, $\boldsymbol{B} = \boldsymbol{i}B_x$ (for example in a homogeneous magnetic field) the anisotropy has a rectilinear easy axis. This the case of oriented iron sheets. If one neglects hysteresis of ferrofluids, then if the external magnetic field does no act, FIMA will disappear and the ferrofluids become isotropic again, including all of their original physical properties. Thus FIMA is a reversible phenomenon.

The magnetic properties of ferrofluids in the state of FIMA are characterized by a permeability tensor. For 2D magnetic field this tensor is expressed by a diagonal matrix

$$\boldsymbol{\mu}(x,y) = \mu_0 \begin{bmatrix} \mu_{rx} & 0 \\ 0 & \mu_r y \end{bmatrix} \tag{1}$$

where μ_0 is the permeability of free space, μ_{rx} and μ_{ry} are the permeability in x and in y direction. The easy axis x of anisotropy has a tangent-direction to the field line of the external magnetic field and y-axis in that point is perpendicular to it.

2.2 Field induced dielectric anisotropy

Microstructural changes in ferrofluid caused by an external magnetic field, may also affect other their physical properties. The changes of permittivity are called field induced dielectric anisotropy (FIDA). Dielectric properties of ferrofluids are then characterized by permitivity tensor, which for 2D the electric field has the form

$$\boldsymbol{\varepsilon}(x,y) = \varepsilon_0 \begin{bmatrix} \varepsilon_{rx} & 0 \\ 0 & \varepsilon_{ry} \end{bmatrix} \tag{2}$$

where ε_0 is the permittivity of free space and ε_{rx} and ε_{ry} are the relative permittivity in x- and in y- direction. Additional properties of the FIMA are analogous as those of the FIMA.

2.3 "Frozen" anisotropy

If the ferrofluids with induced anisotropy changes its state (*eg* it will "freeze") FIMA and FIDA become permanent effects, even if the external magnetic field disappears. The induced magnetic anisotropy is an irreversible phenomenon. The change of state ("freezing") of ferrofluids may occur not only by changing the temperature, but also by chemical reaction such as when the carrier medium of the ferrofluids comprises a monomer which is activated by a treatment with an initiator of ferrofluids at high polymer solids. This technology could be used to create magnetic circuits in solid state, with a perfect orientation according to magnetic field of an excitation coil. In the design of magnetic circuits it would not be necessary to carry out the difficult implementation of cuts and composing the strips of the magnetic circuit from oriented sheets. Unfortunately, the current magnetic fluids have a very low permeability, hence the production of such oriented magnetic circuits has no practical significance.

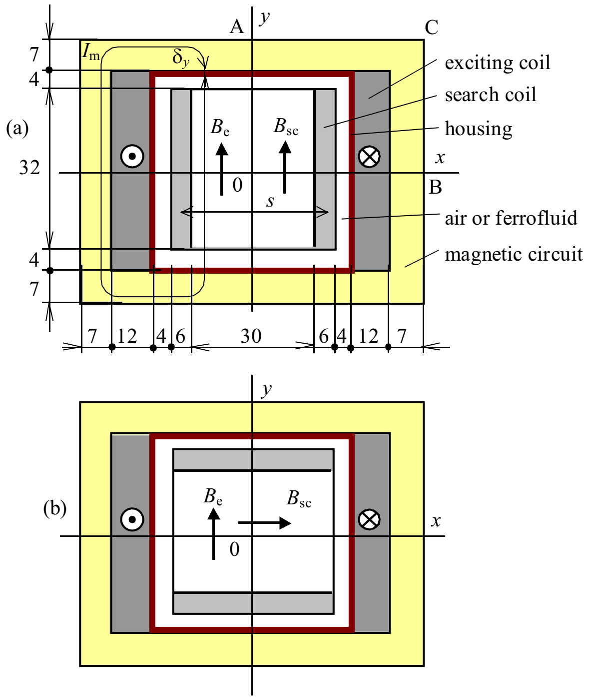

Fig. 2. The device for measuring the permeability tensor components μ_{rx}, μ_{ry} of ferrofluids; (a) — Test coil in longitudinal position, (b) — Test coil in the transverse position

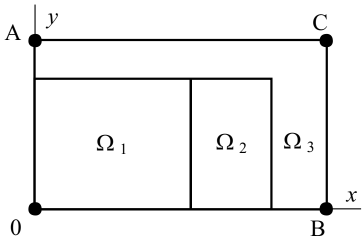

Fig. 3. Definition area. Subareas: Ω_1 — operating room, Ω_2 — excitation coil, Ω_3 — magnetic circuit

Solid medium in the state of induced anisotropy has extremal characteristics, *eg* magnetic circuits have a minimal reluctance. Similarly behave devices with ferrofluids using an electric field. Capacitors with the dielectric formed as a "frozen" ferrofluids can reach maximal capacitance.

3 EXPERIMENTAL INVESTIGATIONS INDUCED ANISOTROPY OF FERROFLUIDS

3.1 Investigations of permeability tensor

Components of permeability tensor μ_{rx} and μ_{ry} will be determined by using self-inductance coil test. For this purpose the test coil is placed in a closed housing which has the shape of a cube. The housing may be filled with the measured ferrofluid. An excitation coil is placed on the housing and its magnetic field brings the ferrofluid into the FIMA state. The housing including the exciting coil is then inserted into the magnetic circuit from a highly permeable material. The described device is shown in Fig. 2. The test coil in the housing has either transverse (Fig. 2a) or longitudinal (Fig. 2b) position. With this configuration it is achieved that in the area of the test coil the excitation coil induces a magnetic field necessary for the creation of FIMA, which is homogeneous. Also, the magnetic field which induces test coil during measuring the self-inductance of coil will be homogeneous. Measuring, proceeds as follows:

- Housing is not filled with ferrofluid. In the surroundings of the test coil is therefore air and the self-inductance of the coil is [7],

$$L_{0i} = \frac{N^2}{R_m + R_{mi} + R_{mc}}\,, \qquad i = x, y \tag{3}$$

where N is the number of turns of the test coil, R_m, R_{mx}, R_{my}, R_{mc} are the magnetic reluctances of the sections of the path, which closes the magnetic field of the test coil. These have lengths l, δ_x, δ_y, l_m. The magnetic shielding circuit has a high permeability and thus its reluctance is $R_{mc} \to 0$. Since the magnetic field of the test coil is uniform, determination of reluctances R_m, R_{mx}, R_{my} is easy (see *eg* [7]). The inductance of the test coil in the transverse position ($i = x$),or in the longitudinal position ($i = y$) is then

$$L_{0i} = N^2 \frac{\mu_0 s}{l + 2\delta_i}\,, \qquad i = x, y\,. \tag{4}$$

- Housing will be filled with the ferrofluid and the excitation coil is powered by direct current; the ferrofluid will be in the state of anisotropy. Set such an excitation current as to saturate the magnetic polarization of the ferrofluid. The inductance of the test coil in the transverse and longitudinal position is then

$$L_i = N^2 \frac{\mu_0 \mu_{ri} s}{l + 2\mu_{ri}\delta_i}\,, \qquad i = x, y\,. \tag{5}$$

We measure the inductance of coil test L_{0x}, L_{0y}, L_x, L_y and from equations (4) and (5) calculate the permeability tensor components

$$\mu_{ri} = \frac{L_i l}{L_{0i} l + 2\delta_i (L_{0i} - L_i)}\,, \qquad i = x, y\,. \tag{6}$$

3.2. Computer simulation of field induced magnetic anisotropy

The described method of examination of the permeability tensor of the ferrofluid which is in the state of FIMA, is based on the assumption that the excitation coil induces a magnetic field that is strong enough to achieve a saturated magnetic polarization of the ferrofluid, *ie* "perfect" arrangement of the chains of nanoparticles and that this field is homogeneous. Furthermore, it is required that

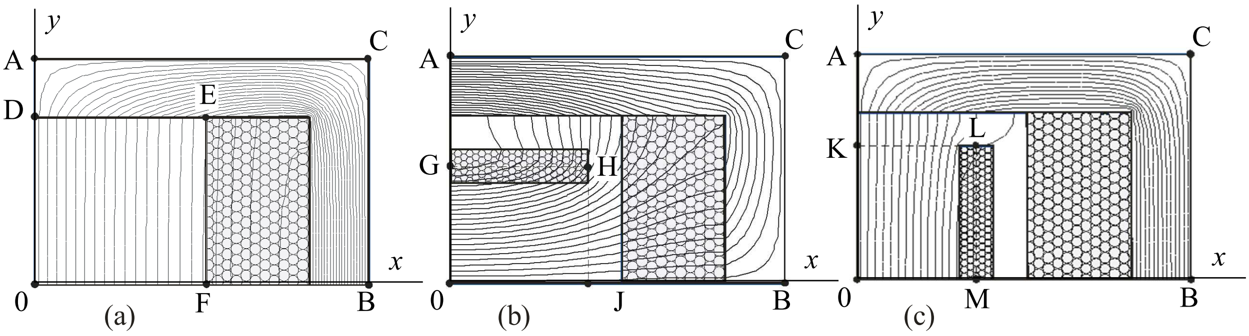

Fig. 4. Magnetic field lines: (a) — in the operating area of 0-F-E-D, (b) — in the area of the test coil in the transverse position 0-J-H-G, (c) — in the area of the test coil in the longitudinal position 0-M-L-K

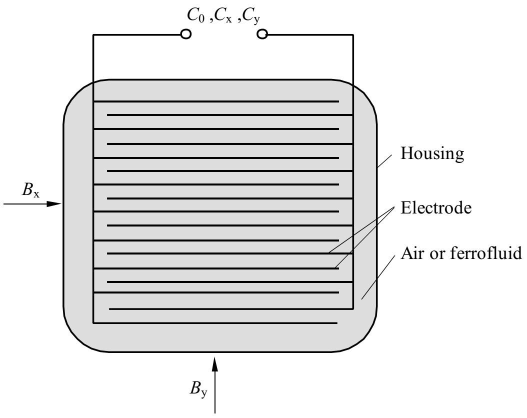

Fig. 5. A device for measuring components ε_x, ε_y of permittivity tensor of ferrofluids

the magnetic field induced by the test coil for measuring the inductance be also homogenous. Deviations from these assumptions must lie within acceptable limits. Verification of these assumptions is performed with computer simulations.

Both investigated magnetic fields (*ie* the magnetic field of excitation coils and magnetic field of test coils) are 3D. To verify the above properties we will analyse them as a 2D field. Solution of the magnetic field in plane (x, y) and in z direction (direction perpendicular to the plane of the drawing) counts as "long" configuration. For the reasons of symmetry, it is sufficient if the definition area for the field will be in the first quadrant of the plane (x, y), Fig. 3.

Numerical solution of the magnetic field was carried out by finite element method (FEM) with program QickField 5.0. The following pictures show the magnetic field lines of excitation coils (Fig. 4a), wherein the test coils in the transverse position (Fig. 4b) and then in longitudinal position (Fig. 4c). These results are valid for relative permeability $\mu_r = 1$, for higher values μ_r (*eg* for $\mu_r = 5$) the shape of the magnetic field is similar. From Fig. 4abc it is obvious that the assumption of homogeneity of the magnetic field in the vicinity the measuring coil is achieved with sufficient accuracy. The homogeneity of the magnetic field was confirmed more precisely by numerically calculating the values of the components B_x and B_y in different positions of the plane which is parallel to plane (x, z), or (y, z).

3.3 Investigations the permittivity tensor

For measuring the permittivity of ferrofluid the capacitance was used of the capacitor test, the dielectric of which is both air and ferrofluid, Fig. 5. First we measure capacitance C_0 of the capacitor, the dielectric of which is air. Then, after filling the housing with the ferrofluid and inserting it in a magnetic field. The ferrofluid is then in the state of FIDA. The magnetic field in the entire volume of the housing has only component B_x and is homogeneous. We measure capacitance C_x. Then we set the housing so that the magnetic field has only component B_y; we measure capacitance C_y. Permittivity tensor components may be calculated from the simple relationship

$$\varepsilon_{ri} = \frac{C_i}{C_0}, \quad (i = x, y). \tag{7}$$

4 EXPERIMENTS, CONCLUSIONS

The aim of this paper is to draw attention to the interesting property od ferrofluids going from the isotropic to anisotropic state, and vice versa. This phenomenon was called FIMA, or FIDA and could find practical application in various fields of technology, *eg* in measuring technology, in sensors, microelectromechanical systems, *etc.* A method has been proposed for measuring the permeability tensor, or, permittivity tensor. This method has been implemented for the ferrofluids from different manufacturers. For example, when Ferro-fluids Ferrotec (USA), catalog No. EFH 1 3-200002 were in the state of FIMA (with saturated polarization) the valuse of the components of relative permability changed by about 34 %. When the same ferrofluids were in the state of FIDA the measured changes of relative permittivity were around 24 %. The author believes that it is meaningless to indicate all measured values, as for other ferrofluids the values of μ and ε are substantially different. It is expected that it will be possible to choose a ferrofluid, in which the changes of μ and ε are much more pronounced.

However, the measured inductance, or capacitance, and thus the identified permeability μ_{rx}, μ_{ry}, and permittivity ε_{rx}, ε_{ry}, depend on the degree of arrangement of dipolar nanoparticles of the investigated ferrofluids, namely on the value of the excitation of magnetic field. The induced anisotropy reaches the maximum value in an external magnetic field, in which the saturated magnetic polarization ferrofluids occurs. It is important that for a certain class of ferrofluids the observed phenomena are considerably significant and therefore usable in applications.

Interesting could be a research of induced dynamic anisotropy, which arises when an external time-variable magnetic field acts on the ferrofluids.

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