Acoustic–Electromagnetic Transformation in Magnetic Nanofluids

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ABSTRACT

We examined the acoustic-electromagnetic transformation accompanying the propagation of sound wave through a magnetic nanofluid. Briefly the experimental procedure was as follows. The magnetic nanofluid was placed in the cylindrical resonator. An external magnetic field was applied along an axis of the cylindrical resonator. This field was obtained by means of a Helmholtz coil system. The induction coil was used to register local oscillations of the magnetic field. The signal was observed when the resonator was excited by the longitudinal sound wave with the frequency corresponding to one of the radial modes of the resonator. The parallel theoretical study supplies an interpretation of some of the experimental observations. An excitation of an electromagnetic field is shown to take place due to the perturbation in the magnetic permeability by a sound wave. It is shown that this effect can be used for the determination of ultrasound velocity and the average size of magnetic nanoparticles.

Keywords: magnetic nanofluid, ultrasound, transformation

1 INTODUCTION

Most experimental methods are based on studying the many-particle system response to an external impact. Recently, there have been gaining momentum combined methods of materials analysis, their key feature is the excitement of one of the interacting subsystems with the corresponding response observed due to the reaction of another subsystem. Particularly, these methods include an electromagnetic acoustic transformation method (EMA), widely applied in solid state physics. Direct EMA transformation involves exciting and registering elastic oscillations with the help of an electromagnetic field [1]. Inverse EMA transformation is based on the elastic oscillations exciting electromagnetic vibrations [2]. Direct EMA transformation in magnetic fluids was considered in paper [3] practically right after magnetic nanofluids synthesis and it was the first to point at a possibility of creating two types of ultrasound radiators based on a magnetic nanofluid. The working principle of one was to use magnetostriction properties and the other device employed the effect of impact of an alternating non-uniform magnetic field. Inverse EMA transformation in a magnetic fluid was first detected experimentally in [4], [5]. According to our reckoning, the discovered phenomenon of EMA transformation in magnetic nanofluids is connected with manifestation of magnetostriction properties of a magnetic nanofluid.

2 THEORETICAL BACKGROUND

Let us consider a linearly magnetized magnetic fluid located in a homogeneous stationary magnetic field with strength of $\boldsymbol{H_0}$. Equations of magnetostatics are the following:

$$\varepsilon_{ijk}\frac{\partial H_{0k}}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial}{\partial x_j}\left(\mu\mu_0 H_{0j}\right) = 0 \tag{2}$$

where $\varepsilon_{i,j,k}$ is the Levi–Civita permutation symbol $(i,j,k = 1,2,3)$, μ_0 is the permeability of free space.

We assume that magnetic permeability μ with a constant strength of the magnetic field is a function of thermodynamic variables, viz. nanofluid density ρ and temperature T.

Propagation of an ultrasonic wave in a magnetic nanofluid causes adiabatic perturbations of magnetic permeability due to density and temperature perturbations in the ultrasonic wave. Maxwell's equations with the account for these perturbations are to be written in the following form:

$$\varepsilon_{ijk}\frac{\partial E_k}{\partial x_j} = -\mu_0\frac{\partial}{\partial t}\left[\left(\mu+\mu'\right)\left(H_{0i}+h_{0i}\right)\right],$$

$$\varepsilon_{ijk}\frac{\partial E_k}{\partial x_j} = -\mu_0\frac{\partial}{\partial t}\left[\left(\mu+\mu'\right)\left(H_{0i}+h_{0i}\right)\right],$$

$$\frac{\partial}{\partial x_i}\left[\left(\mu+\mu'\right)\left(H_{0i}+h_{0i}\right)\right] = 0,$$

$$\frac{\partial E_i}{\partial x_i} = 0.$$

In linear approximation with the allowances for eqs.(1,2) the latter system of equations will look as:

$$\varepsilon_{ijk}\frac{\partial E_k}{\partial x_j} = -\mu_0\mu\frac{\partial h_i}{\partial t} - \mu_0 H_0\frac{\partial \mu'}{\partial t}\,,$$

$$\varepsilon_{ijk}\frac{\partial h_k}{\partial x_j} = \epsilon\epsilon_0\frac{\partial E_i}{\partial t}\,,$$

$$\mu\frac{\partial h_i}{\partial x_i} + H_{0j}\frac{\partial \mu'}{\partial x_j} = 0\,, \qquad \frac{\partial E_i}{\partial x_i} = 0$$

Applying *rot* operation to the first equation of the obtained system and inserting the second equation we shall receive

$$\Delta E_i = -\mu_0\varepsilon_{ijk}H_{0j}\frac{\partial}{\partial x_k}\frac{\partial \mu'}{\partial t}\,.$$

Here we discard the lesser member the order of which is defined by the relation of ultrasound speed to the speed of electromagnetic wave propagation in the medium. We assign the following form to the perturbation of magnetic permeability excited by an ultrasonic wave

$$\mu' = \left(\frac{\partial \mu}{\partial \rho}\right)_s \rho' \exp i(\omega t - k_j r_j)$$

and insert it in the previous equation. As a result, we get that the amplitude of an alternating electric field accompanying an ultrasound wave is determined by the formula

$$E_i = \varepsilon_{ijk}H_{0j}n_k\mu_0\rho'\left(\frac{\partial \mu}{\partial \rho}\right)_s c \qquad (3)$$

Thus, if wave normal of an ultrasound wave propagating in a magnetic nanofluid has a component n_k which is non-collinear to the polarizing field, there is excited a wave with the structure reminding of an electromagnetic one but propagated at a velocity of ultrasound c. It should be noted that similar situation occurs in magnetostriction dielectrics [6].

An electromagnetic field can be experimentally registered by an induction method. In this relation it stands to reason to evaluate the amplitude of electromotive force created in the inductance coil with the effective area S and the number of coils N. Assuming that the external magnetic field and propagation vector of the ultrasonic wave are mutually perpendicular, and the plane of measuring coil is perpendicular to the magnetic field, we transform equation (3) into

$$\mathcal{E} = -NS\omega\rho'\left(\frac{\partial \mu}{\partial \rho}\right)_s H_0.$$

Under the hydrodynamics sound theory, perturbations of density ρ' in an ultrasonic wave are connected with the oscillating speed of a media particle v in linear approximation by expression:

$$\rho' = \rho\frac{v}{c}\,,$$

Therefore, the equation for the amplitude of electromotive force will take the following final form:

$$\mathcal{E} = -NS\omega\left(\frac{\partial \mu}{\partial \rho}\right)_s \rho H_0\frac{v}{c} \qquad (4)$$

The coefficient$(\partial\mu/\partial\rho)_s$ characterises striction tensions in the medium. Thus, we believe that the discovered phenomenon of acoustic–electromagnetic transformation in magnetic nanofluids is connected with manifestation of magnetostriction properties.

3 EXPERIMENTAL RESULTS

A cylindrical vessel (resonator) with the studied magnetic fluid was placed in the electromagnet workspace. Helmholtz coils served as electromagnets. The force of the magnetic field fluctuated from 0 to 69 kA/m. The electric signal from the generator was fed to the piezoelectric transducer, the ultrasound oscillations of which entered the magnetic fluid through a delay circuit. Propagation of the ultrasound wave in the magnetic fluid caused excitement of electromotive force in the coil located co-axially to the resonator. The signal from the coil came to the input of the registering device. To study the influence of cylindrical resonators form and size on the nature of EMA transformations, we employed several types of resonators differing in diameter, height and thickness of the walls. The least inner diameter of a resonator was 5 mm; whereas the biggest amounted to 5 sm. The height of the resonator varied from 7 to 15 sm. The thickness of the walls was 1 mm, which is considerably less than the length of an ultrasound used in the experiment. The resonators were made from ebonite, the wave impedance of which is close to the wave resistance for a magnetic fluid. The resonator coil system was placed in an air bath which ensured the accuracy of thermostat control ± 0.1K within the range of 295 - 353 K. The experiments were made with magnetic fluids based on kerosene with various volume concentrations φ of magnetite particles. There have been experimentally discovered two types of dependences of electromotive force on the magnetic field strength with constant temperatures. With concentration less than 0.1, the amplitude of electromotive force created in the coil grew nonlinearly with the rise of magnetic field intensity and finally reached almost a constant value. Whereas with the concentration of more than 0.1, the amplitude of electromotive force created in the coil went through maximal values with the growth of magnetic field strength, the amplitude maximal value decreased with the rise of temperature at that. To describe magnetostriction properties, let us introduce a dimensionless value

Table 1: Experimental data for $b_T(H)$.

H_0,kA/m	295 K	307 K	315 K	323 K
1,59	0,40	0,35	0,40	0,40
3,19	0,50	0,53	0,52	0,56
4,78	0,83	0,82	0,84	0,83
6,37	1,00	1,00	1,00	1,00
7,97	0,82	0,82	0,81	0,82
9,56	0,60	0,60	0,59	0,60
11,56	0,39	0,42	0,45	0,41
14,3	0,33	0,35	0,38	0,39
33,9	0,16	0,17	0,16	0,17
41,2	0,13	0,13	0,14	0,14

$$b_T(H) = \left(\frac{\partial \mu}{\partial \rho}\right)_{H_i} / \left(\frac{\partial \mu}{\partial \rho}\right)_{H_m},$$

which by virtue of expression (1.3) is calculated from experimental data by the formula:

$$b_T(H) = \frac{\mathcal{E} H}{\mathcal{E}_m H_m},$$

where $\mathcal{E}_m$ is maximal value of electromotive force amplitude obtained with the magnetic field strength of H_m, $\mathcal{E}$ is electromotive force amplitude with the field strength of H. The results of the calculations b_T of kerosene–based magnetic nanofluid sample in which magnetostriction effect is maximal are given in Table 1.

As it follows from the table, the values of relative magnetostriction coefficient with constant strength of a magnetic field for all isotherms vary only in centesimal points. Knowing the dependency of magnetostriction coefficient on the field allows choosing an optimal operation mode of a device for measuring the intensity of ultrasound J having small amplitude which is defined by a well–known formula [7] :

$$J = \frac{\rho c v^2}{2}.$$

The oscillation speed of magnetic fluid particle v, as follows from formula (4), equals

$$v = \mathcal{E} c \left[\mu_0 N S \left(\frac{\partial \mu}{\partial \rho}\right)_s H\right]^{-1}.$$

Inserting this expression in (5.1.4) we obtain

$$J = \frac{\mathcal{E}^2 c^3}{2\rho} \left[\mu_0 N S \left(\frac{\partial \mu}{\partial \rho}\right)_s H\right]^{-2}.$$

Field dependences of electromotive force, measured in isothermal conditions, were employed to estimate average size of particles of magnetic fluid solid phases. The algorithm of this computation boiled down to the following. For a linearly magnetized fluid in the saturation area we have the following estimate

$$\rho \left(\frac{\partial \mu}{\partial \rho}\right)_s H \sim \varphi M_s \left(1 - \frac{k_B T}{p_m H}\right),$$

where p_m is a magnetic moment of solid phase particles having saturation magnetization M_s; k_B is Boltzmann constant. Using this estimate we can derive from expression (4) that with a constant temperature electromotive force amplitude $\mathcal{E}_i$ corresponding to the magnetic field strength H_i is equal to

$$\mathcal{E}_i \sim \omega\ M_s \left(1 - \frac{k_B T}{p_m H}\right) N S \varphi \frac{v}{c}.$$

To eliminate the unsubstantial proportionality factor, let us take the ratios for amplitudes of two different values of magnetic field strength H_i and H_j, i.e.

$$\frac{\mathcal{E}_i H_i}{\mathcal{E}_j H_j} = \frac{p_m H_i - k_B T}{p_m H_j - k_B T}.$$

Assuming the particles to be spherical with one diameter d and dipole moment $p_m = \frac{\pi}{6} M_s d^3$, we may derive from the latter expression the following:

$$d = \left[\frac{6 k_B T}{\pi M_s (\mathcal{E}_i - \mathcal{E}_j)} \left(\frac{\mathcal{E}_i}{H_j} - \frac{\mathcal{E}_j}{H_i}\right)\right]^{1/3}.$$

Defined by this method, the average diameter of particles for kerosene–based magnetic nanofluid with $\varphi = 25\%$ amounted to $12.3\,nm$, the value is in good accord with the result obtained from the acoustic absorption spectres [9].

4 CONCLUSION

The analysis of collected spectre characteristics of the resonator filled with a magnetic fluid and exposed to an external influence of a constant magnetic field allowed making the following conclusions. Firstly, an increase of volume concentration of magnetite particle caused the shift of resonance frequencies towards their decrease. Secondly, with a fixed concentration of particles temperature growth led to a reduction of resonance frequencies. As during the experiment we used resonators with the thickness of the walls significantly less than the length of an ultrasound wave, we thus employ the approximation of the acoustically soft wall to analyze the spectres. Therefore, the observed frequencies were interpreted as radial modes of a resonator with radius R defined by the condition

$$J_0 = (kR).$$

Denoting x_i roots of Bessel zero-order function ($x_1 = 2,4048$, $x_2 = 5,5201$), we get the following expression to determine the velocity of the ultrasound:

$$c = \frac{2\pi f_i R}{x_i}. \quad (5)$$

Table 2: Ultrasound velocities.

$\rho\,, kg/m^3$	$f_1\, KHz$	$c\,, m/s$	$c_s\,, m/s$
1601	52.03	1019	1081
1318	52.94	1036	1113
1089	54.52	1067	1161
921	56.16	1099	1223

Table 2 features the results of calculating the ultrasound speed by this formula with the use of experimental data for the first resonance in four samples of a kerosene-based magnetic fluid.

The fourth column of the table contains values for the ultrasound speed, the values being experimentally obtained by using pulse-phase method at the frequency of 3.19 MHz. The calculated values of velocity turned out to be 5-12 % smaller than the onces determined by direct measurement; notably, the less the concentration of solid phases in a magnetic nanofluid, the bigger the deviation. A likely reason for such deviation is the approximate nature of condition (5), and the existing dispersion of ultrasound velocity. The phenomenon of magnetostriction in magnetic fluids is not narrowed down to magnetostriction of certain solid particles, but represents as in the case with some polar fluids a collective effect, thus it occurs even in case of point dipole fields. It should be noted that the achievements in static description of polar fluids have not yet found their due application in magnetic fluid physics. Thus, for instance, only the results of paper [8], where the authors consider electrostriction in polar fluids, serve the substantiation for magnetostriction occurrence in magnetic fluids [8].

There is another explanation of inverse EMA transformation proposed in [10], [11]. The elastic deformation of magnetic nanofluid placed in cylinder can induce disturbances of the demagnetizing factor and hence changes of the demagnetizing field. These are able to excite electromagnetic oscillations .

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REFERENCES

[1] V. E. Muzhitskii, V. E. Remezov and V. Komarov, "Fundamentals of electromagnetic-acoustic-transformation thicknecc measurements with attachable probes: 1. Direct electromagnetic-acoustic transformation in a normal polarizing field," Russian Journal of Nondestructive Testing, 42, 667, 2006.

[2] V. E. Muzhitskii, V. E. Remezov and V. Komarov, "Fundamentals of electromagnetic-acoustic-transformation thicknecc measurements with attachable probes: 2. Inverse and double electromagnetic-acoustic transformation in a normal polarizing field", Russian Journal of Nondestructive Testing, 43, 48, 2007.

[3] B. B. Cary and F. H. Fenlon, "On the utilization of ferrofluids for transducer applications", JASA, 45, 1210, 1969.

[4] V. M. Polunin, "Indication of a sound wave in magnetic fluid", Proc. 3th All-Union Seminar on Magnetic Fluids, 204,1983. (in Russian).

[5] A. E. Lukyanov, V. V. Sokolov and B. A. Shustrov "Excitation of magnetization waves in ferrofluid", Proc. 16th All-Union Conf. on Physics of Magnetic Phenomena, 256, 1983. (in Russian).

[6] V. E. Lymov, "Polarization effects and an interation anisotropy of acoustical waves in crystals", MSU, 137,1983. (in Russian).

[7] L. D. Landau and E. M. Lifshitz,"Fluid Mechanics",Butterworth Heinemann, 362, 1987.

[8] C.L. Carnie and G. Stell, "Electrostiction and dielectric saturation in a polar fluid", J. Chem. Phys, 77, 1017, 1982.

[9] V. V. Sokolov, "Wave Propogation in Magnetic Nanofluids (A review)", Acoustical Physics, 56, 972, 2010.

[10] V. M. Polunin "Relaxation of magnetization and propagation of sound in magnetic liquids", Akust. Zh, 29, 820, 1983 (in Russian).

[11] R. Badescu, E. Luca, V. Badescu and N. Rezlescu, "On magnetization relaxation in ferrofluids and acousto-electromagnetic conversion," Sensors and Actuators, A58, 89, 1997.