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# RESONANCE ATTENUATION OF ULTRASONIC WAVES IN A HIGH VISCOSITY MAGNETIC LIQUID

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Ultrasonic waves attenuation as a function of frequency in a magnetic fluid APG-832 containing magnetite particles dispersed in a synthetic hydrocarbon was investigated. The measurements were carried out using broadband method in which ultrasonic pulse that has traveled through the sample is analyzed using a Fourier transform algorithm to determine the spectra of amplitude and phase and therefore to estimate the attenuation and dispersion of a given medium. Ultrasonic attenuation spectra of APG-832 magnetic liquid were measured between 1 and 10 MHz at 20 and 40°C. In the presence of the external magnetic field attenuation spectra at 20°C exhibited a single peak at frequency about 3 MHz. Experimental results were analyzed using concept of the resonance absorption of an ultrasonic wave in a magnetic fluid acted on by a magnetic field.

**Keywords:** magnetic liquid, ultrasonic waves, resonance attenuation.

## 1. Introduction

A magnetic liquid consists of magnetic particles dispersed in a carrier liquid. These particles typically have the diameters of 10–40 nm, so they are small enough to constitute a single magnetic domain. In order to prevent coagulation they are coated with the surface-active medium which adds up to the size of the solid particle by about 2 nm. Magnetic liquids are usually described as magnetically soft materials because the magnetization vector follows the applied field without hysteresis. Owing to their exceptional physical properties ferrofluids have recently found wide application in technology and medicine.

In the absence of external magnetic field the ultrasound attenuation in a magnetic liquid can be attributed to the number of mechanisms typical to ordinary colloid solution [1]. They include such processes as absorption in carrier liquid ($\alpha_0$), visco-inertial absorption ($\alpha_\eta$), thermal absorption ($\alpha_T$), and monopole and dipole scattering losses ($\alpha_S$). All these contributions are frequency-dependent and from the ultrasonic spectra it is possible, in principle, to determine the particle size distribution of the magnetic grains [2].

An external magnetic field acting on a magnetic liquid causes certain amount of colloidal particles to join into quasispherical and chain-like aggregates as long as hundreds of nanometers or more [3]. The size of these formations depends on the magnetic field strength, temperature, and the type of the carrier liquid. The compression or stretching of the chain-like structure under the influence of the ultrasonic wave results in a magnetic restoring force which leads to the forced oscillations of the aggregates along the chains. This contributes to the additional damping of the ultrasonic wave that reach a maximum value if the frequency of the wave match the eigenfrequency of the internal chain vibrations. The idea of such resonance absorption was first proposed by TAKETOMI [4] then later refined in papers of BRAND and PLEINER [5] and SHLIOMIS *et al.* [6]. The aim of this study was to demonstrate the resonance attenuation in a high viscosity magnetic liquid and to determine the cluster size on the basis of the resonance frequency.

## 2. Materials and methods

In the ultrasonic measurements the broadband ultrasonic transducer (Optel) with central resonant frequency of 5 MHz and with wide half power frequency band (about 2.5 MHz). Theoretically, this allows to perform measurement between 700 kHz and 12 MHz. In practice due to electronic noise associated with the receiver, amplifier and digitizer chain the frequency bandwidth available for measurement was reduced to 2–6.5 MHz and 2–10 MHz for measurements carried our with and without magnetic field, respectively. The transducer operated in pulse-echo mode and was driven by Optel Pulser/Receiver Card 01/100 which provided unipolar spike pulse with amplitude of 360 V and fall time better than 20 nanoseconds. The received signal was sampled at a rate of 100 MS/s and recorded in a digital oscilloscope LeCroy 9310AM. The reflector in the measuring cell (made of brass) was moved a known distance with the help of step motor. The FFT analysis was performed on the received signals and the attenuation coefficient $\alpha(f)$ as a function of frequency was obtained from the following expression [7]:

$$\alpha(f) = \frac{1}{2L} \ln \frac{A_1(f)}{A_2(f)}, \tag{1}$$

where $A_1(f)$, $A_2(f)$ are the amplitude spectra of the signals transmitted through the sample and $L$ is the difference in the acoustic paths traveled by both signals. The accuracy of the ultrasonic measurements described above amounted to about $\pm$10–15%.

In order to measure the effect of the magnetic field on the velocity and attenuation of the ultrasonic wave the measuring cell was placed between poles of electromagnet which yielded a maximum field of 500 mT which was measured with a Resonance Technology RX21 type teslameter to within 0.5%. The magnetic field was parallel to the propagation direction of the ultrasonic wave. Ultrasonic measurements were carried out in a magnetic liquid denoted as APG832 (produced by Ferrotec Inc.) consisting of magnetite particles $Fe_3O_4$ suspended in synthetic hydrocarbon with the volume fraction of particles, $\phi_V = 0.03$. The shear viscosity coefficient of APG 832 magnetic liquid was measured using a Digital Brookfield Rheometer DV II+ in the cone-plate geometry. The measurements were performed in the temperature range 288–323 K and the following Arrhenius-type equation was used to represent the temperature dependence of viscosity data:

$$\eta = Ae^{B/k_B T}, \tag{2}$$

with $A = 10^{-8}$ Pa·s and $B = 6.95 \times 10^{-20}$ J. The viscosity of carrier liquid, $\eta_0$, was evaluated from the viscosity of the suspension using the well-known Einstein relation [8]:

$$\eta = \eta_0(1 + K\phi_V), \tag{3}$$

where the shape factor $K$ equals to 2.5 for spherical particles.

## 3. Ultrasonic measurements results and discussion

Figure 1 shows the experimental results of ultrasonic attenuation over frequency range from 2.5 to 10 MHz at temperature 20 and 40°C in the APG 832 magnetic liquid in the absence of external magnetic field. As is seen from the figure coefficient of attenuation increases monotonously in the whole frequency range studied. The attenuation can be attributed to the viscosity of carrier liquid and to the friction and heat exchange between the particles and the surrounding medium [2].

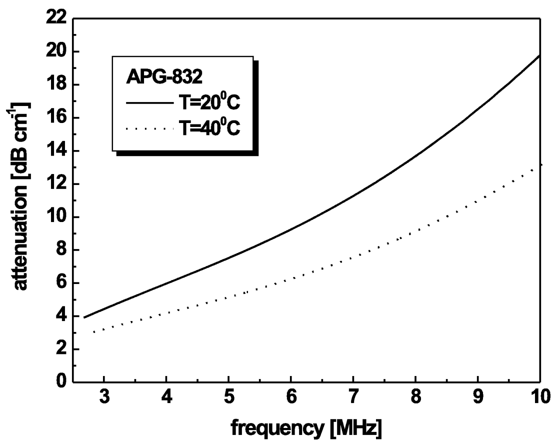


Fig. 1. Ultrasonic attenuation as a function of frequency in the magnetic fluid APG-832 at temperature of 20 and 40°C in the absence of external magnetic field.

The application of the magnetic field to the fluid causes the increase of the coefficient of attenuation due to the magnetoviscous effect [9] and the resonance damping [10, 11]. Figure 2 shows the ultrasonic attenuation as a function of frequency in the APG-832 magnetic liquid for the two temperatures 20 and 40°C in the external magnetic field of 150 kA/m. The maximum visible on the attenuation spectrum for the temperature of 20°C, which is above the uncertainty level as is shown by error bars, can be interpreted as being due to the resonance attenuation caused by the oscillation of the chain-like clusters which tend to align along the field direction. In high viscosity magnetic liquids on the basis of liquid hydrocarbons only quasispherical aggregates are formed due to the molecular forces and a very short chains which vanish with increasing temperature [12]. This is confirmed by the ultrasonic spectra for APG-832 at the temperature of 40°C.

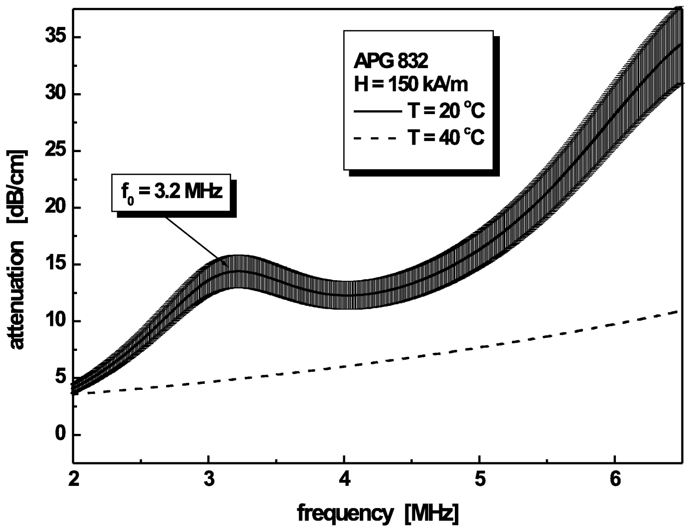


Fig. 2. Ultrasonic attenuation as a function of frequency in the magnetic fluid APG-832 at temperature of 20 (upper curve with 10% error bars) and 40°C in the external magnetic field of 150 kA/m.

According to Taketomi [6] the resonance damping of the ultrasonic wave in ferrofluid under the effect of an external magnetic can be determined from the expression:

$$\alpha_r = \frac{1}{c}\frac{3\pi\eta_0 r\omega^3 VN\left(6\pi\eta_0 r + \rho_0 V\omega\right)}{\left(k\sin\phi - \rho_m V\omega^2\right)^2 + \left(6\pi\omega r\eta_0\right)^2}, \tag{4}$$

where $c$is the velocity of the ultrasonic wave propagating with angular frequency $\omega$, $\rho_0$ and $\rho_m$ are the densities of the magnetic liquid and magnetite grains, respectively, $\eta_0$ is the shear viscosity coefficient of carrier liquid, $r$ and $V$are the radius and volume of the cluster, respectively, $N$ is the number of clusters per unit volume, $k$ is the elastic force constant, and $\phi$ is the angle between the magnetic field and the direction of the ultrasonic wave. The expression for the resonance frequency derived from Eq. (4) takes the form:

$$f_0 = \frac{9}{4}\frac{\eta_0}{\pi r^2\rho_m}\left(1 + \frac{\rho_0}{\rho_m} + 2\left(\frac{\rho_0}{\rho_m}\right)^2\right). \tag{5}$$

Calculating the viscosity coefficient of a carrier liquid at 20°C from Eqs. (2) and (3) and the carrier liquid density from the formula

$$\rho_0 = \frac{\rho_{\text{eff}} - \phi_V \rho_m}{1 - \varphi_V}, \tag{6}$$

where $\rho_{\text{eff}} = 1060$ kg·m$^{-3}$ is the density of APG-832 magnetic liquid at 20°C [13] and $\rho_m = 5180$ kg·m$^{-3}$ is the density of magnetite [14] one arrives to the value of the cluster size $r = 3.3$ μm. On the assumption that the magnetite particles forming the cluster have a radius of $R = 6$ nm and are cubic packed, and that the thickness of the layer of surface-active material amounts to $\delta = 2$ nm, the number of the particles in a cluster equals to $2.4 \times 10^6$.

## 4. Conclusions

In the external magnetic field magnetic particles dispersed in the magnetic liquid tend to join into spherical clusters. On the basis of the resonance attenuation of ultrasonic waves it is possible to detect the presence of the clusters in the magnetic liquid and to evaluate their size. In high viscosity magnetic liquids such as APG-832 the chain-like clusters vanish with the increase of temperature.

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