Journal of Engineering Physics and Thermophysics, Vol. 80, No. 5, 2007

PROCESSES OF TRANSFER IN DISPERSE SYSTEMS

INFLUENCE OF THE CONCENTRATION OF A DISPERSED PHASE AND OF THE MAGNETIC FIELD ON THE ATTENUATION OF ULTRASONIC WAVES IN MAGNETIC FLUIDS

A. R. Baev,[a] **P. P. Prokhorenko,**[a] **and N. Alekseyuk**[b]

UDC 532.52:534.29

The regularities of the propagation of elastic waves of ultrasonic range in magnetic fluids have been experimentally established. The influence of relaxation processes — nonlocal heat exchange and viscous dissipation — on the coefficient of attenuation of sound has been revealed and a comparison to the existing theoretical data has been made. The dependences (anisotropic in form) of the attenuation of the wave's amplitude on the value and direction of the magnetic field have been determined and an interpretation of the results obtained has been proposed.

Introduction. Magnetic fluids belong to the class of highly stable colloidal solutions controlled by magnetic fields. Their long-term existence is due to the balance of forces acting between particles, which is determined by a set of factors of physical and chemical nature [1]. Such media find use in various technical devices and technological processes [1, 2] and in medicine and are of interest to technical acoustics as a unique acoustic material controlled by a magnetic field [3–5]. At the same time, acoustic methods are very efficient for inspecting the quality of the magnetic fluids themselves in both their preparation and the process of their operation as the element of a technical object. Revealing the regularities of the propagation of elastic waves in a magnetic fluid depending on the composition of the magnetic fluid, the frequency of the wave f, and the action of a magnetic field is of both practical and scientific interest [6–9]. The acoustic properties of magnetic fluids have been the focus of numerous works. However, in most of them, no data on the size of magnetic particles in the colloid and the aggregative and sedimentation stability of the latter and on the degree of degassing of the solution are given; also, insufficient attention is paid to the spectral composition of a signal transmitted by the colloid. Sometimes, the influence of the inhomogeneity of a magnetic field induced by the volume itself of a magnetic fluid on the results of acoustic measurements is disregarded. All this has a substantial effect on the reliability of the obtained information necessary for developing a physical model of elastic interactions in magnetic fluids.

Below, we present results of investigation of the acoustic properties of highly stable samples of organic-based magnetic fluids as functions of the frequency of ultrasonic vibrations and the application of a magnetic field. The issues of manifestation of the effects of non-Kneser relaxation and dissipation of acoustic energy in magnetic fields are explained from the data obtained.

Theoretical Analysis of the Problem. The fundamental parameters determining the distinctive features of the transmission of ultrasonic waves in magnetic fluids — the attenuation coefficient α_u and the velocity of a longitudinal wave c — are generally dependent, in a complicated manner, on the composition of the colloid and its stability, the size of suspended particles, the frequency of the wave, the acting magnetic field of strength H, and on other factors. It is common knowledge that the dissipation of elastic waves in fluids is characterized by the absorption coefficient

[a]Institute of Applied Physics, National Academy of Sciences of Belarus, 16 Akademicheskaya Str., Minsk 220072, Belarus; [b]Institute of Fundamental Problems of Technology, Polish Academy of Sciences, Warsaw, Poland.
Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 80, No. 5, pp. 133–140, September–October, 2007. Original article submitted December 23, 2005.

$\alpha_u = \alpha_{St} + \alpha_{vol}$, where the first term describes the classical (Stokes) mechanism of absorption, whereas the second called volume viscosity characterizes, as a rule, local (Kneser) relaxation processes in pure fluids and mixtures. The distinctive features of the attenuation of the amplitude of elastic waves transmitted by suspensions of colloid particles is that a nonlocal (non-Kneser) mechanism of dissipation of acoustic energy is engaged in addition to the Rayleigh scattering. This mechanism has been analyzed in a number of works, among which [9–11] are worth noting. In one work ([10]), the investigation was concerned with dropping suspensions for which a physical model of dissipation of acoustic energy due to the mechanism of nonlocal heat exchange between a suspended particle of radius r and a dispersion base was constructed. Substantial results have been obtained by Allegra and Harly [11] who proposed the most adequate theoretical model of nonlocal mechanisms of dissipation and scattering of elastic waves in diluted suspensions of solid and liquid particles.

Thermal and shear disturbances excited by an elastic wave in the solid and liquid phases of the colloid are characterized by the wavelengths λ_t and λ_s and the corresponding wave coefficients: $k_t = 2\pi/\lambda_t$ and $k_s = 2\pi/\lambda_s$. The wave amplitude P_a in the colloid is dependant on the quantity $k_{t,s,long}r$, where $k_{long} = 2\pi/\lambda_{long}$ is the wave number of the longitudinal wave in the magnetic fluid. Thus, when $k_{t,s,long}r << 1$ the longitudinal wave propagates in the suspension under adiabatic isothermal conditions, i.e., the processes of macroscopic compression and refraction occur adiabatically. However, the temperature difference between the colloid particle and the dispersion medium due to the difference in thermophysical and elastic properties of the contiguous phases manages to be equalized over the period $\tau << 1/f$ and then the process is microscopically isothermal. If, conversely, we have $k_{t,s,long}r >> 1$, no temperature equalization is observed and the manner in which the process occurs is adiabatic and microscopic. Thus, both the dissipative and elastic properties of the colloid must change with variation of the wave frequency.

Considering diluted solutions of two-phase suspensions, Allegra and Harly solved a system of seven equations two of which are the thermodynamic equations of state of a two-phase solution of solid particles. They obtained an expression for the "excess" attenuation coefficient due to the dissipation of acoustic energy as a result of the nonlocal mechanisms — the thermal mechanism ($\Delta\alpha_t$) and the viscous mechanism ($\Delta\alpha_s$) — and to the scattering of wave energy on inhomogeneities ($\Delta\alpha_R$):

$$\Delta\alpha_u = \Delta\alpha_q q f^2 = 1.5 q\, (k_{long})^{-2}\, r^{-3} \sum_{t=1}^{\infty} (2t+1)\,\mathrm{Re}\,A_m = \Delta\alpha_t + \Delta\alpha_s + \Delta\alpha_R + \ldots\,. \tag{1}$$

Using the calculation results [11], we represent asymptotic expressions for the excess specific coefficients of attenuation of sound in magnetic fluids, which have been introduced by us and are due to the nonlocal processes of heat exchange $\Delta\alpha_{sq} = \Delta\alpha_s f^2 q^{-1}$ and to viscous diffusion $\Delta\alpha_{tq} = \Delta\alpha_t f^{-2} q^{-1}$:

$$2.25\Delta\alpha_{sq} \approx \pi^2 r^2 c^{-1} (\Delta\rho)^2 \nu_s^{-1} \rho^{-1}\,, \quad k_s r \to 0\,; \tag{2}$$

$$\Delta\alpha_{sq} \approx 2.25\, (\pi f)^{-1.5}\, \nu_s^{0.5}\, (1 - \rho/\rho_{magn})^2\, (2 + \rho/\rho_{magn})^{-2}\, (cr)^{-1}\,, \quad k_s r \to \infty\,; \tag{3}$$

$$3\Delta\alpha_{tq} \approx 2\pi^2 r^2 c T \rho \rho_{magn}^2\, (C_{p\,magn})^2\, B \rho^{-1} \lambda_{magn}^{-1}\, (0.2 + \lambda_{t,magn}/\lambda_t)\,, \quad k_t r \to 0\,; \tag{4}$$

$$\Delta\alpha_{tq} \approx 6\,(2)^{-0.5} f^{-1.5} r^{-1} c T B\, (\kappa\kappa_{magn} T \rho \rho_{magn} C_{p\,magn} C_p)^{0.5}\, (\lambda_{t,magn})^{-1}\, [(\rho C_p \kappa)^{0.5} +$$

$$+ (\rho_{magn} C_{p\,magn} \kappa_{magn})^{0.5}]^{-0.5}\,, \quad k_t r \to \infty\,, \tag{5}$$

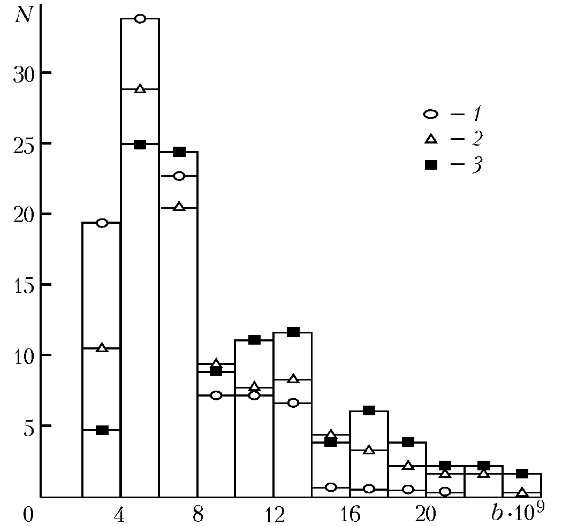

Fig. 1. Size distribution of magnetic particles in magnetic fluids based on kerosene (1), transformer oil (2), and water (3). b, m; N, %.

where $B = \beta(\rho C_p)^{-1} - \beta_{magn}(\rho_{magn}C_{p magn})^{-1}$ and $\Delta\rho = \rho_{magn} - \rho$. The notation for the density ρ, the thermal λ_t and shear λ_s wavelength, the thermal conductivity κ, the velocity of ultrasonic vibrations c, and the specific heat of the dispersion base of the colloid C_p have been given without an additional subscript.

It is noteworthy that the expressions for asymptotic approximations (4) and (5) coincide with the formulas obtained by M. A. Isakovich as applied to solutions of suspended liquid particles [10]. An analysis of $\Delta\alpha_u$ and of $k_{t,s,long}r$ as functions of the wave frequency yields that the quadratic dependence of frequency, $\{\Delta\alpha_{t,s}\} \sim f^2$, will hold in realization of the adiabatic isothermal regime of transmission of sound by a low-concentrated solution of a magnetic fluid, if $k_{t,s,long}r \ll 1$. When $k_{t,s,long}r \gg 1$ we have the coefficient $\Delta\alpha_{t,s} \sim f^{0.5}$, i.e., the root dependence on the wave frequency is true. When $k_{t,s}r \sim 1$ the manifestation of the relaxation of non-Kneser mechanisms of dissipation of ultrasonic-vibration energy should be expected. As far as the mechanism of attenuation of elastic waves because of scattering is concerned, we have $\Delta\alpha_R \sim k_{long}^4 r^3$ and this term can be disregarded for the frequency range of the investigations carried out below. It is assumed in [10, 11] that if $\lambda_{t,s} \ll d$, where $d = s - 2r$, and all colloid particles have the shape of identical spheres of radius r and are arranged uniformly in the solution, the condition mentioned above has the form $d' = \frac{d}{2r} = \frac{s-2r}{2r} = \left(\frac{4\pi}{3q}\right)^{1/2} - 1 \gg 0.5\lambda_{t,s}r^{-1}$. The distance between the particles decreases with increase in q and the exchange of energy between the particles will be carried out for $\lambda_{t,s} \ge d$, which, as is easily shown, must cause the specific energy loss by elastic waves characterized by the coefficients α_{sq} and α_{tq} to change.

Noteworthy is the distinctive feature of the colloid structure of a magnetic fluid that there can exist local interaction of uncompensated magnetic moments of magnetic particles even in the absence of exposure to the external magnetic field for $d' \sim 1$ or smaller [2], which will exert an influence on the manifestation of nonlocal mechanisms of dissipation of ultrasonic vibrations. The application of the magnetic field will transform the colloidal solution from the free highly dispersed system to a structured one. Not only must the particle size change, but the relative velocities of the dispersed phases must also be leveled because of the transformation of the particle motion from the random one to that bounded by the magnetic field. Under certain conditions, this must involve a change in the coefficient of attenuation of sound. We carried out experimental investigations to check the above analysis of the distinctive features of the dissipation of wave energy in magnetic fluids.

Experimental Procedure. The acoustic properties of magnetic fluids have been investigated on samples prepared according to [1] by the method of peptization based on TS-1 aviation kerosene (q = 0–27.1%) and transformer oil (0–23%), i.e., the concentration of the magnetic material (magnetite) varied in a nearly limiting wide range. Oleic

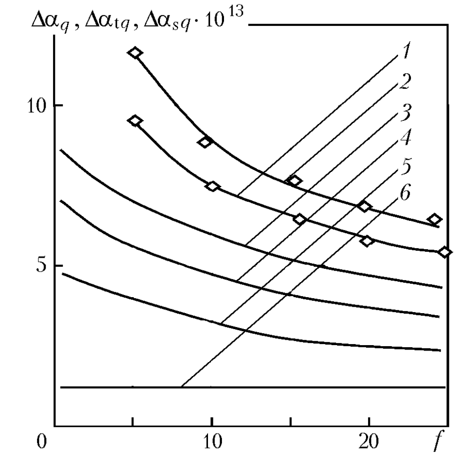

Fig. 2. Frequency dependences of the excess specific coefficients of attenuation of ultrasonic waves in diluted magnetic fluids based on transformer oil (1) and kerosene (2–6): 1–3) $\Delta\alpha_q$; 4 and 5) $\Delta\alpha_{tq}$; 6) $\Delta\alpha_{sq}$; 1 and 2) experimental data; 3, 4, and 6) Allegra and Harly theory [11]; 5) Isakovich theory [10]. $\Delta\alpha_q$, $\Delta\alpha_{tq}$, and $\Delta\alpha_{sq}$, dB·sec^{-2}·m^{-1}·(1%)$^{-1}$; f, MHz.

acid was used as a stabilizing surfactant. Data on the particle distribution by size b have been obtained by the method of x-ray structural analysis [2] and are presented in Fig. 1. To measure the velocity of ultrasound we used the traditional pulse-phase method with a fixed base and the interferometer method with a variable acoustic base [3]; these methods enable us to record changes in the velocity of ultrasonic vibrations with an error no higher than 0.02%. The absolute coefficient of attenuation of ultrasound in magnetic fluids has been investigated under conditions where nonlocal-relaxation effects were pronounced. The frequency range of the investigations was equal to 5–25 MHz. The pulse envelope had a rectangular shape, and the number of oscillations in the pulse was 15–20, which enabled us to eliminate errors caused by the presence of other spectral components in the pulse. The colloid temperature was maintained at 302 $\pm$ 0.1 K. At this temperature, the viscosities of the dispersion bases of the magnetic fluids under study differed by an order of magnitude, in practice [2]. An acoustic cell with a water-cooled jacket was used during the acoustic measurements in the absence of external fields. A steel disk of diameter 0.08 m with a reflecting-surface roughness no worse than 0.1 μm was used as the reflector of ultrasonic waves. The absolute attenuation coefficient in magnetic fluids was measured in the Fresnel zone in the "echo" regime and by the method of variable acoustic base; the maximum measurement error was no higher than 10–12%.

The influence of a homogeneous magnetic field on the attenuation of elastic waves in magnetic fluids has been the focus of the second part of experimental investigations. The investigations were carried out on a setup containing an acoustic cell from nonmagnetic material; the internal cavity of the cell had the shape of an ellipsoid of revolution and was filled with magnetic fluid. It is well known [2] that this enables one to eliminate the nonuniformity of the field strength in the fluid's volume and to ensure correct measurement conditions. A variation of the shape of the cell cavity from that indicated can have a substantial effect on the reliability of measurements, when the magnetization of the colloid is high and its stability is low. The colloid is thoroughly degassed before measurements. (The methodological aspects indicated above are frequently not taken in account in investigating the acoustic properties of both magnetic fluids and ferromagnetic suspensions.) The change in the attenuation coefficient under the influence of the magnetic field was found from the formula $\alpha_H = 20L^{-1} \log (A_1/A_k) - \alpha_0$.

Results of Experimental Investigations. Figures 2–4 give experimental and calculated dependences of the coefficient of attenuation of ultrasonic waves in magnetic fluids on the concentration of the magnetic, the frequency of the wave, and on the strength of the magnetic field H and the angle φ between the direction of its lines of force relative to the acoustic axis of a measuring cell. In the calculations, we took the average value of the diameter of a magnetic particle b from the data presented in Fig. 1. It has been established that a descending dependence of the function $\alpha_u f^2$ characteristic of the relaxation region is observed in the frequency range 5–25 MHz. To characterize relaxation

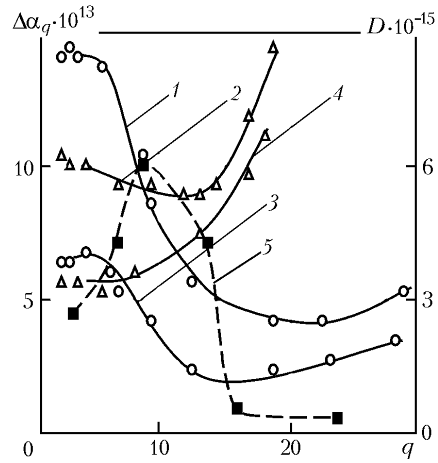

Fig. 3. Experimental dependences of the excess coefficient of attenuation of ultrasound $\Delta\alpha_q$ (1–4) and the diffusion coefficient D (5) on the concentration of the magnetic material in magnetic fluids based on kerosene (1 and 2) and transformer oil (3 and 4): 1 and 2) f = 5 and 3 and 4) 2.5 MHz. $\Delta\alpha_q$, dB·sec^{-2}·m^{-1}·(1%)$^{-1}$; D, m^2·sec^{-1}.

processes in the indicated frequency range f_1–f_2 we introduce the parameter $\Delta n = 2 - n$, where $n = \log(\alpha_{u1}/\alpha_{u2})[\log(f_1/f_2)]^{-1}$. As follows from experimental data, with variation of the magnetic concentration in the magnetic fluid based on transformer oil in the interval of q = 0–23%, the quantity Δn is equal to 0.1 to 0.18, whereas for the kerosene-based magnetic fluid we have Δn = 0.3–0.5 for q = 0–27.1%, i.e., the transition region of relaxation processes is the most pronounced for media with a lower (by an order of magnitude) viscosity of the dispersion base.

For the sake of convenience we consider the behavior of the function $\Delta\alpha_q(q) = (\alpha_u - \alpha_d)q^{-1}f^{-2} = \Delta\alpha_u(q) f^{-2}q^{-1}$ characterizing the specific dissipative loss in propagation of a body wave, where $\alpha_d = \alpha_u$ for $q = 0$. When $q \leq$ 4–5% the solution may be thought of as being of low concentration, and the specific function $\Delta\alpha_q(q)$ may be approximated by a straight line whose slope increases with wave frequency. The approximating dependence $\Delta\alpha_q(q)$ is a straight line that is parallel to the q axis. The distance between particles is $s = (4\pi/3q)^{1/3}r \geq 4.5r$ and it is assumed that the influence of magnetic dipole and molecular forces on the source side of neighboring particles on the processes of thermal and viscous diffusion can be disregarded. A comparison of the experimental data obtained and the existing theoretical data [10, 11] demonstrates their satisfactory qualitative agreement. The quantitative disagreement is minimum in the case where simultaneous account of the acoustic-energy loss caused by the nonlocal viscous and thermal diffusion and of some other features of the interaction between the elastic wave and the suspended solid particle is taken in the theory [11].

The experimental dependences obtained (Fig. 2) confirm the fact that the contribution of the nonlocal mechanism of dissipation of ultrasonic-wave energy by viscous diffusion is substantially dependent on both the wave frequency and the viscosity of the dispersion base. When the frequency of the wave is quite low ($f < f^*$), its energy loss by viscous diffusion will be larger in the colloid sample in which the viscosity of the dispersion phase is lower. (As follows from formula (2), we have $\Delta\alpha_{sq} \sim (\rho\nu_s)^{-1}$ for $k_{sr} \ll 1$). Calculations from formula (1) taken from [6] in the frequency range 5–25 MHz under study have shown that $\varepsilon \approx$ 20–25% if the dispersion base of the magnetic fluid is kerosene and $\varepsilon <$ 2% if the base is transformer oil. Since the thermophysical and elastic properties of the media indicated are close, according to the calculations performed with the data of [11], the values of α_{tq} differ by no more than 5–10% for both types of colloids. Thus, it is assumed that different manifestations of the mechanism of dissipation of the wave energy by viscous diffusion — the slip of a particle relative to the "liquid matrix" — are mainly responsible for the disagreement of the $\Delta\alpha_q(q)$ curves for both types of diluted solutions of magnetic fluids.

The dependences given in Fig. 3 $\Delta\alpha_q(q)$ are nonlinear functions in a wide range of variation in the colloid concentration. It has been established that if the base of the magnetic fluid is of low viscosity (kerosene), these functions have a pronounced minimum at 22% $> q >$ 12% and a maximum when $q = q^* <$ 4–5%. The ratio $\Delta\alpha_{q<q*}/\Delta\alpha_q$

as a function of the wave frequency and the concentration of magnetic particles can increase two to three times. The dependences $\Delta\alpha_q(q)$ constructed for the magnetic fluid based on transformer oil have a weak maximum at the frequency f = 5 MHz, whereas for $q > 8$–10% they lie higher than the corresponding curves obtained for kerosene-based samples. The maximum disagreement between them attains ~10 dB (at the same frequency).

As has been indicated above, conditions where the interparticle interaction is weak are created for $q < 4$–5%. As q increases, the average distance between particles s decreases according to the law $\sim rq^{-1/3}$, which is accompanied by growth in the intensity of mutual interaction of the particles through the transfer of thermal and viscous disturbances and in the "local magnetic interaction" [2]. If the distance between particles is $d = s - 2r \leq d^* \approx 2h$, the so-called forces of kinetic repulsion of surfactant molecules, which give rise to the additional dissipation of ultrasonic-vibration energy, must most substantially be manifested along with dipole forces. According to [1], the thickness h of the stabilizing shell of the surfactant on a magnetic particle is selected such that the volume of this shell V_{surf} is equal to the volume of the solid-state particle base V_{magn}. Thus, when $q \geq q^{**} \approx 20\%$ we observe a sharp growth in the attenuation coefficient, where the value q^{**} corresponds to a density of the magnetic fluid of 1750 kg/m^3. It is noteworthy that the presence of the high viscosity of the dispersion base in the magnetic fluid based on transformer oil levels the above-considered mechanism of dissipation of ultrasonic waves and the $\Delta\alpha_q(q)$ dependence's behavior characteristic of the kerosene-based magnetic fluid.

Also, the behavior of the $\Delta\alpha_q(q)$ dependences can be influenced by different degrees of aggregation and order of magnetite particles in the solution, caused by the mutual influence of their dipole, molecular, and other forces. This is demonstrated by data [1, 2] showing that a bend of the concentration dependence of the magnetic susceptibility is observed in the vicinity of the values q = 5–6%. In [12], it is assumed that a volume concentration of dipoles of 5% is "separated," since the system of dipoles transforms into the state of spin (dipole) glass. Mössbauer investigations performed on samples of magnetite magnetic fluids with a kerosene base [14] enabled us to reveal the maximum of the particle-diffusion coefficient D characterizing the mobility of the particles in the vicinity of the values $q \approx 8\%$, where a decrease in the effective size of suspended particles (aggregates) is assumed.

Influence of the Magnetic Field. As far as concentration is concerned, the samples selected for investigations covered the classes of diluted, moderately concentrated, and highly concentrated magnetic fluids. For moderately concentrated solutions of magnetic fluids, the effect of dipole-dipole interaction of an ensemble of particles, which correlates their space paths and influences the dynamics of formation and disintegration of conglomerates is significant. For highly concentrated solutions with $q \geq 18$–20%, molecular attractive and repulsive forces (steric forces) acting between particles along with dipole forces are substantial [1]. Figure 3 gives experimental data on investigating the change in the coefficient of attenuation of the wave as a function of the magnetic-field strength $\alpha_H = \alpha_u(\mathrm{H}) - \alpha_u(H = 0)$ and the coefficient characterizing the anisotropy of attenuation of ultrasonic waves $\alpha_\varphi = \alpha_u(\varphi) - \alpha_u(\varphi = 0)$ and determined for a certain H.

As follows from the investigation results, the most sensitive parameter characterizing structural changes in the colloidal solution in the magnetic field is the attenuation coefficient having a pronounced anisotropy; the angle φ_{max} at which the maximum of attenuation of the wave is observed is determined by the concentration of the magnetic phase in the solution. Thus, for magnetic-fluid samples having q = 3.8–6%, the α_φ maximum is pronounced at $\varphi_{max} \approx 22$–28^{o}. As q increases, a trend toward decreasing φ_{max} is observed. The α_φ minimum is in the vicinity of $\varphi = \pi/2$. Also, it has been established that the maximum value of the change in the attenuation of ultrasonic vibrations in the magnetic field $\Delta(\alpha_H)_{max} = (\alpha_H)_{max} - (\alpha_H)_{min}$ is ~10–10^2 dB/m for different φ and H. The specific coefficient of attenuation of the wave in the magnetic field $\Delta(\alpha_{Hq})_{max} = \Delta(\alpha_H)_{max}/q$ is predominantly maximum for diluted kerosene-based solutions. This is evidence of the nonlocal mechanism of additional dissipation of ultrasonic vibrations due to the viscous friction of particles in the "liquid matrix" on exposure to the magnetic field. (The manifestation of a thermal relaxation process is not ruled out.) In aggregation of colloid particles in the magnetic field, their effective size grows and, according to the calculations from formula (2), the wave frequency f = 5 MHz corresponds to the beginning of the transition zone of the relaxation process, where $\Delta\alpha_u \sim r^{-p}$ and $p > 1$. Increase in the concentration of the magnetic in a certain characteristic range (to $q < q^*$) is accompanied by decrease in the distance between the particles, which constrains the relative velocity of aggregate motion and reduces the dissipation of wave energy due to the local friction of the particles in the "liquid matrix". Furthermore, it is easily shown that at thermal wavelengths comparable to the distance between particles the specific dissipation of wave energy by thermal diffusion will

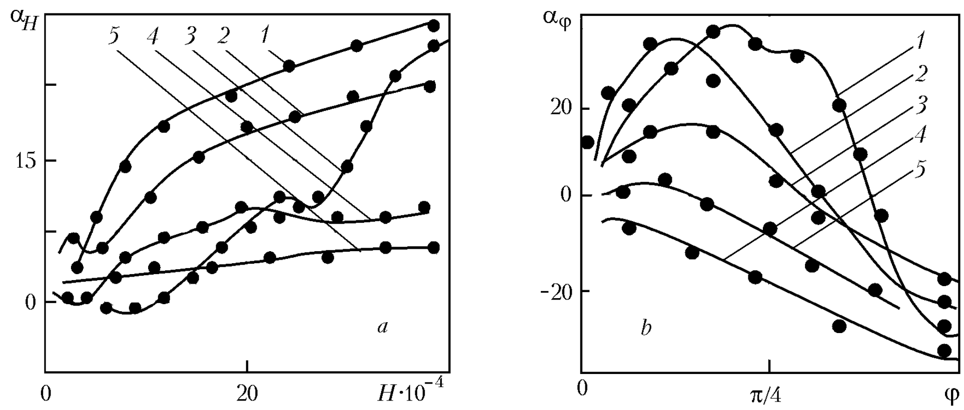

Fig. 4. Attenuation of ultrasound in the magnetic fluid vs. magnetic-field strength H and angle φ between the direction of the lines of force of the field and the acoustic axis of the cell: a) the base is kerosene: 1) q = 27.3, 2) 19.7, 3) 5, and 4 and 5) 12.5%; 1–4) φ = 0 and 5) $\pi/2$; b) 1) q = 5, 2) 3.9, 3) 7.2, 4) 12.5, and 5) 19.7%; 1, 2, 4, and 5) the base is kerosene and 3) water. H, A/m; φ, rad.

decrease. An indirect confirmation of what has been said above is the fact that the specific attenuation coefficient measured experimentally in diluted magnetic fluids is several times larger than that in highly concentrated ones.

It is noteworthy that the difference in the behavior of the angular dependences of the attenuation coefficient in the magnetic field, observed for low-concentrated and highly concentrated samples of magnetic fluids, is qualitatively the same as that in the liquid crystals with impurities or without them in the nematic phase [14].

The results of experimental investigations are of interest for studying the structure of not only magnetic fluids but ferromagnetic suspensions as well in both the absence of the exposure to magnetic fields and their presence. Improvement in the accuracy characteristics of measurement of the coefficient of attenuation of ultrasonic vibrations and the extension of its frequency range are very important in structuroscopy of the colloid: revealing the dynamics of interparticle interaction and determining the size of colloid particles. It is noteworthy that the measurement procedure developed and the results of investigation of the attenuation of sound in magnetic fluids in magnetic fields can successfully be used for reliable rapid evaluation of the aggregative and sedimentation stability of the colloid in the processes of its preparation and operation in magnetofluid devices. As the comparative tests have shown, the above-mentioned coefficient of anisotropy of the attenuation of ultrasonic vibrations is a highly sensitive parameter correlating with the stability of the colloid structure [1, 2]. As follows from the investigation results given above (Fig. 4), knowledge of the magnetic concentration in the solution is required. When these data are absent, we can use the fact that the velocity of ultrasonic vibrations in the magnetic fluid is $c_{\text{m.f}} = (\rho_{\text{m.f}}\beta_{\text{m.f}})^{-0.5}$, where its density $\rho_{\text{m.f}}$ and the adiabatic (macroscopic) compressibility $\beta_{\text{m.f}}$ can be determined from the additive law of addition of the corresponding quantities of the components introduced into the colloidal solution [3]. Measuring $c_{\text{m.f}}$, we determine q according to the formula derived on the basis of the above-mentioned assumptions and relations:

$$q = -0.5\,(a_1^{-1} + a_2^{-1})\left\{1 \pm [1 - 4\,(1 - \delta^{-2})\,a_1 a_2\,(a_1 + a_2)^{-2}]^{0.5}\right\},$$

where $\delta = c_{\text{m.f}}/c$ and $c_{\text{m.f}} = c$ for $q = 0$.

Conclusions. We have obtained the experimental dependences of the change in the coefficient of attenuation of ultrasonic waves as a function of the concentration of magnetic particles in magnetic fluids based on kerosene (q = 0–27.1%) and transformer oil (q = 0–23%) in the frequency range f = 5–25% MHz. We have refined the distinctive features of the manifestation of nonlocal (non-Kneser) mechanisms of dissipation of elastic-wave energy by heat exchange and viscous diffusion in magnetic fluids and have shown a qualitative agreement between the calculated data of Allegra and Harly and the experimental data obtained on samples of magnetic fluids with $q \le$ 0–5%. It has been established that the specific function of change in the attenuation coefficient relative to the magnetic concentration in the kerosene-based magnetic fluid $\Delta\alpha_q$ in the frequency range investigated has a pronounced minimum for 12% $< q <$ 22% and a maximum for $q <$ 4–5%. The difference in the behavior of the function $\Delta\alpha_q(q)$ in the magnetic fluids based on kerosene and transformer oil significantly differing by the base viscosity has been interpreted.

It has been shown experimentally that the coefficient of attenuation of ultrasonic waves in the magnetic field has a pronounced anisotropy from the angle between the wave vector and the direction of the lines of force of the magnetic field. The attenuation minimum of the wave corresponds to the angle $\varphi_{min} = \pi/2$, whereas the maximum φ_{max} is determined by the concentration of the magnetic in the solution. The function $\Delta(\alpha_{Hq})_{max}$ characterizing the change in the specific attenuation coefficient on exposure to the magnetic field in diluted and low-concentrated magnetic fluids is several times higher than that in "concentrated" solutions with $q >$ 15–20%.

It has been proposed that the coefficient of anisotropy of the attenuation of ultrasonic vibrations in homogeneous magnetic fields be used as a sensitive parameter characterizing the aggregative and sedimentation stability of magnetic fluids in the process of both their preparation and operation.

The samples of magnetic fluids were prepared by N. P. Matusevich, senior scientific associate of the Institute of Applied Physics of the National Academy of Sciences of Belarus.

This work was carried out with support from the Belarusian Republic Foundation for Basic Research, grant No. T04-285.

NOTATION

A_m, coefficient of the corresponding potential of excited waves; a_1 and a_2, coefficients characterizing the "excess" density and compressibility of the components introduced into the colloid; b, average value of the transverse dimension of a particle or effective diameter, m; C_p and $C_{p\text{magn}}$, specific heats of the dispersion base and the magnetic, J/(kg·K); c and $c_{\text{m.f}}$, velocity of sound in the dispersion base and the magnetic fluid; D, diffusion coefficient of magnetic particles in the magnetic fluid, m^2/sec; d, distance between the nearest points on the surface of neighboring particles, m; f, frequency of a sound wave, MHz; H, magnetic-field strength, A/m; h, thickness of the stabilizing surfactant shell on the solid-state particle base; k_{long}, k_{t}, and k_{s}, wave numbers of the longitudinal (sound), thermal, and shear waves respectively, m^{-1}; L, length of the acoustic base; M, magnetization of the magnetic fluid, A/m; N, particle-size-distribution function, %; n and Δn, coefficients characterizing the exponent of growth in the coefficient of attenuation of a wave as a function of its frequency; P_{a}, wave amplitude, Pa; q, volume concentration of the magnetic in the colloid, %; r, particle radius; Re, real part; s, distance between the centers of spherical particles, m; T, temperature of the magnetic fluid, K; V, volume, m^3; α_{u} and α_{d}, coefficients of attenuation of sound in the magnetic fluid and its base, dB/m; α_{St} and α_{vol}, Stokes and volume attenuation coefficients in fluids, dB/m; α_H, coefficient of change in the attenuation of the wave in the magnetic fluid as a function of the magnetic-fluid strength, dB·sec^{-2}·m^{-1}; α_0, coefficient of attenuation of the wave in the magnetic fluid without a magnetic field, dB·sec^{-2}·m^{-1}; $(\alpha_H)_{max}$ and $(\alpha_H)_{min}$, maximum and minimum values of the coefficient of attenuation of ultrasonic vibrations in the magnetic field, dB·sec^{-2}·m^{-1}; α_φ, coefficient characterizing the change in the attenuation of ultrasonic vibrations as a function of the direction of the lines of force of the magnetic field, dB·sec^{-2}·m^{-1}; $\beta_{\text{m.f}}$, β, and β_{magn}, adiabatic compressibilities of the magnetic fluid and its base and of the magnetic respectively, sec^2·kg^{-1}·m^{-2}; $\Delta\alpha_{\text{u}}$, excess coefficient of attenuation of sound in the colloid, dB/m; $\Delta\alpha_{\text{t}}$ and $\Delta\alpha_{\text{s}}$, excess coefficients of attenuation of sound due to the nonlocal processes of heat exchange and viscous diffusion in the magnetic fluid, dB/m; $\Delta\alpha_{\text{R}}$, excess attenuation coefficient due to the Rayleigh scattering of waves on colloid particles, dB/m; $\Delta\alpha_{tq}$ and $\Delta\alpha_{sq}$, excess specific coefficients of attenuation of sound in the magnetic fluid due to the nonlocal processes of heat exchange and viscous diffusion in the magnetic fluid respectively, dB·sec^{-2}·m^{-1}·(1%)$^{-1}$; $\Delta\alpha_q$, total excess specific coefficient of attenuation of sound in the magnetic fluid, dB·sec^{-2}·m^{-1}·(1%)$^{-1}$; $\Delta(\alpha_H)_{max}$, maximum change in the attenuation of the wave in the magnetic fluid in the magnetic field, dB·sec^{-2}·m^{-1}·(1%)$^{-1}$; $\Delta(\alpha_{Hq})_{max}$, maximum change in the specific coefficient of attenuation of the wave on exposure to the magnetic field, dB·sec^{-2}·m^{-1}·(1%)$^{-1}$; δ, ratio of the velocities of ultrasound in the magnetic fluid and its base; $\varepsilon = \Delta\alpha_{sq}/(\Delta\alpha_{sq} + \Delta\alpha_{tq})$, ratio of the excess attenuation coefficients; $\Delta\rho = \rho_{\text{magn}} - \rho$, kg·m^{-3}; κ_{magn} and κ, thermal conductivities of the magnetic and the dispersion base of the magnetic fluid, W·m^{-1}·K^{-1}; λ_{long}, length of the longitudinal (sound) wave; λ_{t}, length of the thermal wave; λ_{s}, length of the shear wave, m; ν_{s}, kinematic viscosity of the dispersion base of the magnetic fluid, m^2/sec; ρ_{magn} and ρ, density of the magnetic and the dispersion base of the magnetic fluid, kg·m^{-3}; τ, relaxation time, sec; φ, angle between the lines of force of the magnetic field and the acoustic axis of the cell, rad. Subscripts: a, amplitude; magn, magnetic; s, shear; d, dispersion (base of the magnetic fluid); t, thermal; k, ordinal number of the reflected acoustic signal; long, longitudinal (sound) wave; m.f, magnetic fluid; m, number of the corresponding potential of excited waves; vol, volume; u, ultrasound; q, division of the corresponding quantity by q; max and min, maximum and minimum values of the corresponding quantity; φ, coefficient characterizing the change in the attenuation of ultrasonic vibrations as a function of the direction of the lines of force of the magnetic field in relation to the acoustic-cell axis; ′, making d dimensionless; ** and *, lower and upper limits of the quantity q.

REFERENCES

1. V. E. Fertman, *Magnetic Fluids* [in Russian], Vysheishaya Shkola, Minsk (1988).
2. É. Ya. Blum, M. M. Maiorov, and A. O. Tsebers, *Magnetic Fluids* [in Russian], Zinatne, Riga (1989).
3. A. R. Baev, P. P. Prokhorenko, and E. M. Grintsevich, Physical principles and application of magnetic fluids to ultrasonic testing, *J. Magn. Magn. Mater.*, **85**, 261–263 (1990).
4. A. R. Baev, On the utilization of magnetic fluids to ultrasound directivity control, in: *Proc. 13th World Congress on Acoustics*, Rep. Congress, Vol. 4, Belgrade (1989), pp. 390–393.
5. A. R. Baev, P. P. Prokhorenko, and D. N. Silkov, Equilibrium magnetofluid forms applied to technical acoustics, *J. Tech. Acoustics*, No. 3, 5–11 (1997).
6. V. M. Polunin, *Acoustic Effects in Magnetic Fluids*, Author's Abstract of Doctoral Dissertation (in Physics and Mathematics), Leningrad (1993).
7. V. V. Sokolov, *Ultrasound and Dynamic Properties of Magnetic Fluids*, Author's Abstract of Doctoral Dissertation (in Physics and Mathematics), Moscow (1997).
8. N. F. Patsegon and L. N. Popova, Anisotropy of the acoustic characteristics of a magnetic fluid, *Magn. Gidrodin.*, No. 1, 116–124 (1996).
9. N. S. Kol'tsova, Attenuation of ultrasonic waves in unmagnetized magnetic fluids, *Akust. Zh.*, No. 5, 510–512 (1986).
10. M. A. Isakovich, Mandelshtam and propagation of sound, *Usp. Fiz. Nauk*, **29**, Issue 3, 539–552 (1979).
11. J. R. Allegra and S. A. Harly, Attenuation of sound in suspensions and emulsions: Theory and experiments, *Amer. JASA*, **51**, 1545–1564 (1970).
12. N. P. Petrakov and V. V. Shcherbakova, Susceptibility of interacting superparamagnetic grains, *Fiz. Tverd. Tela*, No. 12, 3732–3733 (1978).
13. E. N. Shkol'nikov, *Mössbauer Studies of a System of Single-Domain Magnetite Particles in Condensed Media*, Author's Abstract of Candidate's Dissertation (in Physics and Mathematics), Kursk (1996).
14. R. Miyano and L. Ketterson, Ultrasonic study of liquids crystals, *Phys. Rev.*, **12A**, 615–635 (1975).