Impulsively-Laser Excitation and Propagation of Ultrasonic Waves through Nanomagnetic Fluid

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Abstract

Magnetic fluids belong to the class of nanomaterials with a high gain of light absorption, aggregative and sedimentation stability as well as controllability by external fields, which is of interest to use in the field of optoacoustics. The purpose of the work was to experimentally study the effect of the optoacoustic transformation in a magnetic fluid, depending on the concentration of magnetic colloidal particles, boundary conditions, intensity of the laser as well as to identify the possibilities of using the magnetic fluid as an element of the optoacoustic transformation in a number of applications.

A brief analysis of the optoacoustic transformation mechanism in a magnetic fluid was carried out and a technique and an installation that implements the shadow measurement variant developed. A Lotis type laser was used as a source of ultrasonic pulse-laser excitation in magnetic fluids. A quartz and air were used as a material transmitting the energy of laser radiation in a magnetic fluid. Receiving of ultrasound signals was made by a piezoelectric probe at a working frequency of 5 MHz. In the measurement process, the concentration of the dispersed phase in tmagnetic fluid was varied from zero to 8 % and the energy in the impulse – from zero to 10 mJ.

For the first time, it was established that: a) an amplitude of the function of the optoacoustic transformation in a magnetic fluid, depending on the concentration of the dispersed phase, has a maximum determined by the fluid physical properties and boundary conditions; b) for all samples within the measurement error, a quasilinear dependence of the specified amplitude of energy in the laser pulse in the range of 0–8 MJ has been established.

A number ways of the optoacoustic effects in magnetic fluids to use in ultrasonic testing, measuring the intensity of the laser radiation had been suggested.

Keywords: optoacoustic transformation, magnetic fluid, ultrasound.

Импульсно-лазерное возбуждение и прохождение ультразвуковых волн через наномагнитную жидкость

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Магнитные жидкости относятся к классу наноматериалов, обладающих высоким коэффициентом поглощения света, агрегативной и седиментационной устойчивостью, а также управляемостью внешними полями, что представляет интерес для использования в области оптоакустики. Цель работы состояла в экспериментальном исследовании эффекта оптоакустического преобразования в магнитной жидкости в зависимости от концентрации дисперсной фазы и способа воздействия на неё лазерного излучения, а также выявления возможностей использования магнитной жидкости в качестве элемента оптоакустического преобразования в ряде приложений.

Проведён краткий анализ механизма оптоакустического преобразования в магнитной жидкости и разработана методика и установка, реализующая теневой вариант измерений, где в качестве источника импульсно-лазерного воздействия на магнитную жидкость использован лазер типа Lotis. В качестве материала световода, передающего энергию лазерного излучения в магнитной жидкости, использованы кварц и воздух. Приём ультразвуковых сигналов производился пьезопреобразователем на рабочей частоте 5 МГц. В процессе измерений варьировалась концентрация дисперсной фазы в магнитной жидкости (0–8 %) и энергия в импульсе (0–10 мДж).

Впервые установлено, что: а) амплитуда функции оптоакустического преобразования в магнитной жидкости в зависимости от концентрации дисперсной фазы, имеет максимум, величина и положение которого на оси концентраций определяется свойствами световода; б) для всех образцов в пределах погрешности измерений установлена квазилинейная зависимость указанной амплитуды от энергии в импульсе в диапазоне 0–8 мДж.

Предложен ряд схемных решений использования эффекта оптоакустического преобразования в магнитной жидкости для ввода сигнала в исследуемые объекты – применительно к их дефектоскопии и структуроскопии, а также для решения обратной задачи – измерения интенсивности лазерного излучения.

Ключевые слова: оптоакустическое преобразование, магнитная жидкость, ультразвуковые волны.

Introduction

The development of methods of laser acoustic diagnostics and control of object in different phase states with structural inhomogeneity in hard-to-reach places requires the application of original approaches, new tools and materials [1]. Particularly, this concerns the combined methods of measurements where excitation of ultrasonic waves (UW) is performed by impulse-laser radiation and receiving by contact or non-contact transducers, for example [2–6]. This allows solving a number of important tasks on widening the possibilities of high-frequency acoustic probing of objects with powerful pulses by essentially increasing method sensitivity and simplifying the problems of information signal receiving.

Recently magnetic fluids (MF) related to the class of nanomaterials [7] are of essential interest for the use in acoustic measurement technique (and optoacoustics). Magnetic fluids are colloidal solutions possessing aggregative and sedimentary stability relatively magnetic suspended particles under the influence of external fields, including magnetic, electric and others while maintaining fluidity. Earlier it was proposed to use unique properties of MF in a number of acoustic applications including creation of acoustic contact, sound excitation by a variable magnetic field, directional control of acoustic fields and others [8].

Taking into account high stability of MF structure in magnetic fields, fluidity of the medium, and also the data on MF optical propertiesobtained before, it is of interest to consider the possibility of using MF as a distinctive matching managed optoacoustic (OA) element in a number of applications. Particularly, MF can be used as an OA converter or in ultrasound fluctuations that simultaneously combine the function of a controlled sound line, which creates a contact with the object of research, to form a focus and excitation of various elastic modes in materials with a minimum noise background; clearing the possibility of MF using to measure the intensity of laser radiation.

It is also necessary to pay attention to a number of works [9–12], in which magnetic field acts on birefringence, the rotation of the polarization plane, the change in the intensity of the light radiation passing through the MF films, and etc. Interesting

from the point of view of the using MF as an element of OA transducer is the data obtained in [13, 14], where it is shown that in the vicinity of the boundaries of the media there is an inhomogeneity of the concentration of the dispersed phase. It is also necessary to pay attention to a number of works, for example [9–12], in which the effects of the magnetic field influence on birefringence, the rotation of the polarization plane, and the laser light passing through the MF films, etc.

In the case of using MF as an element of OA converter and controlled by the magnetic field of the sound line [8], it is possible to excite in various media acoustic pulses of high intensity and low duration up to ~ 1–10 nS.

In the formation of the acoustic field in the test object to test it is neces-sary to take into account the fact that the laser radiation energy with an OA conversion to me-dium having characteristic thermo-physical (TP), acoustic (AC) and opti-cal (OP) properties are transmitted to MF, follo-wed by transformation according to the sche-me: light – heat – ultrasonic waves (UW). And then the UW propagate into the object under study, which amplitude according to [2] can be represented as:

$$\widetilde{A} \sim J_0(t, \Gamma_i)\, \widetilde{K}_{OA}(\omega, TP, AC, OP)\, \widetilde{F}[\omega, AC]D_{MF, O}, \quad (1)$$

where $J_0(t, \Gamma_i)$ is a flow of laser radiation, falling on the boundary light guide-MF; $\widetilde{K}_{OA}$ and $\widetilde{F}$ – integral (spectral) functions characterizing the passage of the radiation flow through the boundary of the light MF guide with the subsequent trans-formation into longitudinal waves, as well as the propagation of the latter through the MF sound line correspondingly; D_{MF} – the sound transmission coefficient of the boundary MF-object; ω – circular frequency.

It is interesting thet there are the data obtained in [13, 14], where it is shown that in the vicinity of the boundaries of media there is an inhomogeneity of the concentration of the dispersed phase. It should be noted that the UW pulses arising from the OA transformation give us information about the space-time characteristics of the heat absorbed and the features of the heat transformation mechanism into acoustic energy. At the same time, it was shown in [13, 14], that the absorption coefficient of laser radiation in the vicinity of the boundaries of the media partition normally coefficient of the light attenuation is $\alpha_l = \alpha_l(z)$.

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Those, it is varying in the surface layer according to normal to its boundary, which is due to the peculiarities of the technology of stabilization of the colloid system [7].

Using the results of research [2], the velocity of the laser excited UW and transmitted through rigid (*r*) or free boundary (*f*) into object to study can be presented as:

$$V_{r,f} = \frac{\beta I_0}{\rho_0 A_p} \int\limits_{\infty}^{\infty} \tilde{F}(\omega) \exp(-i\omega\tau) \int\limits_{0}^{\infty} Y_{r,f} g(\alpha_l, \xi) d\xi, \quad (2)$$

where I_0 is a laser light intensity incident on the former, boundary, $g(\xi)$ describes the space distribution of the UW sources,

$$Y_r = \cos(\frac{\omega}{c_0}\xi); Y_r = \sin(\frac{\omega}{c_0}\xi),$$

β – is a temperature coefficient of MF compressibility, c_0, ρ_0 and α_l are velocity, density and coefficient of the light extinction in MF respectively.

We assume that the diameter size of the light beam $\lambda_T << d >> \alpha_l^{-1}$ where length of the excited heat $\lambda_T = \frac{(\chi_T / \omega c_p)^{1/2}}{2\pi}$, wave where χ is the heat capacity and thermal conductivity of the MF.

As shown by formulas (1) and (2), there is a direct link between the spectral and amplitude characteristics of the OA conversion and physical properties of MF, depending on the volume content *Q* of the colloid and the degree of structuring as well as from the dispersion base. According to the previously research [13], the amplitude of the OA transformation function $\tilde{A}(Q)$ measured in echo way, has a characteristic maximum as a result of concurrence of the thermophysical and acoustic properties of the MF samples and the boundary materials.

Interesting is the fact that with the characteristic concentration of the colloid $Q \geq Q_H \approx 2$–3 % the spectrum of an excited in MF acoustic pulse is almost identical to the spectrum of the laser pulse. That is, the "long pulse" mode is implemented. If $Q = Q_L < 0.5$ % and the emitting mode of a "short pulse is realized".

The purpose of the work was to investigate experimentally the effect of OA transformation in MF depending on the concentration of disperse phase and the method of influence of laser radiation on the surface and also to detect the possibilities of using MF as an element of OA transformation in a number of applications.

Experimental research technique and scheme

An experimental scheme of investigation is given in Figure 1 where a Lotis laser was used as LR source for research. The setup comprises an optical quantum generator with an electromagnetic radiation wavelength of 1.06 µm, consisting of an electrical pulse generator, an optical tube with a quantotronome, an optical system for correcting LR intensity, which provides its given value and uniformity on the front. LR pulse width at e^{-1} level is ≈ 8 µs. After OA transformation on the boundary of the light-guide-MF, passing through MF and the protector, USO goes to the receiver from which a signal is received successively on the amplifier and then on the oscillograph BORDO 200, which is connected to the computer for processing the measurement results. The quantum generator and oscilloscope are started synchronously.

The cell has a cylindrical cavity filled with MF, ensuring a drop of LR with a diameter of $d \approx 5$ mm to the boundary of the light-guide-MF, where as a material of the light-guide air and quartz are used, which differ substantially on acoustic and thermal-physical properties. Moreover, in the first case a free boundary for OSU excited in MF surface layer was realized, and in the second case it was rigid in relation to the normal wave component. USO is received by a piezoelectric converter (PEC) with an operating frequency of 5 MHz and an oscillation period in a pulse almost 60 times less than the effective LR duration. The surface of PEC piezoplate is in contact with the solid-state acoustic line-protector, and its other side is in contact with the damper, as shown in Figure 1*b* and 1*c*. MF samples are made on the basis of mineral oil with a volume content of dispersion phase $Q = 0.3$–8 %.

The intensity of the laser pulse and duration of measurements are regulated so that in the result of thermal absorption non-linear effects will not appear and the temperature change of MF samples during measurement shall not exceed 1ºC. Stability of the energy flow emitted by LR generator is ≈ 5–7 %. By changing the intensity of LR source and measuring it with the PE-25SH device, a normalized dependence of the fixed electric radiation on the power of laser radiation *J* in mJ was constructed.

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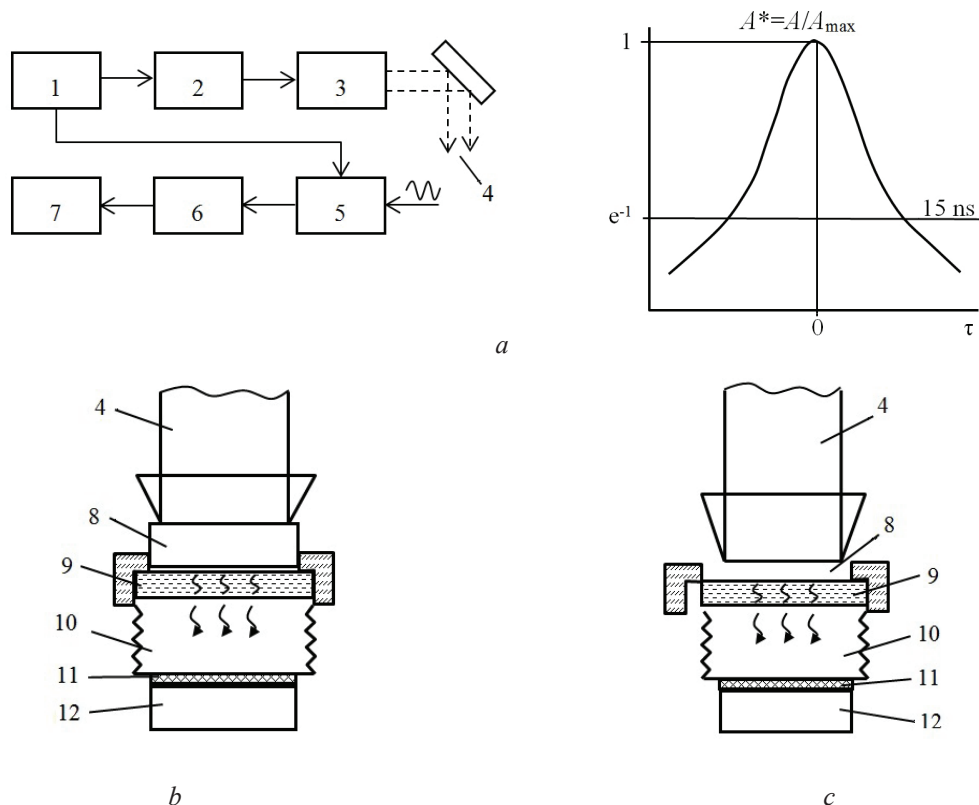*A.R. Baev et al.*

Figure 1 – Basic scheme of the electronic part of the installation with a characteristic form of a laser pulse (*a*) and ultrasonic cells (*b, c*) for the study of pulse-laser excitation and propagation of ultrasonic waves through magnetic fluid: 1 – generator of electrical pulses; 2 – laser; 3 – device for the correction of the laser beam; 4 – laser beam; 5 – preamp; 6 – oscilloscope BORDO 220; 7 – computer; 8 – light guide; 9 – magnetic fluid; 10 – protector; 11 – piezoplate; 12 – damper

Results of experimental studies

Below mainly the results of experimental studies devoted to the effect of OA transformation in MF are illustrated in Figure 2 and 3.
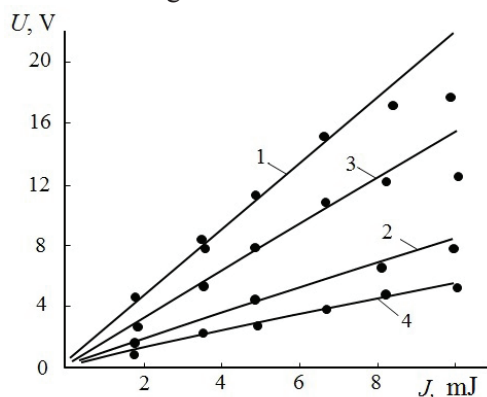

Figure 2 – Dependences of the acoustic amplitude excited by optoacoustic conversion on the energy of the laser pulse: action of the laser radiation on the air-magnetic fluid boundary (2, 4) and quartz-magnetic fluid (1, 3), where mineral oil is the dispersion base: Q, % = 0.3 (1, 2); 8 (3, 4)

The qualitative analysis of the present experimental results is performed in comparison with those obtained earlier in the echo way. The characteristic dependences of the acoustic signal amplitude at OA-conversion depending on the laser pulse energy is in Figure 2 and on the dispersed phase concentration is in Figure 3 when the light flux penetrates into the MF sample through the quartz and air light guides are shown in Figure 1*b* and *c*.

As seen from the obtained in the present work and comparative data, the character of changes in the studied dependences of the informative signal is significantly influenced not only by the colloid concentration and dispersion base, but also by the boundary conditions of contact of the light guide with the MF.

We draw attention to the available qualitative similarity and difference between the behavior of normalized amplitudes of the function of the optoacoustic transformation when implementing the shadow (Figure 3*a*) and the previously studied echo measurement way (Figure 3*b*). The likeness lies in

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the fact that the curves $A^*(Q) = A/A_{max}$ regardless of the boundary conditions have a maximum of characteristic and different values $Q = Q^*$. So, when contacting a quartz glass with MF and $Q > Q_{max}$, then dependence $A^*(Q)$ decreases monotonically by only less than 10 % achieved at $Q \to 8$ %. If the shadow mode is used then A^* decreases by ≈ 3 times. Note that the maxima of $A^*(Q)$ take place when a quartz glass contacts with MF in our experiment (shadow mode) and in [13] (echo mode) that is observed at different values of Q.
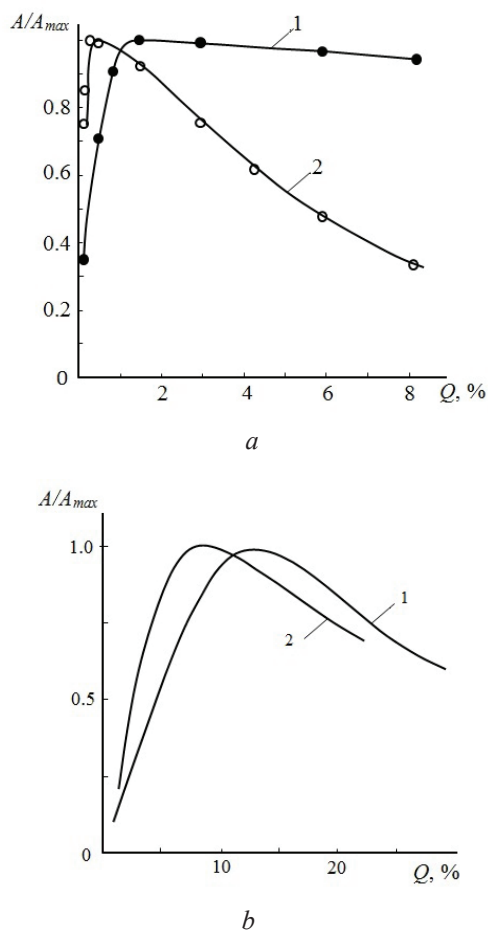
Figure 3 – Normalized amplitude of the acoustic waves at the receiving PEP excited by pulsed laser radiation, depending on the concentration of the dispersed phase in the magnetic fluid: *a* – shadow and *b* – echo mode of probing samples of magnetic fluid; light guide medium is quartz (1) and air (2); the base of the magnetic fluid is oil; *b* – light guide medium is quartz; the base of the magnetic fluid is transformer oil (1) and kerosene (2) [13]

Those, the content of the colloid in the solution of Q_B corresponds to the mode of OA conversion of a long pulse, and the Q_N – a short pulse. Interestingly, in the latter case, when $Q > Q_N$, then there is a sharp

drop of the dependence $A^*(Q)$. So in the vicinity of the extreme boundary of the variable range of concentrations of colloid $(A^*)_1/(A^*)_2 \to 4$.

To explain the dependency obtained above, we use expressions (1) and (2) as well as the calculated data, which have a significant effect on the parameters of the optoacoustic transformation function, which relate to changes in the thermophysical and acoustic properties of samples of MF and the light transparent material when varying the dispersed concentration phases in MF.

Attention is also drawn to the experimental dependences of the function $A^*(Q)$ obtained in [13–14], where the reception of acoustic oscillations was produced by a broad band receiver, as well as the results of a study of the depth of light penetration into the colloid in both echoes and the shadow modes.

First of all, we will pay attention to the difference between the characteristics of the excitation and the propagation of the informative signal on the OA path. When the shadow method is realized after the transformation of laser radiation into acoustic oscillations, the latter applies to the MF sound guide pass through the PEP piezoplate.

According to the spectral theory, in relation to the present problem, the amplitude of the probing signal will, first of all, depend on the operating frequency of the receiver and the length of the absorption zone of the light energy l, determined as $l \sim \alpha_l^{-1}$, where $\alpha \approx 1$–3.

As can be seen from Figure 3*a*, at the concentration of the colloid $Q \approx 0.43$, the value of this zone reaches to $l \approx 150$–200 μm, which corresponds to the time interval $\Delta t \sim l/2C_{MF}$, close to the PEP oscillation in pulse period $(f_p)^{-1}$ and determines mainly the position of the maximum of the amplitude of the signal.

A more detailed analysis of the phenomenon under study shows the necessity of taking into the influence of the effect of the wave phase inversion on the boundary of the light guide. Thus, on the boundary MF-air a phase shift $\Delta\beta \to \pi$ will be observed. I. e. this boundary is a kind of second source with oscillation vectors of the particles of the medium directed oppositely. And in this case at $Q > Q_{max}$ there will be a continuous decrease in the dimensionless distance $h_\lambda = h/\lambda_l$ or a phase shift between the sources mentioned, where k is some correction factor:

$$\Delta\psi \approx -\pi(1-2kh_\lambda), \qquad (3)$$

where $h_\lambda \sim (\lambda\alpha_l)^{-1}$.

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As for the excitation of elastic waves in the "long pulse" mode, then as is seen, with the growth of Q and, of course, the absorption light coefficient α_l, the effect of addition of amplitudes of the two sources will appear. Here part of the energy of the source localized at the division boundary of the MF-quartz will be emitted into a solid medium with an coefficient of transparency on energy:

$$D_{MF,qu}=4R_{MF}R_{qu}(R_{MF}+R_{qu})^{-2},$$

which will lead (as calculations show) to a slight decrease in signal amplitude and what is observed in the experiment, where R_{MF} and R_{qu} – are specific acoustic resistance of MF and quartz.

It is necessary to pay attention to the fact that the efficiency of the operation of MF as an OA element in specialized devices depends on the stability of the OA conversion process. As shown by numerical estimates, made using tabular data, as well as experimental studies with a frequency of 10 Hz and power in a pulse $\approx$ 3 mJ, the greatest temporal stability of the probing signal is observed in the case when quartz glass is used as a light guide coefficient.

Some directions for using magnetic fluid as an optoacoustic converter

As mentioned above, the MF is a kind of nanomaterials with a form varying under the influence of magnetic fields, which has previously been used for both manual control and in some cases – mechanized and automated in ultrasonic flaw detection [8]. On the other hand, as shown [13], MF is a medium with a absorption coefficient, practically close to what is achieved in modern devices based on specially synthesized solid substrates with limited use. The following is a brief analysis of the possibilities of using MF for acoustic diagnostics and non-destructive testing of objects, including living (in vivo), as well as such colloids as a sensitive element for measuring the intensity of laser radiation, which is explained in Figures 4 and 5.

Figure 4 shows the constructions of OA-transducers designed to solve various practical problem. In particular, in Figure 4*a*, a MF thin layer performs a function of a purely flat "lining" on the probe prism converting whether in longitudinal waves transmitted to the prism for excitation in objects surface waves at the velocity of C_R, subsurface longitudinal (C_{SL}) and transverse (C_{ST}), as well as Lamb modes (C_{La}). At the same time, the relationship between the speed of the corresponding acoustic modes, excited in the object $C_{R,SL,ST,L}$ in the OA-converter prism C_1 is $\beta = \arcsin(C_1/C_{R,SL,ST,La})$.
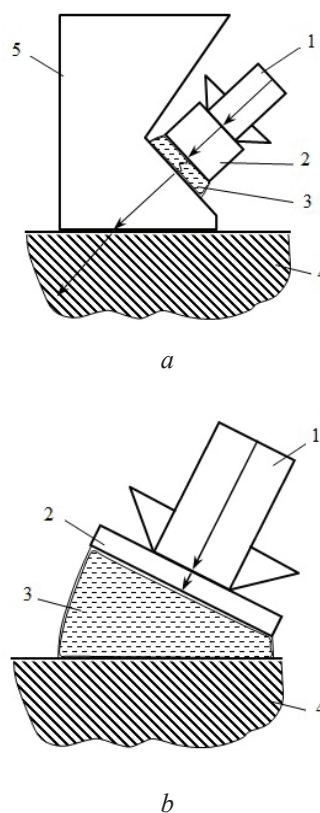

a

b

Figure 4 – Some types of optoacoustic transducers with magnetic fluid for acoustic spectroscopy and evaluation of the physicomechanical properties of materials: 1 – laser beam; 2 – light guide; 3 – magnetic fluid; 4 – an object to test; 5 – prism of PEP

In such OA-transducers it is possible to easily change the MF free surface form under action of magnetic field, the light absorbing ability tocarry out the focusing of the acoustuc beam, rotate its acoustical axis in the liquid and solid materials to test them and also control the sensitility of its arrangement when measuring the intensity of laser pulsed radiation.

In Figure 4*b*, the MF layer performs a function not only of the OA-transducer, but also a sound line to create acoustical contact with objects of a complex surface relief, located in difficult places, in conditions of weightlessness. Figure 4 demonstrates a method of ultrasonic testing by using of above modes the materials with an unknown or changing speed. So, it is possible to find the velocity of the corresponding mode correlating with various informative parameters and to determine the mechanical stresses

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in materials, depth and distribution of hardness in hardening inhomogeneous surface layers of solids, thickness of thin coatings and walls of products of complex profile. To optimize the input of ultrasonic mode to the objects of a high-frequency pulse with minimal distortion, it is necessary to take the optimal concentration Q^* of the nanomagnetic particles, the dispersion base for magnetic fluid and its thickness. It is necessary to study influence of the MF thermal heating which affects the thermophysical and acoustic properties of colloid and measurement stability. As it was also experimentally shown earlier, a quartz with high thermal conductivity and heat capacity should be used for these purposes. It should also be noted that the further MF using as an optoacoustic material requires the study of the peculiarities of the absorption of whether in a wide range of wavelength $\lambda_l \sim 0.1$–10 μm and the pulse duration $t_l \sim 0.001$–1 μs, and action of stationary and nonstationary magnetic fields on the generation of UW with an OA transformation.
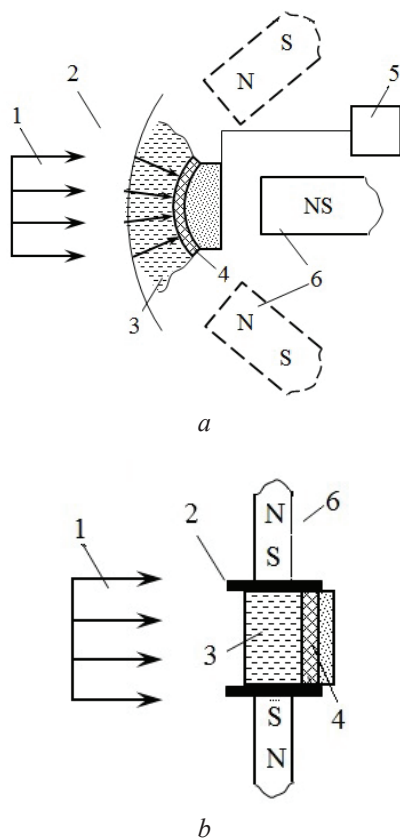

a

b

Figure 5 – Laser radiation measurement schemes, when the surface of the magnetic fluid is of quasi-spherical or quasi-cylindrical (*a*) or flat (*b*) form: 1 – laser beam; 2 – diaphragm; 3 – magnetic fluid; 4 – receiving piezoelectric element; 5 – electrical receiver; 6 – magnetic system for MF formation

One of the directions arising from the experimental studies and theoretical analysis is primarily due to the use of MF as an OA element for measuring the intensity of the laser radiation. Figure 5 shows the possible schemes that implement the method of measuring the intensity J or the laser radiation flow $\Phi(S_0)$ by placing of the MF between the PEP and hold it using the field of the magnetic source or light transparent material, and then determining of the response signal amplitude.

The advantage of the proposed method of measuring the intensity or flows of laser radiation befor tradition al methods lies in the simplicityes of a substantial expansion of the ware length range of the laser radiation – from infared to ultraviolet.

Conclusion

A brief analysis was carried out and the optoacoustic path was examined for the pulse-laser excitation and the propagation of longitudinal waves in the samples of magnetic fluids based on synthetic oil. The possibilities of using magnetic fluid as an object combining the function of the optoacoustic transducer and sound guide are considered.

The technique and installation that implement the shadow measurement way to study effect of the optoacoustic transformation in magnetic fluid are developed, where the Lotis-220 laser is used as a source of the laser radiation with a wavelength of 0.54 μm, and the ultrasonic piezoelectric probe at a working frequency of 5 MHz to receive longitudinal waves propagating in the magnetic fluids. Amplitude dependences of the acoustic wave excited by the pulse-laser radiation are obtained v. s. the concentration of magnetic nanoparticles ($Q = 0$–8 %) and the light pulse energy (0–10 MJ), as well as the method of transmitting the light flow in magnetic fluid through a quartz light guide and air.

The quasilinear dependence of the amplitude A^* of the OA transformation in the samples of the magnetic fluid on the pulse energy in the range from zero to ≈ 8 mJ had been got. But dependences of $A^*(Q)$ have a maximum, the value and the position of which on Q-axes are determined by the boundary conditions for input the light beam in the colloid through the quarts light guide. Moreover, the value of the maximum of A^*, obtained by using a quartz guide by ≈ 40 % more than in the absence of it. The interpretation of data obtained on the basis of the analysis of the thermophysical and elastic properties of magnetic fluids and light guides of contacting media.

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It was shown that here are some ways for using the effect of OA transformation in magnetic fluids, including excitation of high-intensity broadband acoustic pulses of bulk, transverse, surface, etc. in solids for testing of their structure and flaw detection and to measure the power of laser radiation in a wide range of the length of the light wave.

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