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ANOMALOUS REFLECTION OF A LONGITUDINAL ULTRASONIC WAVE FROM A STRONGLY DISSIPATIVE MEDIUM

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Normal reflection of a longitudinal acoustic wave from the plane interface between a solid acoustic line and a strongly dissipative medium (an epoxide resin compound in the process of solidification) has been experimentally investigated. A 14-fold change in the reflection coefficient of pulsed signals and a decrease in their duration have been detected and the point of phase transmission has been reliably determined by the minimum of the reflection coefficient. The coefficient of reflection of continuous acoustic waves with frequencies of 1–10 MHz from the interface between a plexiglas (or aluminum) and an epoxide resin compound in the process of solidification has been measured. The influence of the amplitude-frequency characteristic of an ultrasonic piezoelectric transducer on the measurement data obtained has been analyzed. The change in the viscosity coefficient of an epoxide resin compound in the process of its solidification has been calculated by the spectral transform method with the use of computer programs and experimental data on the reflection coefficient dynamics.

Introduction. Reflection of continuous and pulsed acoustic waves from the interface between nonabsorbing media has been investigated theoretically and experimentally in sufficient detail in [1, 2]. Reflection of acoustic waves from the interface between a solid nonabsorbing medium and a strongly dissipative medium (composite materials in the process of solidification, polymeric materials in the process of swelling, adhesives, soil, grounds, loose materials, layers in microelectronic devices in the process of their fabrication, and other such materials [6]) has been theoretically investigated in [3–5].

To further investigate this phenomenon, we will analyze the process of normal reflection of a longitudinal, continuous acoustic wave from the plane interface between a solid acoustic line 1 and a strongly dissipative medium 2 (Fig. 1). The amplitude coefficient of reflection R_ω and the phase Ψ_{R_ω} of this wave will be defined as

$$R_\omega = \frac{1 - \tilde{\varepsilon}}{1 + \tilde{\varepsilon}}\,, \tag{1}$$

$$\tan \Psi_{R_\omega} = -\frac{2\varepsilon\,(1 + x^2)^{1/4} \sin \dfrac{\Psi}{2}}{1 - \varepsilon^2 (1 + x^2)^{1/2} \cos \Psi}\,, \tag{2}$$

where $\tilde{\varepsilon} = \varepsilon(1 - ix)^{1/2}$; $\varepsilon = Z_2/Z_1$; $Z_1 = \rho_1 s_1$ and $Z_2 = \rho_2 s_{2,0}$; $x = \omega/\omega_c$; $\Psi = -\arctan x$; $\omega_c = c_2/b_2$ is the effective frequency characterizing the strongly dissipative medium, and b_2 is the parameter of dissipative losses, which, for the weak-heat-conductivity materials considered here, is approximately proportional to their viscosity factor.

If $x = 0$ in expression (1), it is transformed into a frequency-independent, classical Fresnel relation. In this case, $R_0 = -2.36 \cdot 10^{-2}$ for the plexiglas–epoxide resin (ER) compound system is small as compared to $R_0 = 0.46$ for the aluminum–ER compound system. Here, the minus sign points to the inversion of the reflected signal relative to the incident one. At low frequencies $\omega \sim \omega_c$, R_ω differs markedly from R_0 [3].

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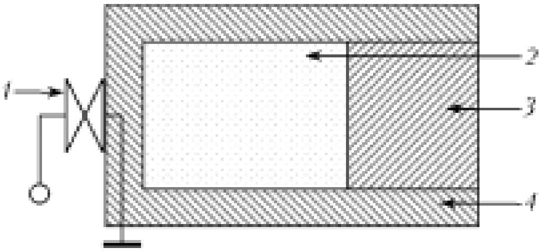

Fig. 1. Cell for acoustic measurement: 1) ultrasonic piezoelectric transducer, 2) strongly dissipative medium; 3) movable wall; 4) cuvette.

Note that the smaller the duration of a pulsed signal, the broader its frequency spectrum [7]. According to (1), different frequency components of a signal reflect differently. As a result of the reflection of a signal, its duration and spectrum change, and these changes are most significant in the case where ω_0 is close to ω_c. Thus, spectral investigations of the reflection of ultrasonic waves from the boundary of a strongly dissipative medium allow one to obtain valuable information on the state and properties of this medium. Note that measurements of the frequency-phase characteristics of an object allow one to obtain more exact information on it (by several orders of magnitude) as compared to measurements of its amplitude characteristics [8, 9].

Experimental Setup. An ultrasonic piezoceramic transducer (UPT) with a mechanical-resonance frequency of 3.5, 5.0, or 7.5 MHz, operating in the combined emission–reception regime, was excited by a pulse generator or a continuous-harmonic-signal generator. The emitted and reflected signals were recorded by an S1-117 oscillograph displaying the amplitude of signals and the time intervals between them in digital form. As the signal source, a G5-54 pulse generator or a G4-158 harmonic-signal generator was used. The oscillograph measured the amplitude of signals with an accuracy of 3% at a sensitivity of 0.1 mV and the time intervals between them with an accuracy of 3% at a sensitivity of 0.1 μsec.

The acoustic measurement cell (see Fig. 1) was a cuvette made from a solid material (plexiglas or aluminum) with a UPT stuck to it by a thin layer of epoxide resin. The design of the cuvette made it possible to vary the thickness of the inside reservoir and, in doing so, investigate the propagation of an acoustic signal not only at the interface between the solid (i.e., the cuvette material) and the strongly dissipative medium, but also in the thin layer of this medium.

To obtain ultrashort pulses, we used a UPT fabricated in the following way. The piezoelement with operating frequencies of 3.5, 5.0, or 7.5 Hz was a disk of diameter 18, 16, or 12 mm with a plane back face and a spherically concave emitting surface with a radius of curvature of 80, 60, or 60 mm, respectively. It was made from an RKR-1 piezoceramics with a low $Q \approx 70$ produced at the Special Design Office of the Institute of Physics of Rostov State University. The inhomogeneity of the piezoelement along its thickness allowed it to be excited and to reliably detect signals in the frequency range 2–4, 4–6, or 6–9 MHz because each conditionally separated ring of the disk represented a halfwave resonator having a definite mechanical-resonance frequency depending on its thickness. This made it possible to increase the bandwidth of the UPT and so decrease its Q factor since these quantities are inversely related to each other. For the purpose of further decreasing the Q factor of the transducer, the back face of the piezoelectric element was given a 6-mm coat of a damping material, an epoxide resin with a filler — lead oxide, and its emitting face was given a matching, quarter-wave coat of an epoxide resin with a filler — tungsten oxide. The matching layer was ground very carefully. In the process of grinding, the reflected acoustic signal was measured on a special acoustic meter — a parallel-sided, plexiglas plate. The grinding was terminated and the UPT was considered as ready for work when a maximum reflected signal was detected or the losses in it caused by its double transformation were reduced to a minimum. Then an inductor was connected in parallel to the UPT to adjust it to the electric resonance with the transducer capacitor, which made it possible to decrease the Q factor of the UPT to $Q \approx 3$. In this case, the duration of the maximum signal of 60 dB reflected from the free surface of the acoustic standard was 1 μsec at a UPT frequency of 3.5 MHz. Measurements of the amplitude-frequency characteristics of the UPTs used in our experiments for a signal of 3 dB have given frequencies comprising 70% of the resonance frequency, i.e., they have shown that a 5-

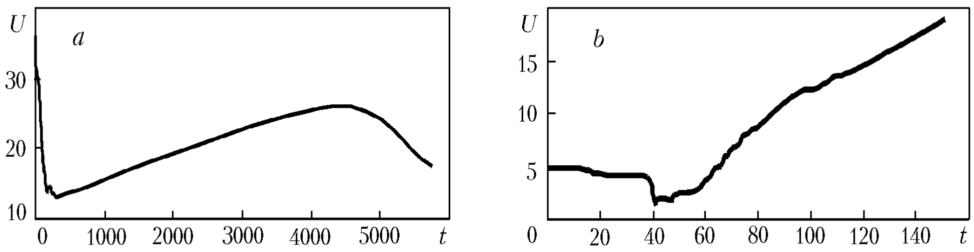

Fig. 2. Experimental time dependences of the coefficient of reflection of a signal from the plexiglas–ER compound interface at an epoxide resin–solidifier ratio of 10:1.2 (a) and 2:1 (b) in the compound. U, mV; t, min.

MHz UPT can operate effectively in the frequency range 3.2–6.8 MHz and, by its amplitude-frequency characteristics, one can determine the frequency dependence of the reflection coefficient of the signal R_ω and its phase Ψ_{R_ω}.

In the case where an inductor is connected in parallel to the electrodes of the piezoelement, the detected signal is six times higher as compared to that in the case where an inductor is absent. It has been theoretically shown [7] that this connection makes it possible to obtain a parallel resonance of emission and the connection of an inductor to the piezoelectric element in series is favorable for a series resonance of reception.

The duration of the pulse fed from the pulsed-signal generator to a UPT provided a maximum reflected signal. This made it possible to eliminate the small deviation of the operating frequency of the UPT operating in the combined regime from the resonance frequency of the piezoelement, which can be due to the matching and damping coats given to the piezoelement, the inductor connected to it, and the output and input impedances of the excitation generator and the recording device, respectively.

Reflection of Pulsed Signals. A complete cycle of measurements lasted no less than 10 h. In this case, the interval between measurements was 5 min at the first stage of duration, 2 h, and it was decreased to 1 min at the stage corresponding to the minimum of the measured curve where the frequency of measurements was maximum. At the stage corresponding to the slanting portion of the curve, measurements were conducted at an interval of 30 min. This irregularity of intervals between measurements is explained by the fact that these experiments are prolonged and tedious. In the figures presented, we did not plot individual experimental points because their number is very large, especially on the initial portions of the curves. The continuous curves were constructed with the use of the Matlab program package. The experiments, except in the special cases noted, were carried out at a UPT frequency of 3.5 MHz.

An acoustic line of plexiglas was used in the majority of experiments and an ÉD-20 epoxide resin compound at different stages of solidification was used as the strongly dissipative medium. Some experiments were conducted with an aluminum–ER compound system. The percent ratio between the epoxide resin and the solidifier was varied.

In the process of solidification of the epoxide resin prepared in accordance with the State Standard (for every 10 g of epoxide resin there were 1.2 g of the solidifier), the coefficient of reflection of a pulsed signal from the plexiglas–ER compound interface decreased by a factor of 2.5 and its duration τ changed from 3 to 2 μsec (Fig. 2a). It is precisely this weight composition of the compound at which epoxide resin molecules attract solidifier molecules and, reacting chemically with them, form a solid structure. It is known from the theory that, at the point of phase transition, one or several physical parameters of a substance behave anomalously. In the case considered, the amplitude of a pulsed, acoustic signal reflected from the above-indicated interface was minimum at the point of phase transition where all the solidifier molecules are bonded to epoxide resin molecules. From this point on the space lattice formed only stabilizes. Since a phase transition represents a first-order structural transition, it arises spontaneously. To ensure that this transition proceeds homogeneously everywhere over the volume of the compound, it will suffice to carefully mix the compound in advance.

In the case of other ratios between the epoxide resin and the solidifier, an excessive or deficient number of bonds are formed, with the result that a part of the epoxide resin or the solidifier remains nonreacted in the compound formed [10].

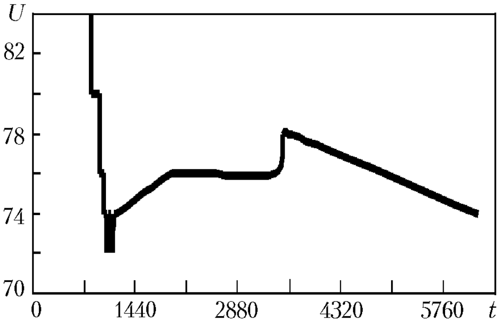

Fig. 3. Experimental time dependences of the coefficient of reflection of a signal from the aluminum–ER compound interface at an epoxide resin–solidifier ratio of 2:1 in the compound. U, mV; t, min.

A significant result was obtained in an experiment conducted under the same conditions but with an ER compound having a volume ratio of 2:1 (Fig. 2b). In this case, the reflection coefficient of a signal was decreased by a factor of 14 and its duration τ was changed from 3 to 1.5 μsec.

We did not detect significant anomalies in investigating analogous dependences for the aluminum–ER compound system, which is probably explained by the substantially larger reflection coefficient R_0 for it. In the case where the ER compound of volume ratio 2:1 was used, the amplitude of the reflected signal decreased only by 12% (Fig. 3). The signal duration increased from 1.4 to 1.7 μsec at the point of phase transition and then decreased to 1 μsec. It should be noted that the coefficient of reflection of an ultrasonic wave from the ER compound changed somewhat over three or more days, even though the compound solidified within several hours. In our opinion, this is due to the physicochemical transformations proceeding in the epoxide resin at the microlevel.

The difference between the acoustic impedances of the liquid and solid phases of epoxide resin is insignificantly large in order that the anomalous changes revealed in the reflection coefficient and duration of signals could be explained using the classical Fresnel formulas. In the process of solidification, the temperature of the mixture increased by no more than 10°C as compared to room temperature, and its volume remained unchanged [10]. In the experiments, the reflection coefficient of an ultrasonic wave was measured in the process of solidification of the ER compound as a time function, i.e., as a function of the time-dependent ultrasound attenuation in the dissipative medium, while the fundamental harmonic frequency ω_0 of the emitted signal remained unchanged, since the UPTs used are resonance and consequently not frequency-tuned. It is evident that the viscosity of the dissipative medium and the ultrasound attenuation in it reach the maximum at the point of phase transition. However, it is difficult to measure the corresponding quantitative dependences.

Since an acoustic pulse emitted by a UPT passes a certain distance in the plexiglas (or aluminum) before it reflects from the interface between this material and the ER compound, it will be attenuated differently in the case of use of different UPTs because the ultrasound attenuation in the acoustic line material depends on the UPT frequency. It is known that the absorption of an acoustic wave changes with increase in the UPT frequency in accordance with the theoretically obtained dependence $\alpha \sim f^2$ [1]. Using the data of [7], we have obtained the following values for α: at a frequency of 3.5 MHz, $11\cdot10^{-5}$ dB/cm for aluminum, 1.6 dB/cm for plexiglas, and 21 dB/cm for epoxide resin; at a frequency of 5.0 MHz, $22\cdot10^{-5}$ dB/cm for aluminum, 3.2 dB/cm for plexiglas, and 42 dB/cm for epoxide resin; at a frequency of 7.5 MHz, $50\cdot10^{-5}$ dB/cm for aluminum, 7 dB/cm for plexiglas, and 94 dB/cm for epoxide resin (the values of α were determined for the solid epoxide resin). The measured values of the attenuation of signals at frequencies of 3.5, 5.0, and 7.5 MHz were larger than the calculated ones and were equal, respectively, to 3, 7 and 11 dB/cm for the plexiglas and 34, 56, and 110 dB/cm for the epoxide resin. This is explained by the fact that the measured values account for not only the absorption of sound but also its scattering and diffraction on the inhomogeneities of the medium, the losses in the signal in the adhesive joint between the UPT and the acoustic line, and the losses caused by the acoustic beam divergence. It should be noted that the absorption of ultrasound in a material can be calculated only approximately. To decrease the above-indicated losses in the acoustic energy to a minimum in experimental acoustic investigations, it is necessary to decrease the thickness of the adhesive joint, make this joint from a high-acoustic-admittance material, and use a weakly absorbing acoustic line whose cross-sectional diameter is larger

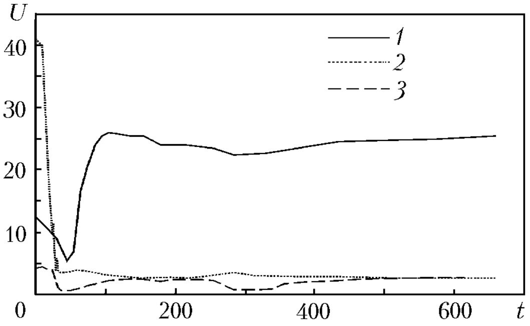

Fig. 4. Reflection of an ultrasonic pulse from the plexiglas–ER compound interface at different resonance frequencies of the UPT: 1) 3.5, 2) 5.0, and 3) 7.5 MHz. *U*, mV; *t*, min.

than the diameter of the piezoelement. An acoustic signal should reflect from the interface in the first Fresnel zone $x_{\text{I}} < d^2/\lambda$, in which the deviation of the acoustic beam from its calculated trajectory can be ignored. The longitudinal dimensions of the first Fresnel zone x_{I} for the three frequencies considered are as follows in the case where plexiglas (or aluminum) are used as the acoustic line material: 177, 149, and 168 mm (421, 474, and 400 mm). Obviously this requirement was met in our experiments.

We also measured the dependences of the reflection of pulsed signals from the plexiglas–ER compound at three different resonance frequencies of a UPT (Fig. 4). The deepest minimum of the amplitude of the detected pulses was obtained at a UPT frequency of 3.5 MHz. Note that, for all three frequencies considered, the minima were detected at one and the same instant of time — 45 min later the ER compound was prepared. This points to the fact that the ultrasound frequency has no effect on the phase transition in the process of ER-compound solidification. Therefore, the phase transition can be detected at an arbitrary frequency of probing. The appearance of the broad minima on the dependences measured approximately 5 h after the compound had been prepared at frequencies of 3.5 and 5.0 MHz cannot be explained only by the measurement errors. It may be suggested that, since the compound was prepared not in accordance with the State Standard and hence in it for a group of ER molecules there were an unduly large number of solidifier molecules as compared to that necessary for the formation of chemical bonds, an additional phase transition can occur as a result of the breaking of excess bonds or the stabilization of the molecular skeleton of the substance formed.

Reflection of Continuous Signals. A 3.5-MHz UPT was used in the experiments. Figure 5 shows the amplitude characteristics of continuous signals of frequency 1–7 MHz reflected from the plexiglas (aluminum)–ER compound interface in the case of solidification of the ER compound over 6 h. The time interval between measurements was decreased in this case as compared to the previous case because all the anomalous changes in the ultrasonic wave appear at the initial stage of its interaction with the substance and because of the necessity of taking a large number of measurements. The amplitude of the detected pulses reached the maximum at a frequency of 3 MHz independently of the time of their detection, which points to the resonance excitation of the UPT.

To make clear which resonance is the case in point, we will consider the theory of emission and reception of ultrasonic signals by one and the same UPT excited by a continuous-wave oscillator, having finite input active and reactive impedances and analogous output impedances, in more detail. It is known from radio engineering that in order that a maximum electric energy be transferred from a power source to a load, the power source should be matched to the load, i.e., their ohmic and reactive impedances should be equal (with accuracy to the sign) [7]. A parallel connection of an inductor to the UPT electrodes is especially favorable for increasing the amplitude of the emitted waves. In this case there arises a parallel resonance of the inductor with the capacitor of the piezoelement, and the input reactive impedance of the UPT is practically equal to zero. Now it remains to match the active impedances. Standard oscillators are designed, as a rule, for a load of 50 Ω. The input impedance of the UPTs used in our experiments was close to this value. The radiation resonance is frequently called the electric resonance since, in the case of this resonance, the electric energy is transferred from the oscillator to the UPT and is partially converted into mechanical energy. An emitted acoustic signal propagating in the object studied reflects partially from the interface, returns to the same UPT, and, in doing so, generates a potential difference across its electrodes; this potential difference will be maximum in the case where reflection of the acoustic signal from the surface of the receiving UPT is absent (or small) and there are conditions for the appearance of mechanical resonance, i.e., when the halflength of the wave is equal to the piezoelectric-element thickness. For the purpose of measuring the voltage across the piezoelement electrodes, these electrodes are terminated in a recording device with an input resistance of several megaohms, which makes it possible to minimize the losses in the signal arising as a result of its double transformation.

It should be noted that electric and mechanical resonances occur at different frequencies in one and the same piezoelement. These frequencies are related by the relation

$$\omega_{\mathrm{el}} \approx \omega_{\mathrm{m}} \left(1 - \frac{2}{\pi^2} K^2\right)^{1/2}. \tag{3}$$

In our case, the relation between the UPT resonance frequencies will be even more complex because of the influence of the inductor connected to the transducer, the matching and damping layers, the object studied, the output resistance of the oscillator, and the input resistance of the recording device (oscillograph or voltmeter). However, the electric resonance frequency is always lower than the mechanical resonance frequency, and the larger the electromechanical coupling constant of the piezoelectric material the larger the difference between these frequencies.

To mechanically match a piezoelement to the medium studied, it is necessary to give its emitting surface a quarterwave coat with an acoustic impedance equal to the mean geometric value of the acoustic impedances of the media adjacent to it. In this case, an acoustic signal of resonance frequency penetrates completely into the object studied. In the case where a UPT has no matching layer, a small portion of radiation with a frequency falling in a narrow range penetrates into the object studied because of the large difference between the impedance of this object and the impedance of the piezoceramics. In the case considered, not only did the amplitude of the emitted signals increase, but their frequency range also increased by the same number of times, which was favorable for obtaining short acoustic signals. The damping of the piezoelement leads to complete absorption of an acoustic pulse emitted by it in the opposite direction and so decreases the power of the UPT as a converter of electric energy into mechanical energy approximately by a factor of 2; however, the duration of the emitted signal decreases in this case by the same number of times. All the measures taken decrease the sensitivity and hence the efficiency of a UPT but also decrease the duration of the emitted signals, i.e., increase the spatial resolution and decrease the Q factor of the UPT. In the case of reception of acoustic signals from a medium transparent for sound, the matching and damping of a UPT leads to the same results.

We considered operation of a UPT at its fundamental harmonic frequency. The efficiency of operation of a UPT at higher harmonics will be lower. In our case, the decrease in the UPT efficiency will be significant because the piezoelectric ceramics used had a low Q factor. Therefore, we did not consider piezocrystal materials with a high Q factor, such as quartz, in which the Q factor reaches 10^5 at K of no more than 2%. This allows quartz transducers to be used in practice for generation of the tenth and even higher harmonics.

It is seen from Fig. 5a that, in addition to the main maximum, the reflected signal amplitude has a weakly defined second maximum at a frequency of ~6 MHz. This maximum appeared when the UPT operated at the second harmonics. The dependences obtained represent the amplitude-frequency characteristics (AFC) of a UPT operating in the combined emission–reception regime and loaded with the object studied. The AFC of such a UPT is the product of the AFC of the UPT operating in the regime of emission ($\mathrm{AFC_{em}}$), the AFC of the UPT operating in the regime of reception ($\mathrm{AFC_{rec}}$), and the AFC of the propagation of a signal in the waveguide ($\mathrm{AFC_{prop}}$). Let us consider the $\mathrm{AFC_{prop}}$ in more detail. The waveguide (because of the frequency-dependent attenuation of sound in it) and the interface between it and the dissipative medium (the boundary conditions are also frequency-dependent) will transform acoustic waves differently, i.e., the attenuation of continuous waves in the waveguide increases with increase in the frequency, and the interface makes the largest contribution to the signal transformation at $f \sim f_{\mathrm{med}}$.

The $\mathrm{AFC_{em}}$, $\mathrm{AFC_{prop}}$, and $\mathrm{AFC_{rec}}$ cannot be measured separately. Within the limits of the first electric resonance, the $\mathrm{AFC_{em}}$ has a maximum at a frequency of f_{el} and a definite frequency band Δf_{el}. The ratio between f_{el} and Δf_{el} determines the Q factor of the UPT in the regime of emission. On the other hand, within the limits of the first mechanical resonance, the $\mathrm{AFC_{prop}}$ has a maximum at a frequency of f_{m}. Furthermore, the $\mathrm{AFC_{prop}}$, which is not a constant, has a characteristic maximum at a frequency of f_{med}. Thus, the total amplitude-frequency characteristic of the

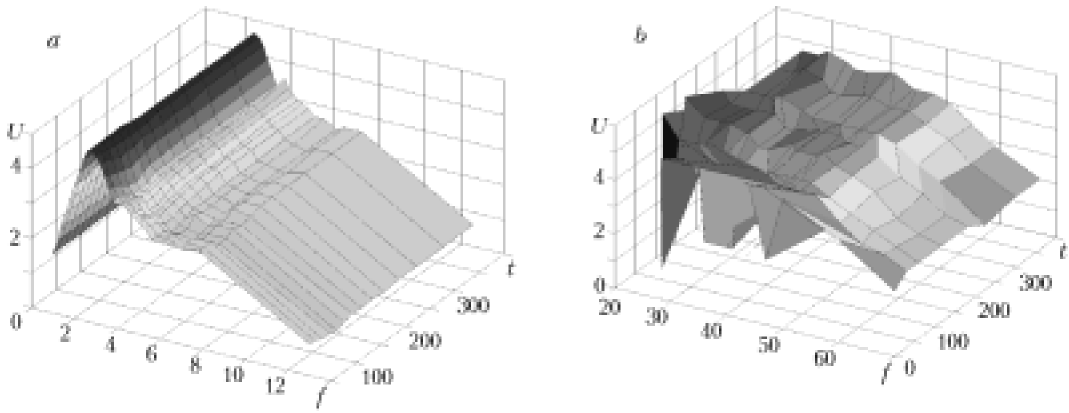

Fig. 5. Reflection of a continuous signal from the plexiglas–ER compound interface (a) and the aluminum–ER compound interface (b). U, mV; f, MHZ; t, min.

UPT can have as much as three maxima within the limits of the first resonance; however, more often than not, it has a single maximum at a frequency f' that differs from the above-mentioned frequencies f_{el}, f_{m}, and f_{r} and was earlier called the operating frequency of the UPT. In this case, the UPT will also have another frequency band $\Delta f'$. The detected signal, because of the filtration properties of the receiving transducer, differs markedly from the signal propagating in the medium. This is also true for pulsed signals. Note that the $\mathrm{AFC}_{\mathrm{prop}}$ of a pulsed signal can be represented as the product of the $\mathrm{AFC}_{\mathrm{at}}$ and the $\mathrm{AFC}_{\mathrm{int}}$ characterizing, respectively, the contribution of the sound attenuation in the acoustic line and in the interface between it and the strongly dissipative medium to the formation of the spectrum of this signal. In our investigations, it is most important to determine the $\mathrm{AFC}_{\mathrm{int}}$ because the $\mathrm{AFC}_{\mathrm{em}}$, $\mathrm{AFC}_{\mathrm{prop}}$, and $\mathrm{AFC}_{\mathrm{rec}}$ are constants in the case where one and the same UPT and one and the same acoustic cell are used in the experiment. If the cell is not filled with a substance, the product of the three last-mentioned characteristics can be easily measured. The product of $\mathrm{AFC}_{\mathrm{em}}$ and $\mathrm{AFC}_{\mathrm{prop}}$ can be determined on condition that an acoustic line made from a material not absorbing signals at the frequencies considered is used. Thus, the $\mathrm{AFC}_{\mathrm{int}}$ can be calculated separately and the effect of the dissipative medium on the reflection of a signal from the interface can be estimated. However, since we performed dynamic measurements of the reflection coefficients, their absolute values were not calculated and only the relative changes in them were fixed. This is also explained by the fact that in the reference books there are no data on the acoustic parameters (velocity of sound, impedance, sound attenuation) of strongly dissipative media in the process of their solidification.

Figure 5b presents the time dependence of the amplitude of the reflected signal detected by a UPT in the case where an aluminum was used as the waveguide.

Construction of the Time Dependence of the Viscosity of a Strongly Dissipative Medium. Knowing the theoretical dependence $R_{\omega}(\omega/\omega_{\mathrm{med}})$ and the value of the effective frequency ω_{med} for the solid phase of an epoxide resin, one can calculate the dependence of ω_{med} and, consequently, the sound attenuation α in the ER compound and the viscosity of this compound $b_2 = \xi_2 + 4/3\eta_2$ on the time of its solidification by the spectral transform method. The time dependence of the effective frequency ω_{med} and, which is most important, of the viscosity of the strongly dissipative medium in the process of its solidification is determined on the basis of experimental data on the reflection of an acoustic signal modeled with the use of a computer.

The inverse problem can be solved with the use of a powerful computer on the basis of experimental data on the reflection of a signal at different ω_{med} or on the basis of data of its computer modeling.

In the first case, it is necessary to store the measured or calculated characteristics of reflected pulsed signals, as standards, in the computer memory. The characteristic parameters of a signal, in particular ω_{med}, are determined by comparison of its measured and standard values. One of the main advantages of this approach is the possibility of using the measured values of the parameters difficult to calculate. However, the application of this method is limited by the volume of the computer memory and the problems of obtaining a complete data base on standard signals. Since the parameters of reflected signals are substantially dependent on both the parameters of the emitted signals and the

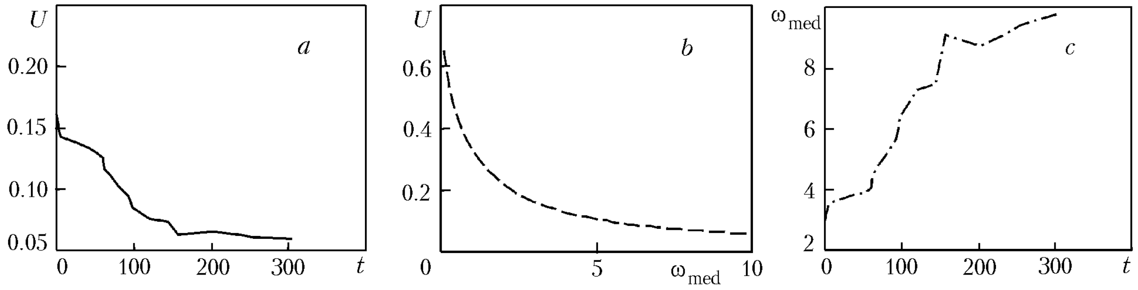

Fig. 6. Initial data for construction of the time dependence of ω_{med}: a) experiment; b) calculation; c) calculated time dependence of ω_{med}. U, rel. units; t, min; ω_c, MHz.

characteristics of the adjacent media, it is very difficult to consider all the variants with an acceptable step. The problem becomes simpler in the case where only the data on signals selected in accordance with any criterion are stored in the data bank and numerical methods are used for interpolation of the intermediate values.

The second method of solving the inverse problem requires less computer memory but a larger capacity of the computational subsystem since the boundary reflection should be repeatedly modeled with the aim of finding parameters at which the calculated reflected signals are closest to the measured ones. This approach can be considered as most optimum if a computer of sufficient capacity and adequate models are used. However, this approach, as also the first approach, is associated with problems characteristic of the spectral transform method such as: the nondependence of the results obtained on the errors in the experimental data and the uniqueness of the solution obtained.

The above-described methods can be realized with the use of the software devised by us. The initial data and the data obtained as a result of solution of the inverse problem are presented in Fig. 6 (the signal amplitude is given in relative units). It is seen from this figure that the effective frequency ω_{med} decreases by a factor of 9 in the process of solidification of a freshly prepared ER compound until its point of phase transition is attained. Since the velocity of a longitudinal wave changes only by tens of percents in this case, the change in the modulus of elasticity will be of the same order. Consequently, the viscosity of a strongly dissipative medium and the absorption of an ultrasonic wave in it change approximately by the same number of times as compared to the change in the frequency ω_{med}.

CONCLUSIONS

We have experimentally investigated reflection of longitudinal acoustic pulsed signals of fundamental frequency 3.5, 5.0, and 7.5 MHz and continuous signals of frequency 1–10 MHz from the plane interface between a solid acoustic line and an ER compound of various compositions in the process of its solidification. It has been shown that the detection of the point of structural phase transition in such compounds is independent of the frequency of an ultrasonic signal probing the object studied. The determination of the viscosity of a substance by the spectral acoustic analysis method proposed has been demonstrated. The method proposed can be used for investigating a broad range of substances undergoing phase, structural, aggregate, and chemical transformations and substances subjected to the action of strong temperature, electromagnetic, and other fields, changing their physical parameters (density, velocity of sound, elasticity, plasticity, viscosity or internal friction, heat conduction).

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NOTATION

b_2, parameter of dissipative losses in the strongly dissipative medium, Pa·sec; c_2, modulus of elasticity, J/m^3; d, diameter of the piezoelectric plate, m; f, frequency, Hz; f', operating frequency of the UPT, Hz; f_{med}, characteristic frequency of the strongly dissipative medium, Hz; f_m, frequency of mechanical resonance, Hz; f_{el}, frequency of electric resonance, Hz; K, electromechanical coupling constant; Q, Q factor of the UPT; R_0 and R_ω, amplitude, frequency-independent and frequency-dependent coefficients of reflection; s_1, velocity of a longitudinal wave in the solid acoustic line, m/sec; $s_{2,0}$, velocity of a longitudinal wave in the strongly dissipative medium in the case where dissipation is absent (at $\omega = 0$), m/sec; t, times, sec; U, voltage across the UPT, V; x_I, first Fresnel zone, m; Z_1, acoustic impedance of the solid semispace for a longitudinal wave, kg/(m^2·sec); Z_2, acoustic impedance of the strongly dissipative medium in the case where dissipation is absent, kg/(m^2·sec); AFC$_{\text{int}}$, AFC of the interface between the acoustic line and the strongly dissipative medium; AFC$_{\text{at}}$, AFC of the attenuation in the acoustic line; AFC$_{\text{em}}$, AFC of the UPT operating in the regime of emission; AFC$_{\text{rec}}$, AFC of the UPT operating in the regime of reception; AFC$_{\text{prop}}$, AFC of the propagation of a signal; α, sound-absorption coefficient, dB/m; η_2, shear viscosity of the strongly dissipative medium, Pa·sec; λ, wavelength, m; ξ_2, volume viscosity of the strongly dissipative medium, Pa·sec; ρ_1, density of the solid acoustic line, kg/m^3; ρ_2, density of the strongly dissipative medium, kg/m^3; τ, duration of an acoustic pulse, sec; Ψ_{R_ω}, phase of the reflected wave, rad; ω, cyclic frequency, Hz; ω_0, frequency of the fundamental harmonic of a pulsed signal, Hz; ω_{m}, cyclic frequency of mechanical resonance, Hz; ω_{med}, cyclic frequency characterizing the strongly dissipative medium, Hz; ω_{el}, cyclic frequency of electric resonance, Hz. Subscripts: ω, denotes frequency, frequency-dependent quantity; 1, denotes a solid acoustic line; 2, denotes a strongly dissipative medium; int, interface; at, attenuation; m, mechanical; rec, reception; prop, propagation; med, medium; el, electric.

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