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ANOMALIES OF THE BOUNDARY REFLECTION OF ULTRASOUND FROM THE FILM OF A DISSIPATIVE MEDIUM

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Theoretical consideration has been given to the reflection of continuous and pulsed longitudinal and transverse acoustic waves from the film of a dissipative medium which is in contact with a solid-state half-space. It has been shown that the reflection coefficient and its phase substantially depend on the coefficient of attenuation of ultrasound in the dissipative-medium film and on its phase thickness. The shape of the reflected acoustic pulsed signal has been calculated using software. The application of the results obtained to investigation of the acoustic properties of viscous fluids is discussed.

Introduction. The reflection of continuous and pulsed acoustic vibrations from the interface of media has been studied theoretically and experimentally in sufficient detail [1, 2]. Nonetheless, the case of reflection of an acoustic wave from a medium possessing a high absorption of sound vibrations is unknown to us and can turn out to be of interest in both scientific and applied aspects. Earlier, we considered theoretically the reflection and transmission of longitudinal acoustic (continuous and pulsed) signals by a plane boundary of a solid body with a strongly dissipative medium (SDM) for which one can use a viscous fluid or an organic material [3–5]. We also analyzed the propagation of such acoustic vibrations through the layer of an SDM between two solid-state half-spaces. In all the indicated cases we found the reflection and transmission coefficients for an acoustic wave; these coefficients had a complex form different from the known Fresnel formulas [2] and depended on the dissipative-loss parameter of the SDM determined by the medium's viscosity and thermal conductivity. The results of theoretical investigations were confirmed by the experimental observations of the propagation of continuous longitudinal acoustic waves of the frequency range 1–10 Hz and of pulsed longitudinal acoustic signals with a frequency of 3.5 and 5 MHz of their fundamental carrier (rf) harmonic [5]. As the SDM we used a compound — epoxy resin with a hardener. It is the most available (as far as the preparation is concerned) and efficient object with a high and significantly variable viscosity in the process of hardening. Depending on the percentage of the compound used, in the course of its hardening, the coefficient of reflection of the longitudinal acoustic pulsed signal of a fundamental frequency of 3.5 MHz which propagated in the acrylic plastic was 14 times relative to its initial value, where one part of the hardener by volume was added to two parts of the epoxy resin by volume. Simultaneously with the change in the reflection coefficient we observed a reduction in the duration of the reflected signal from $\tau = 3$ μsec to $\tau = 1.5$ μsec, i.e., the spectrum of the reflected signal became wider.

It should be noted that the state of the SDM has a qualitative influence on the reflection and transmission coefficients and on the phase of both continuous and pulsed acoustic signals. Since phase measurements are more accurate than amplitude ones, one can judge from them the absorption of sound in the SDM and, by employing the method of the inverse problem, restore the time dependence of the viscosity of the substance prepared and visualize the readiness of one technological product or another for use.

For such investigations it is necessary to consider the distinctive features of reflection of an acoustic signal from the boundary between a solid body and an SDM film coating it. This enables one to relate the coefficient of reflection of the wave and its phase and spectrum to the characteristics of the state of the coating and its adhesion stability and to provide the possibility of controlling flexibly the synthesis of the substances of the coating with

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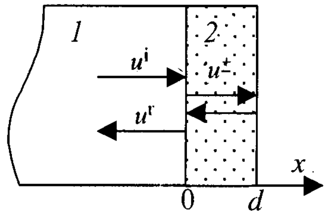

Fig. 1. Propagation of an acoustic wave in a layered structure.

prescribed optimum properties and of decreasing, at the same time, the energy consumption in the technological process and increasing the service life of the coatings.

Reflection of Longitudinal Sound from the SDM Film. Let a continuous harmonic longitudinal wave be incident on an SDM layer from the solid half-space 1; the wave is partially reflected and penetrates into the layer (Fig. 1). The wave equations for the wave in each material of the layered structure are written as follows [2]:

$$\rho_1 \ddot{u}_x = c_1 u_{x,xx}\,, \quad \rho_2 \ddot{u}_x = c_2 u_{x,xx} + b_2 u_{x,xx\,\mathrm{t}}\,, \tag{1}$$

where $u_{x,xx} = \partial^2 u_x / \partial x^2$ and $u_{x,xx\,\mathrm{t}} = \partial^3 u_x / \partial^2 x \partial t$. The coefficient of reflection of sound α in the film is unambiguously expressed in terms of the dissipative-loss parameter b_2 according to the expression $\alpha = \omega^2 b_2 / 2\rho_2 s_{2\,\mathrm{long}}^3$.

Solutions for the incident and reflected waves are sought in standard form [1]:

$$u_x^{\mathrm{i}} = u_{10}^{\mathrm{i}} \exp\,[i\,(k_1 x - \omega t)]\,, \quad u_x^{\mathrm{r}} = u_{10}^{\mathrm{r}} \exp\,[i\,(-\,k_1 x - \omega t)]\,,$$
$$u_x = u_0^{+} \exp\,(-\,k'' x)\exp\,[i\,(k' x - \omega t)] + u_0^{-} \exp\,(-\,k'' x)\exp\,[i\,(-\,k' x - \omega t)]\,, \tag{2}$$

where $k_1 = \omega / s_{1\,\mathrm{long}}$ is the wave number.

The boundary conditions represent a continuity of elastic displacements and stresses at the boundary of the media and have the form

$$u_x^{\mathrm{i}} + u_x^{\mathrm{r}} = u_x\,, \quad c_1 u_{x,x}^{\mathrm{i}} + c_1 u_{x,x}^{\mathrm{r}} = c_2 u_{x,x} + b_2 u_{x,x\,\mathrm{t}} \quad \text{for} \quad x = 0\,,$$
$$c_2 u_{x,x} + b_2 u_{x,x\,\mathrm{t}} = 0 \quad \text{for} \quad x = d\,, \tag{3}$$

where $u_{x,x} = \partial u_x / \partial x$ and $u_{u,x\,\mathrm{t}} = \partial^2 u_x / \partial x \partial t$.

The solutions (2) satisfy the corresponding wave equations (1) and, being substituted into (3), yield the system of linear equations to determine the reflection coefficient R_ω which is expressed by the relation

$$R_\omega = \frac{A - iZ_{1\,\mathrm{long}}}{A + iZ_{1\,\mathrm{long}}}\,, \quad A = Z_{2\,\mathrm{long}}\,(1 - ix)\left(i - \frac{x^{1/2}}{[(1 + x^2)^{1/2} + 1]^{1/2}}\right)\frac{\exp\,(\gamma)\exp\,(-\,i\beta) - \exp\,(-\,\gamma)\exp\,(i\beta)}{\exp\,(\gamma)\exp\,(-\,i\beta) + \exp\,(-\,\gamma)\exp\,(i\beta)}\,, \tag{4}$$

where $Z_{1\,\mathrm{long}} = \rho_1 s_{1\,\mathrm{long}}$, $Z_{2\,\mathrm{long}} = \rho_2 s_{2\,\mathrm{long}}$, $\beta = k'd$, $\gamma = k''d$, and $x = \omega/\omega_{\mathrm{m}}$.

By numerical methods (using a computer) we have calculated the frequency dependence of the modulus of the reflection coefficient and its phase $\Psi_{R_\omega} = k'd$ on x (see Fig. 2) for layered structure containing an epoxy-resin film. The reflection coefficient is $R_\omega = -1$ for $\omega \to 0$ and $R_\omega \to 1$ for $\omega \to \infty$. With change in the frequency when $n\lambda/4$ wavelengths fit into the layer thickness the extrema of R_ω appear, i.e., the oscillations of the coefficient of reflection of the wave occur.

In addition to the amplitude coefficient of reflection found, of interest are the coefficients of reflection of the velocity wave $R_u = \dot{u}^{\mathrm{r}}/\dot{u}^{\mathrm{i}}$, the pressure wave $R_p = p^{\mathrm{r}}/p^{\mathrm{i}}$, and the intensity wave $R_J = J^{\mathrm{r}}/J^{\mathrm{i}}$. Since, according to (2), differentiation with respect to time does not change condition (3), $R_{\dot{u}} = R_\omega$. By virtue of the existence of the relation between the pressure and the vibrational velocity $p/\dot{u} = \pm Z_1$, where the upper sign is taken for the wave propagating in the positive direction x while the lower sign is taken for the wave propagating in the opposite direction, we find

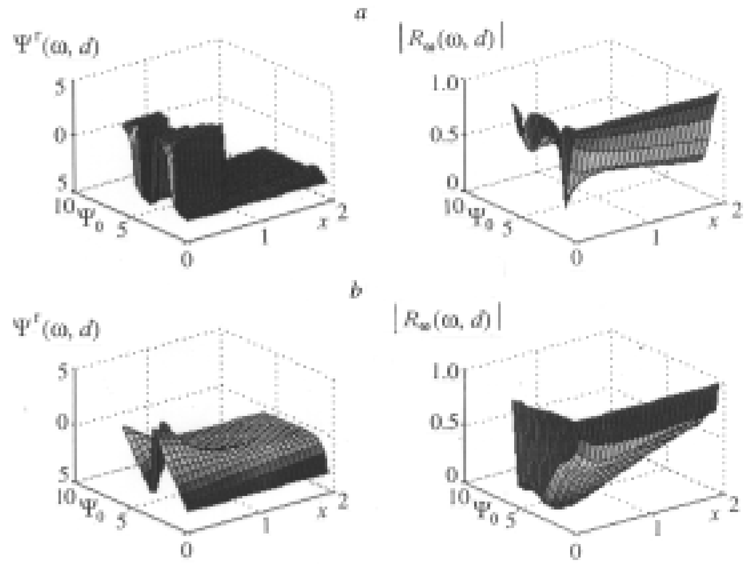

Fig. 2. Coefficient of reflection of longitudinal sound for the aluminum–epoxy resin structure [a) $Z_{1\,\text{long}}$ = 17.33·10^6 kg/(m^2·sec), $Z_{2\,\text{long}}$ = 3.25·10^6 kg/(m^2·sec), $s_{1\,\text{long}}$ = 6.42 km/sec, $s_{2\,\text{long}}$ = 2.68 km/sec, ρ_1 = 2.70·10^3 kg/m^3, and ρ_2 = 1.21·10^3 kg/m^3)] and the acrylic plastic–epoxy resin structure [b) $Z_{1\,\text{long}}$ = 3.1·10^6 kg/(m^2·sec), $s_{1\,\text{long}}$ = 2.7 km/sec, and ρ_1 = 1.15·10^3 kg/m^3)] (the data are given for the solid phase of the epoxy resin).

$R_p = -R_\omega$. Consequently, the given frequency dependences of the modulus of the amplitude reflection coefficient and its phase coincide with the modulus of the reflection of the pressure wave and its phase.

Since the pressure and intensity of the wave in a nondissipative medium are related by the relations $J_\text{i} = p_\text{i}^2/2Z_1$ and $J_\text{r} = p_\text{r}^2/2Z_1$, the coefficient of reflection of sound is determined by the formula $R_J = |R_\omega^2|$.

By virtue of the law of conservation of energy the intensity sound-transmission coefficient in the SDM is $T_J = 1 - R_J$, whereas the amplitude transmission coefficient is $T_\omega = 1 + R_\omega$. The entire given intensity in the SDM film is irreversibly converted to heat. From the practical viewpoint, the recording of reflected signals is more informative than the recording of attenuated signals transmitted by the SDM film. Therefore, here and in what follows emphasis is placed on consideration of the processes of reflection of a wave.

From consideration of the reflection of a continuous signal we pass to investigation of the reflection from the boundary and transmission, by it, of a pulsed acoustic signal which is the closest to an actual signal emitted by an ultrasonic piezoceramic transducer. At the interface of the media $x = 0$ such a signal has the shape [3–5]

$$u_x^\text{i}(x=0, t) = u_{10}^\text{i} \exp\left(-\Gamma \frac{|t|}{T}\right) \exp\left(i2\pi \frac{t}{T}\right)\left[\theta\left(t - \frac{\tau}{2}\right) - \theta\left(t + \frac{\tau}{2}\right)\right], \tag{5}$$

where $T = 2\pi/\omega_0$ and $\tau = nT$, and n is a certain integer equal to the number of periods of the emitted pulse.

On the basis of the given dependence of R_ω and by employing expression (5) for an actual acoustic signal and direct and inverse Fourier transformations, one can calculate, using a computer, the shape of the reflected signal for the layered structures indicated above [6].

The calculation results are presented in Fig. 3 in the form of the curves of the pulse swing D and demonstrate a substantial dependence of the amplitude and phase of the reflected pulse on the frequency ω_0 of the fundamental harmonic of the pulsed signal. The phase of the reflected pulse is understood with a higher degree of generalization than is the case for continuous vibrations, namely, as the displacement of the intersection of the emitted and transmitted pulses and the time axis. The Fourier transformation applied to the emitted $u_x^\text{i}(x, t)$ and reflected $u_x^\text{r}(x, t)$ pulses yields their spectra, which differ [7].

We note that the software used makes it possible to elucidate the distinctive features of reflection for any shape of the emitted pulses. Analytical calculations are partly possible for the simplest shapes of emitted signals (for

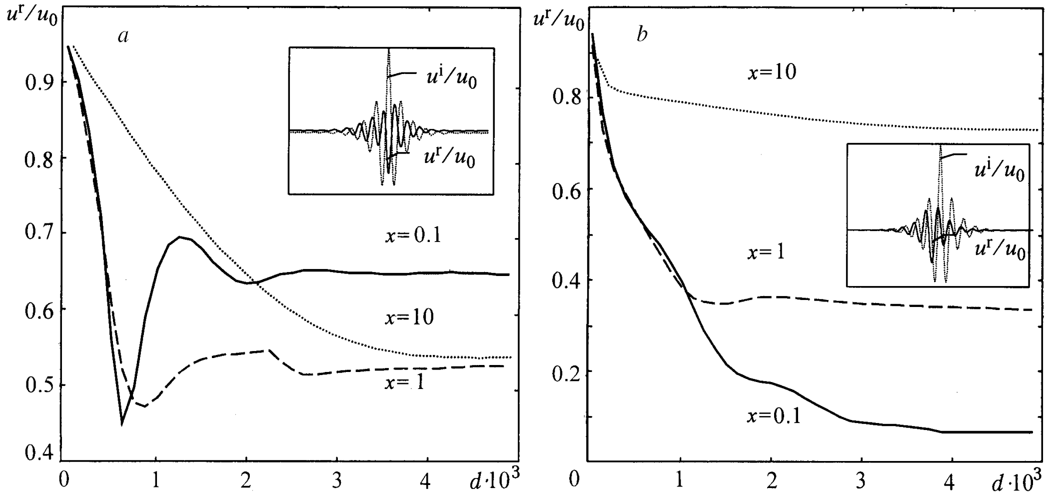

Fig. 3. Incident and reflected longitudinal acoustic signals and the dependence of their amplitude on the thickness of the SDM film for the aluminum–epoxy resin (a) and acrylic plastic–epoxy resin (b) structures.

example, for a rectangular signal or several periods of a sine one, which are not practical), but the nontrivial frequency-dependent form of R_ω makes it difficult or impossible to analytically find the spectrum and shape of the reflected and transmitted signals.

Reflection of Transverse Sound from the SDM Film. Whereas longitudinal waves propagate with a significant attenuation in a viscous fluid, the propagation of transverse waves in the fluid is impracticable, according to [1]. Thus, for continuous oscillations of the frequency f = 1 MHz their attenuation is $1.1\cdot10^{26}$ m^{-1} ($8.6\cdot10^6$ dB/m) for a wavelength of $\lambda = 6$ μm and $2.3\cdot10^{17}$ m^{-1} ($8.6\cdot10^4$ dB/m) for $\lambda = 630$ μm in glycerin. Nonetheless, for small gaps $d \ll \lambda$ between two solid-state half-spaces we can have the infiltration of a transverse wave because of the presence of the shear or Stokes viscosity η_2, in addition to the volume or second viscosity ξ_2, in the real fluid [3]. This circumstance, in particular, explains the effective transfer of a Rayleigh wave propagating over the upper surface of one solid-state half-space to the lower surface of the second solid-state half-space contacting the first solid body via a small fluid gap, which is substantiated theoretically and confirmed experimentally.

When the shear viscosity of the SDM is disregarded the reflection of a transverse wave normally incident on a plane boundary with the SDM on the source side of the solid body is 100% without a phase shift and is equivalent to the reflection of this wave from the boundary with vacuum. When the shear viscosity is taken into account a small penetration of the transverse wave into the SDM (which is rapidly attenuated there) occurs. This distinctive feature is attributed to the change in the boundary conditions for displacements and stresses and, depending on the phase thickness of the film coating, can produce a significant difference of the amplitude reflection coefficient from unity and the dependence of the phase of the reflected wave on the viscosity of the SDM and the phase thickness of the film.

Transverse waves fundamentally differ physically from longitudinal ones and have a number of advantages over them, i.e., low velocity of propagation and higher-than-average sensitivity to the shear acoustic parameter of a substance. Therefore, in a number of cases it turns out to be more preferable to employ transverse waves and not longitudinal ones, for example, in investigating the dimensional properties of the coatings of solid-state substrates.

Wave equations in each of the materials of the layered structure will be written as follows [2, 8]:

$$\rho_1 \ddot{u}_{1y} = \mu_1 u_{1y,xx}\,, \quad \rho_2 \ddot{u}_{2y} = b_2 u_{2y,xx\,t}\,, \tag{6}$$

where $b_2 = 4\eta_2/3$, $u_{1y,xx} = \partial^2 u_{1y}/\partial x^2$, and $u_{2y,xx\,t} = \partial^3 u_{2y}/\partial^2 x \partial t$.

The solutions for the incident (i) and reflected (r) transverse waves are sought in the form [2]

$$u_y^{\mathrm{i}} = u_{10}^{\mathrm{i}} \exp\left[i\,(k_1 x - \omega t)\right]\,, \quad u_y^{\mathrm{r}} = u_{10}^{\mathrm{r}} \exp\left[i\,(-k_1 x - \omega t)\right]\,,$$

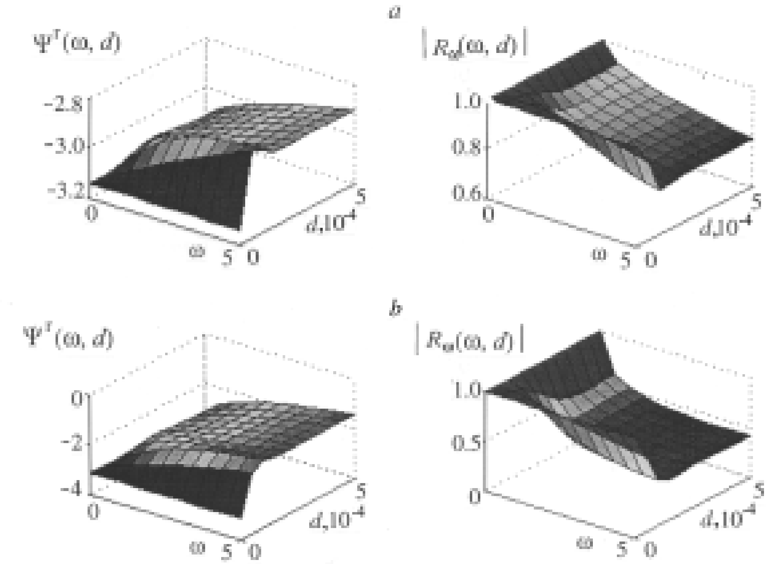

Fig. 4. Coefficient of reflection of transverse sound for the aluminum–epoxy resin structure [a) Z_{1t} = 8.21·10^6 kg/(m^2·sec), Z_{2t} = 1.39·10^6 kg/(m^2·sec), s_{1t} = 3.04 km/sec, and s_{2t} = 1.15 m/sec)] and the acrylic plastic–epoxy resin structure [b) Z_{1t} = 1.26·10^6 kg/(m^2·sec) and s_{1t} = 1.1 km/sec]. d, m; ω, MHz.

$$u_{2y} = u_0^{+} \exp(-k_0 x) \exp[i(k_0 x - \omega t)] + u_0^{-} \exp(k_0 x) \exp[i(-k_0 x - \omega t)] , \tag{7}$$

where $k_1 = \omega / s_{1t}$ is the wave number for the transverse sound and $k_0 = (\rho_2 \omega / 2b_2)^{1/2}$.

The law of dispersion of sound in a dissipative medium yields the following relations for the phase and group velocities: $v_{ph} = \omega^{1/2}[2b_2/\rho_2]^{1/2}$ and $v_{gr} = 2v_{ph}$.

The analysis shows that as the frequency increases ($\omega \to \infty$) the phase velocity of sound is $v_{ph} \to \infty$ and the group velocity is $v_{gr} \to \infty$ since the SDMs considered were assumed to be Newtonian fluids. The attenuation of sound in the SDM is $\alpha = k_0 = (\rho_2 \omega / 2b_2)^{1/2}$.

The boundary conditions are a continuity of elastic displacements and stresses at the boundary of the media and have the form

$$u_y^{i} + u_y^{r} = u_y^{T} , \quad \mu_1 (ik_1 u_y^{i} - ik_1 u_y^{r}) = b_2 [u_0^{+} (-i\omega)(-k_0 + ik_0) + u_0^{-} (-i\omega)(k_0 - ik_0)] \quad \text{for} \quad x = 0 ,$$
$$b_2 [u_0^{+} \exp(-k_0 d) \exp(ik_0 d)(-i\omega)(-k_0 + ik_0) + u_0^{-} \exp(k_0 d) \exp(-ik_0 d)(-i\omega)(k_0 - ik_0)] = 0 \quad \text{for} \quad x = d . \tag{8}$$

The solutions (7) satisfy the corresponding wave equations (6) and, being substituted into (8), yield the system of linear equations to determine the reflection coefficient $R_\omega = u_{10}^{r} / u_{10}^{i}$ which is determined by the relation

$$R_\omega = \frac{A - B}{A + B} , \tag{9}$$

where $A = \tilde{Z}_2 \exp(i\pi/4)[\exp(2\Psi_0) - \exp(i2\Psi_0)]$ and $B = iZ_{1t} [\exp(2\Psi_0) + \exp(i2\Psi_0)]$, $\tilde{Z}_2 = (b_2 \rho_2 \omega)^{1/2}$, $\Psi_0 = k_0 d$.

After simple mathematical manipulations we give the expression for the square of the modulus of the amplitude reflection coefficient:

$$|R_\omega^2| = \frac{g_1 \tilde{Z}_2^2 - 2g_2 Z_1 \tilde{Z}_2 + 2g_3 Z_1^2}{g_1 \tilde{Z}_2^2 - 2g_2 Z_1 \tilde{Z}_2 + 2g_3 Z_1^2} , \tag{10}$$

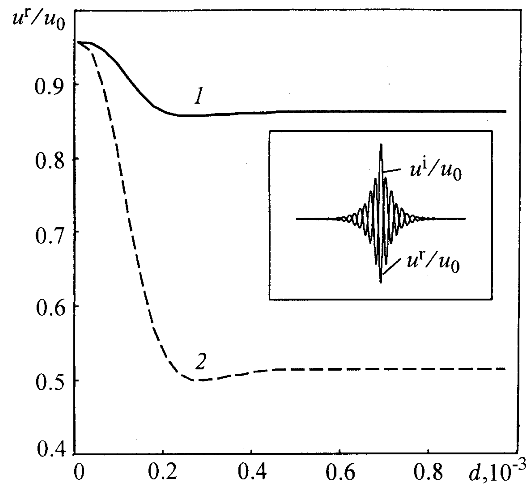

Fig. 5. Incident and reflected transverse acoustic signals for the aluminum–epoxy resin (1) and acrylic plastic–epoxy resin (2) structures. *d*, m.

where $g_1 = \exp(4\Psi_0) - 2\exp(2\Psi_0)\cos 2\Psi_0 + 1$, $g_2 = \exp(4\Psi_0) - 2\exp(2\Psi_0)\sin 2\Psi_0 - 1$, and $g_3 = \exp(4\Psi_0) + 2\exp(2\Psi_0)\cos 2\Psi_0 + 1$. It is easy to show that in all the cases $|R_\omega^2| \le 1$.

For the phase of the reflected wave we obtain the relation

$$\tan \Psi_{R_\omega} = -\frac{2g_2 Z_{1t}\tilde{Z}_2}{g_1\tilde{Z}_2^2 - 2g_3 Z_{1t}^2}. \tag{11}$$

We have numerically calculated (using a computer) the frequency dependences of the modulus and phase of the reflection coefficient for different values of the coating-film thickness (Fig. 4). At low frequencies and for a small thickness of the coating, the reflection is total with inversion of the signal phase. As the frequency increases the reflection is total no longer; it decreases significantly due to the processes of absorption of the incident ultrasonic energy in the film coating and a certain phase shift of the reflected signal occurs. For example, when $\omega = 2\pi\cdot 10^7$ Hz and $d = 10^{-4}$ m, $|R_\omega| = 0.7$ and $\varphi = 1.45$ for aluminum and $|R_\omega| = 0.46$ and $\varphi = 1.15$ for acrylic plastic. Detailed analysis of the coefficient of reflection of the signal shows that at certain and quite practical frequencies $f = 1$–10 MHz one can measure the thickness of superthin coatings using both amplitude (by R_ω) and more sensitive phase (by φ) instrumentation. For example, for the measurement frequency $f = 10$ MHz the changes in the reflection coefficient and its phase are, respectively, of the order of 10^{-4} and 1^0 for the two cases in question. Thus, whereas it is impossible to record the attenuation of the reflected signal by easily available amplitude instrumentations, the recording of the phase shift (given above) is realizable since the accuracy of phase measurements attains 10^{-2} degrees or higher. We note that the phase of the reflected signal is $\Psi_{R_\omega} = -\pi$ when $\omega = 0$ and $\Psi_{R_\omega} \to 0$ when $\omega \to \infty$, whereas the reflection coefficient R_ω has its minimum when $\omega \approx 2\pi\cdot 10^7$ Hz and $R_\omega \to 1$ when $\omega \to 0$ and when $\omega \to \infty$. With change in the frequency when $n\lambda/4$ wavelengths fit into the layer thickness, the extrema of R_ω occur, which suggests the oscillation of the reflection coefficient and its phase.

We note that for transverse waves the velocity, pressure, and intensity reflection coefficients correspond to the relations given earlier for longitudinal waves.

On the basis of the dependence of R_ω and employing (5), we calculated, using a computer, the shape of the reflected and transmitted signals in the layered structures indicated above. The calculation results (Fig. 5) demonstrate a substantial dependence of the amplitude and phase of the reflected signal on the frequency ω_0.

Conclusions. In modern electronic production and machine building, of importance is continuous control of the quality and structure of coatings in the process of their deposition on the substrates of materials. The proposed method of ultrasonic phase-time measurements can allow the diagnostics of a fine structure of substances which undergo physicochemical transformations as a result of the processes of molecular and laser epitaxy, electro- and photolithography, electrochemistry, plasma spraying and vacuum deposition, and soldering and brazing. In most of the above cases, we have a strong local heating and phase, aggregative, and chemical transformations in individual regions of a product which, under such conditions, are SDMs in physical properties since changes in the density and the elastic moduli and an increase in the absorption of ultrasonic vibrations occur in these regions.

NOTATION

τ, duration of the acoustic pulse, sec; ρ_1, density of the material of the solid-state half-space, kg/m^3; u_x, component of the elastic displacement in the longitudinal wave, m; c_1, elastic modulus for the solid-state half-space, J/m^3; ρ_2, density of the SDM film, kg/m^3; c_2, elastic modulus for the SDM film, J/m^3; b_2, parameter of dissipative loss in the film, Pa·sec; α, sound-absorption coefficient, dB/m; ω, cyclic frequency, Hz; $s_{2\,\mathrm{long}}$, velocity of the longitudinal wave in the film, m/sec; u_x^{i}, emitted longitudinal acoustic signal, m; u_{10}^{i}, amplitude of the emitted acoustic signal, m; i, imaginary unit; $k = k' + ik''$, complex wave number for the film, m^{-1}; k_1, wave number for the solid-state half-space, m^{-1}; t, time, sec; u_x^{r}, longitudinal acoustic signal reflected from the film, m; u_{10}^{r}, amplitude of the acoustic signal reflected from the film, m; u_x, elastic longitudinal displacement, m; u_0^+, amplitude of the acoustic signal propagating in the forward direction, m; u_0^-, amplitude of the acoustic signal propagating in the backward direction, m; x, coordinate along the abscissa axis, m; d, SDM-film thickness, m; R_ω, amplitude reflection coefficient; $Z_{1\,\mathrm{long}}$, acoustic impedance of the solid-state half-space for longitudinal sound, kg/(m^2·sec); $Z_{2\,\mathrm{long}}$, acoustic impedance of the film for longitudinal sound in the absence of dissipation, kg/(m^2·sec); ω_{m}, characteristic frequency of the SDM, Hz; Ψ_{R_ω}, phase of the reflected wave, rad; λ, wavelength, m; $R_{\dot{u}}$, reflection coefficient of the velocity wave; R_p, reflection coefficient of the pressure wave; p, pressure, Pa; p^{i}, pressure in the incident wave, Pa; p^{r}, pressure in the reflected wave, Pa; R_J, reflection coefficient of the intensity wave; J^{i}, intensity of the incident wave, W/m^2; J^{r}, intensity of the reflected wave, W/m^2; T_ω, amplitude sound-transmission coefficient; T_J, intensity sound-transmission coefficient; Γ, dimensional parameter determining the envelope of the incident acoustic pulsed signal; T, period of the pulse, sec; ω_0, frequency of the fundamental harmonic of the signal, Hz; θ, Heaviside function; D, pulse swing; f, frequency, Hz; ξ_2, volume viscosity, Pa·sec; η_2, shear viscosity, Pa·sec; μ_1, second Lamé coefficient; u_{1y}, component of the elastic displacement in the transverse wave for the solid-state half-space, m; u_{2y}, component of the elastic displacement in the transverse wave for the film, m; u_y^{i}, emitted transverse acoustic signal, m; u_y^{r}, reflected transverse acoustic signal, m; $s_{1\mathrm{t}}$, velocity of the transverse wave in the solid-state half-space, m/sec; v_{ph}, phase velocity, m/sec; v_{gr}, group velocity, m/sec; u_y, transmitted transverse acoustic signal, m; $Z_{1\mathrm{t}}$, acoustic impedance for transverse sound, kg/(m^2·sec); $\tilde{Z}_2$, effective acoustic impedance of the SDM, kg/(m^2·sec); Ψ_0, phase thickness of the SDM film, rad; φ, phase shift of the reflected signal, rad. Subscripts and superscripts: long, longitudinal wave; 1, medium 1 (see Fig. 1); 2, medium 2 (Fig. 1); x, longitudinal displacement; y, transverse displacement; i, incident wave; r, reflected wave; +, positive direction; –, negative direction; ω, frequency, frequency-dependent; $\dot{u} = \partial u/\partial t$; p, pressure; J, intensity; gr, group velocity; ph, phase velocity; t, transverse wave.

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