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PARAMETRIC ACOUSTICS

Determination of the Elastic Properties of Layered Materials Using Laser Excitation of Ultrasound

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Abstract—It is proposed to use ultrasonic signals excited by a laser pulse to investigate the elastic properties (impedances, speeds of sound, and densities) of layered media. The results of studying both a model medium with known parameters and a layered composite are reported. The experimental data are in good agreement with the known properties of the samples investigated.

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1. INTRODUCTION

Examples of the structures studied are layered composites, whose range of application in industry (in particular, aircraft construction) constantly increases. These materials have two significant advantages: small specific weight and high strength. However, the absence of reliable methods for monitoring these materials hinders their wide application. To solve this problem, it is necessary to use high-resolution systems to determine location of defects of different types and identify them. Currently, such materials are monitored using X-ray tomography and ultrasonic analysis. A significant drawback of X-ray tomography is its insensitivity to stratifications (the latter may be caused by deviation of adhesive component concentration from nominal during preparation). Ultrasonic flaw detection has a low sensitivity and is difficult for analysis, although in principle it can be used to reveal various defects [1–6].

Let us consider layered composites, which are generally sets of layers, cemented by a particular adhesive. An example is carbon–epoxy composites, where each sheet is a texture formed by graphite fibers. These textures are interlinked by a polymer adhesive under forming pressure. An analysis of this structure is fairly difficult because of the wide range of spatial scales of the composite structure. Therefore, such materials should be studied using a broadband probe pulse (with a frequency band up to 10 octaves). Standard ultrasonic sources cannot provide such a wide working frequency band; however, the optoacoustic effect makes it possible to excite fairly short (i.e., having a wide spectral band) acoustic signals. The theory of this effect was described in detail in [7].

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2. THEORY

Excitation of a pressure pulse in optoacoustic generator occurs as a result of thermal expansion of a thin layer of light-absorbing medium under pulsed laser irradiation. Using short laser pulses, one can obtain smooth acoustic pulses down to several tenths of nanoseconds wide [7]. A schematic for studying layered media based on a PLU-6P-01 laser ultrasonic converter is shown in Fig. 1. A laser beam is incident on the left-hand side of light-absorbing layer (generator *0*) through the optically transparent boundary of sound guide *3* (PMMA). The other side of the generator is in acoustic contact with an object *1* of study. The absorption of laser pulse leads to fast heating of the generator layer, which expands to

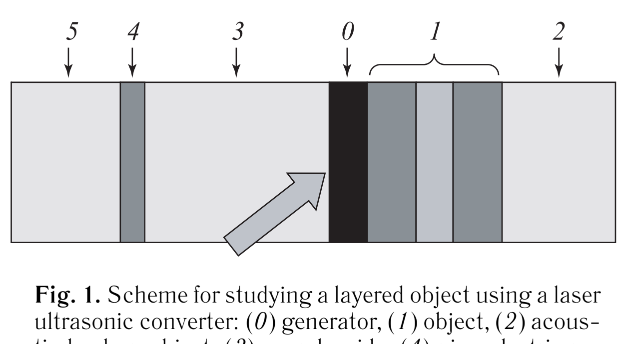

Fig. 1. Scheme for studying a layered object using a laser ultrasonic converter: (*0*) generator, (*1*) object, (*2*) acoustic load on object, (*3*) sound guide, (*4*) piezoelectric receiver, and (*5*) acoustic load on piezoelectric receiver. The arrow shows the direction of incident laser radiation.

produce an acoustic wave. The acoustic radiation is received by a damped piezoelectric cell *4*, located at the opposite side of sound guide *3*. This receiver is well damped and has a wide frequency band of sensitivity, due to which ultrasonic signals with a high time resolution (about 0.05 μs) can be correctly received. To reduce the level of spurious echo signals, the acoustic impedances of individual elements of the converter acoustic channel are matched. Two acoustic waves are excited upon light absorption, one of which (reference signal) propagates toward the receiver, while the other propagates toward the object monitored. The waves reflected from the structure of object *1* propagate backward throughout the entire converter and are also detected by receiver *4*.

Propagation of an ultrasonic pulse in a layered medium is accompanied by numerous rereflections, which are generally difficult to analyze. The strong effect of the layered medium structure on the transmitted optoacoustic and RF signals was shown in [8] and [9, 10], respectively.

The reflection of acoustic pulse with a peak amplitude value A_0 from the boundaries of the first and second layers is schematically shown in Fig. 2. The pulse is incident from the side of the medium indexed by *0*, whose parameters are known (to example, the generator layer). In this case, the amplitude of the signal reflected from the interface between media *0* and *1* is given by the formula $A_1 = A_0 R_{01}$, where $R_{ij} = (Z_j - Z_i)/(Z_j + Z_i)$ is the reflectance of interface between media i and j for incidence from the side of medium i and Z_i is the impedance of medium i. The error in determining the reflectance has the form

$$S_{R_{01}} = S_A \frac{A_0 + A_1}{A_0^2}, \quad (1)$$

where S_A is the error in determining the signal amplitude.

The impedance of medium *1* can be expressed in terms of the reflectance R_{01} as

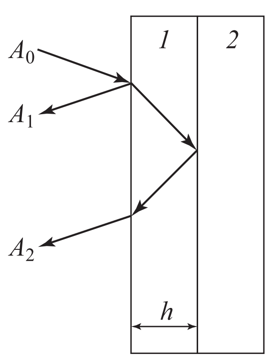

Fig. 2. Incidence of acoustic wave with an amplitude A_0 from the side of medium *0* on the front boundary of a layered medium composed of two layers (indices 1 and 2).

$$Z_1 = Z_0 \frac{1 + R_{01}}{1 - R_{01}}. \quad (2)$$

Its absolute and relative measurement errors can be written as

$$\begin{aligned} S_{Z_1} &= S_{Z_0} \frac{Z_1}{Z_0} + \frac{2 S_{R_{01}} Z_0}{(1 - R_{01})^2}, \\ \delta_{Z_1} &= \delta_{Z_0} + \delta_{R_{01}} \frac{2 R_{01}}{1 - R_{01}^2}, \end{aligned} \quad (3)$$

where $\delta_{Z_0} = S_{Z_0}/Z_0$, $\delta_{Z_1} = S_{Z_1}/Z_1$, and $\delta_{R_{01}} = S_{R_{01}}/R_{01}$ are the relative errors in measuring Z_0, Z_1, and R_{01}, respectively.

It follows from formulas (3) that the error in measuring the impedance of the first layer depends strongly on the reflectance. Based on (3), one can conclude that the stronger the acoustic mismatch between media *0* and *1*, the larger the error in determining the impedance of medium *1*.

The part of the wave transmitted to medium *1* is reflected at the interface between media *1* and *2*. The amplitude of the received signal, corresponding to this reflection, is expressed by the formula $A_2 = A_0(1 - R_{01}^2) R_{12}$. Based on this relation, one can calculate the reflectance and its error:

$$\begin{aligned} R_{12} &= \frac{A_2}{A_0(1 - R_{01}^2)}, \\ S_{R_{12}} &= \frac{R_{12}}{A_2} \left[S_A (1 + R_{12}) + 2 A_0 R_{01} R_{12} S_{R_{01}} \right]. \end{aligned} \quad (4)$$

The second-medium impedance and its error are determined from formulas (2) and (3), with indices 0 and 1 replaced by 1 and 2, respectively. The impedance of the next layer can be found from the same formulas, with the only difference: now layer *1* plays the role of layer *0*.

The velocity of longitudinal acoustic waves in layer *1* can be calculated from the formula

$$\begin{aligned} c &= \frac{2h}{\tau_2 - \tau_1}, \\ S_c &= S_h \frac{c}{h} + S_\tau \frac{c}{\tau_2 - \tau_1}, \end{aligned} \quad (5)$$

where h is the thickness of layer *1*; τ_1 and τ_2 are the delays corresponding to the arrival of signals A_1 and A_2, respectively; S_c is the error in determining the speed of sound; S_τ is the error in determining the time delay; and S_h is the error in measuring the layer thickness. The layer density can be calculated based on its impedance and speed of sound in it,

$$\rho = \frac{Z}{c}, \quad S_\rho = S_Z \frac{\rho}{Z} + S_c \frac{\rho}{c}, \quad (6)$$

where S_ρ is the error in determining the layer density.

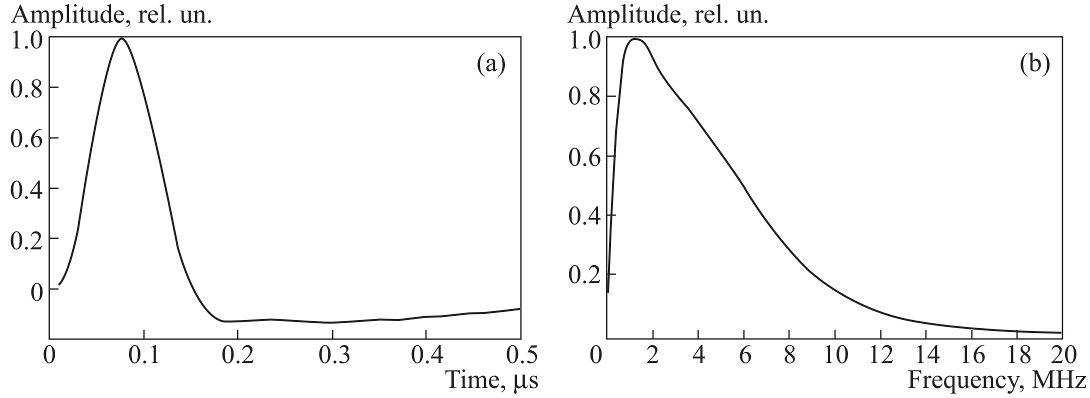

Fig. 3. (a) Time and (b) spectral profiles of probe signal.

Absorption in layer *1* should lead to pulse broadening and decrease in the peak value A_2 and, as a result, to additional errors in calculating the layer parameters. To avoid this effect, it is expedient to analyze the low-frequency signal component, which is less absorbed. For optoacoustically excited video pulses, it is more convenient to use not signals but integrals over them:

$$I(t) = \int_{-\infty}^{t} P(t')\, dt', \qquad (7)$$

where $P(t)$ is the time dependence of the pressure induced by the signal received and $I(t)$ is the corresponding integral.

It is convenient to use $I(t)$ instead of $P(t)$ because under pulsed sounding the function $I(t)$ is composed of piecewise-constant segments connected by smooth transitions having a duration of the same order of magnitude as the probe pulse. In this case, the above formulas contain the corresponding integral steps instead of the reflected signal amplitudes A_i. Absorption in the layer increases the duration of the transitions from one level to another but barely affects the value of steps.

This method makes it possible to determine the impedances of media in the presence of absorption, but its accuracy decreases with an increase in the layer number. This is caused by the strong effect of diffraction, which manifests itself in the integrals as a slope of horizontal line in the intervals between steps. Nevertheless, the impedances of the first several layers can be determined due to the smallness of diffraction effects.

3. EXPERIMENTAL SETUP

The experimental setup consists of a PLU-6P-01 optoacoustic converter, which is schematically shown in Fig. 1. The principle of its operation was described above in the theoretical part. Radiation of a Nd:YAG diode-pumped Q-switched laser, a pulse-repetition frequency of 1 kHz, pulse width of 10 ns, and energy of 60 μJ was supplied to the converter through an optical fiber. Acoustic waves were detected by a piezoelectric film 110 μm thick, with a frequency band up to 20 MHz. The electric signal from the film is amplified and applied to a 12-bit analog-digital converter (ADC). Its discretization frequency is 100 MHz and analog band is 70 MHz. The digital data from the ADC are supplied to a computer for further processing.

4. PROBE PULSE

The probe near-Gaussian pulse is followed by a diffraction tail. The pulse duration at a level of $1/e$ is $\sim$100 ns. The temporal and spectral pulse shapes are shown in Fig. 3. The signal frequency range is from 200 kHz to 7 MHz.

To obtain the ultrasonic reflectance, we corrected the signal taking into account the pulse transient characteristic of the converter acoustic channel. The treatment of experimental signals implied their deconvolution with the probe signal and subsequent filtration. A hyper-Gaussian window was used as a filter.

5. STUDY OF THE MODEL MEDIUM

The method was verified on two two-layer samples. The first was a squared aluminum plate, 0.68 ± 0.01 mm thick and a lateral-side width of 35.4 mm. An epoxy resin layer (1.54 ± 0.02 mm thick) was deposited on its surface. This sample is an example of acoustically mismatched layered medium with an absorbing layer. The other sample (an example of absorbing medium with layers having similar acoustic impedances) consists of a squared

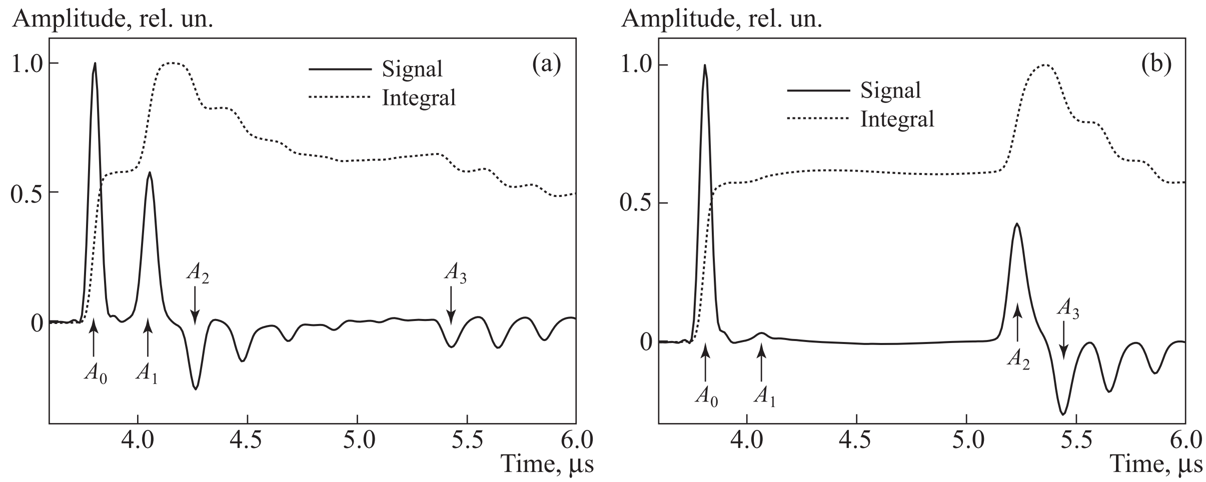

Fig. 4. Signals and their integrals obtained upon reflection from a two-layer aluminum–epoxy resin structure; measurements from the sides of (a) aluminum and (b) epoxy resin.

Table 1. Impedances of two-layer media measured by the step of integral values

Sample	Side for measuring	Impedance (measurement results), 10^6 kg m^{-2} s^{-1}	
PMMA–epoxy resin		PMMA	Resin
	PMMA	3.33 ± 0.06	3.27 ± 0.08
	Epoxy resin	3.70 ± 0.12	3.19 ± 0.07
Aluminum–epoxy resin		Aluminum	Resin
	Aluminum	18.7 ± 0.9	4.0 ± 0.3
	Epoxy resin	18.9 ± 0.6	3.44 ± 0.08

PMMA layer (2.74 ± 0.01 mm thick and a lateral face width of about 40 mm) with an epoxy resin layer 1.39 ± 0.01 mm thick on its surface.

The epoxy resin surfaces of the samples were polished to make them plane-parallel. The samples were studied from both sides, due to which the layer impedances could be measured both directly and against the background of another layer. An acoustic contact was provided by an immersion liquid (water).

The elastic characteristics of both plates were measured before epoxy resin deposition. The speed of sound was determined from formula (5), and the density was found by weighing. The impedances of the aluminum plate and PMMA layer were, respectively, $(18.7 \pm 0.9) \times 10^6$ and $(3.1 \pm 0.2) \times 10^6$ kg m^{-2} s^{-1}.

The experimental signals from the aluminum–epoxy resin sample and integrals of these signals are shown in Fig. 4. Here, one can see well the difference in the arrival times of the probe pulse A_0 and the pulse reflected from front boundary, A_1. Panel (a) corresponds to the analysis from the side of the aluminum plate. A pulse A_2, reflected from the aluminum–epoxy resin boundary and rereflected in the aluminum plate, arrives after the pulse A_1. Then a signal A_3, reflected from the boundary of second layer in epoxy resin, comes. The integral over this signal indicates that the diffraction contribution is still small. In panel (b), the same sample was investigated from the side of epoxy resin. It is clearly seen that the pulse A_2, reflected from the epoxy resin–aluminum interface, is wider than the probe pulse. This is caused by strong absorption. The results of measuring impedances are presented in Table 1. It can be seen that in the case of layered PMMA–epoxy resin medium the epoxy resin impedances measured from different sample sides are fairly close. The measured PMMA impedances differ, depending on the measurement direction. This can be caused by acoustic wave scattering from air bubbles in epoxy resin (when measuring from the resin side).

The aluminum plate impedances for the aluminum–epoxy resin sample are similar, which can be explained by a smaller number of air bubbles in the epoxy resin layer than in the previous sample. This mechanism is also confirmed by the higher impedance of the resin layer in this sample. When measuring from the side of the aluminum plate, the error is fairly large because of the strong mismatch between the

Table 2. Impedances of samples measured by the peak values of reflected signals

Sample	Side for measuring	Impedance (measurement results), 10^6 kg m^{-2} s^{-1}	
PMMA–epoxy resin		PMMA	Resin
	PMMA	3.35 ± 0.04	3.28 ± 0.04
	Epoxy resin	3.42 ± 0.05	3.17 ± 0.04
Aluminum–epoxy resin		Aluminum	Resin
	Aluminum	11.0 ± 0.2	4.72 ± 0.09
	Epoxy resin	7.7 ± 0.1	3.12 ± 0.04

acoustic impedances of the object of study and generator. The error in determining the resin impedance is large for the same reason.

For comparison, the same data, but calculated from the peak amplitudes of reflected signals, are listed in Table 2. It can be seen that for aluminum–epoxy resin sample the aluminum plate impedances differ strongly from each other and from the tabular value. This difference is caused by the absorption of reflected acoustic wave in the epoxy resin layer. The impedances of the PMMA–epoxy resin sample are close to the results listed in Table 1. The effect of absorption in the layer is weak due to the small signal amplitude (because the reflectance is small).

6. STUDY OF LAYERED COMPOSITE

We investigated a layered composite consisted of three aluminum plates (average thickness $414 \pm 36\,\mu$m) cemented by fiber glass fabric layers (average thickness $109 \pm 21\,\mu$m). The layer thickness was measured by a metallographic microscope with a scale, whose error was $5\,\mu$m.

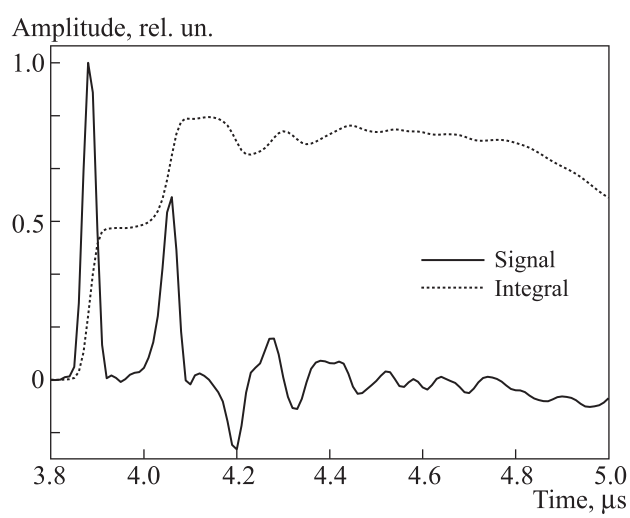

Fig. 5. Signal and its integral (solid and dotted lines, respectively) from a three-layer structure.

A processed signal and its integral are shown in Fig. 5. The parameters obtained for the first layer are as follows: impedance $Z = (18.1 \pm 1.0) \times 10^6$ kg m^{-2} s^{-1}, speed of sound $c = (6.5 \pm 0.6) \times 10^3$ m s^{-1}, and density $\rho = (2.8 \pm 0.4) \times 10^3$ kg m^{-3}. These values are in good agreement with the tabular values for aluminum alloy. These parameters for the cementing layer were found to be $Z = (3.4 \pm 0.2) \times 10^6$ kg m^{-2} s^{-1}, $c = (2.9 \pm 0.6) \times 10^3$ m s^{-1}, and $\rho = (1.2 \pm 0.3) \times 10^3$ kg m^{-3}. The analysis of the next layers was hindered by the significant decrease in the amplitude of the corresponding signal due to the strong reflection from the first layers.

7. CONCLUSIONS

Laser-excited acoustic signals are an efficient tool for analyzing layered structures. To determine the ultrasonic reflectances for individual layers and calculate their impedances, it is convenient to use integrated ultrasonic signals. The impedances of the layers of model media, measured by reflectances, were found to be in good correspondence with the impedances found by measuring the density and speed of sound in the layers that confirms the efficiency of the optoacoustic method used.

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