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Laser ultrasonic investigation of laminate disbonding

***Abstract*—Contact laser-ultrasonic evaluation (CLUE) provides ultrasonic testing with sharp probe ultrasonic pulse. It makes it possible to enhance spatial resolution at relatively lower frequency band than piezoelectric ultrasonic testing. The advantage of CLUE is the possibility to distinguish the acoustic wave reflection at the soft or rigid boundary. This feature can be effectively used for the investigation of disbonding in laminate structures. The sample consisting of three aluminum shits glued with polymer layers is tested with CLUE. The results of back-reflection coefficient measurement are compared with the numerical simulation. The signatures from regular area and area with disbonded layer are compared. The sensitivity and resolution of testing is discussed.**

***Index Terms*—optoacoustic, ultrasonic, nondestructive testing**

I. INTRODUCTION

Composite materials are very important for industry (for making panels and other heavy loaded sets for airplanes). Production of such materials is a complicated process, which needs permanent control. Composite parts have to be controlled during exploitation. Ultrasonic investigation could give a lot of information about mechanical properties and texture of such material.

Generally, composite materials are layered structures that consist of different materials. Transmission and reflection of ultrasonic waves in laminated structures is a complex process. Theoretical foundations of ultrasonic wave propagation in layered structures can be found in [1]. The size of components that form a composite structure varies over a wide range. Due to this fact probe ultrasonic pulse should have wide bandwidth. Practically, one needs frequency band of 10 octaves to investigate the texture of a composite. Traditional ultrasonic transducers could not emit signal with such a wide band. Fortunately, laser ultrasonics could provides signals with sufficient bandwidth [2].

Experimental and numerical investigation of transmitted acoustic fields with narrow band was made in the paper [4]. Similar work for broadband signals was performed in [3].

However, recording of transmitted ultrasonic signals ("shadow" method) may be difficult or impossible in practice, because the back of the studied structure may not be accessible. More convenient is to use an alternative approach, namely the reflection mode, when the source and the receiver are placed at thee same side of the object. In reflection mode it is fairly easy to determine depth of a defect, because it is related to the time delay of the corresponding signal.

In this work layered structures are analyzed by the laser-ultrasonic method in pulse-echo mode.

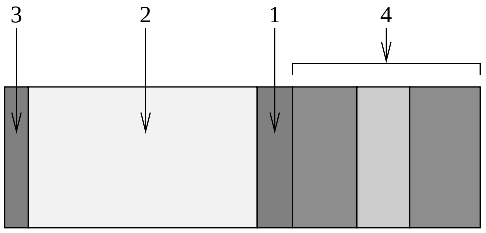

Fig. 1. Scheme of ultrasonic control of composite materials. 1 - generator, 2 - acoustic conductor, 3 - receiver, 4 - object of control

II. THEORETICAL MODEL

Laser ultrasonic method uses short monopolar acoustic videopulses generated during absorption of laser pulses. Temporal waveform of theses laser-generated pulses is well investigated in optoacoustic [2]. Peak pressure and duration of the acoustic pulse depends on duration of the laser pulse and light absorption factor of absorbing medium ("generator"). Thanks to possibility of using short laser pulses, the acoustic pulse duration can be less than a nanosecond.

Scheme of the optoacoustic transducer shown in Fig. 1. A laser pulse falls on the the left side of a light absorbing layer (generator, 1) through an optically transparent acoustic conductor block (2). The opposite side of the generator is contacting an object of control (4). The generator and conductor are acoustically matched with each other. Acoustic pulse is emitted as a result of the light pulse absorption in the generator. At the other side of the acoustic conductor, a piezoelectric receiver is placed (3). It is made from a thin piezoelectric PVDF film and due to that has a wide frequency bandwidth. When light pulse is absorbed in the generator, two acoustic waves are excited that propagate in opposite directions. First of them prorogates to the left-hand side (see Fig. 1) through the conductor (2) to the receiver (3). The other wave propagates initially to the right, then reflects from all layers of the object and prorogates to the receiver, like the first wave.

Let us consider a situation when an acoustic videopulse is reflected from one layer with its back side contacting air (this happens when delamination occurs in the structure). Modeling of this situation was made with the help of transfer matrix method [1], [4]. Results are shown in Fig. 2 by solid line. The probe acoustic pulse is purely positive, with Gaussian waveform. Its duration is 70 ns, it is shifted by 0.1 μs for the presentation convenience. Reflected signal from the boundary between the generator and the object comes to the receiver

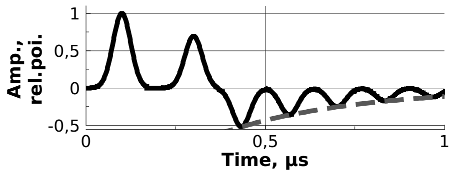

Fig. 2. Modeling results for the signal reflected from a layer contacting air (solid line). Dash line shows decay of the signal peak values

after this first pulse. It also has positive polarity and its delay is reflects prorogation time inside the generator. Other pulses reflect from the back soft boundary of the layer, which explains its negative polarity. Decrease of the reflected signals peak values is shown in Fig. 2 by dash line. This decay is described by the following expression:

$$p(t) = R_{21}T_{01}T_{10}\exp\left(\frac{c_1}{2l}\ln\left[R_{21}R_{01}\right](t-t_0)\right),$$

where $R_{ij} = (Z_i - Z_j)/(Z_i + Z_j)$ - reflection coefficient of waves falling to bound of mediums i and j from medium j, $T_{ij} = 2Z_j/(Z_i+Z_j)$ - transparent coefficient that have similar notation. Layer of generater marked by digit “0”, investigated layer - “1” and layer of air - “2”. c_1- velocity of sound in layer, l - height of layer, t_0 - time of first reflection from bound of air and layer.

In real materials essential role plays attenuation in object and acoustic conductor. This limits the possibility of evaluating acoustic impedance ratio from the levels of reflected signals, especially at high frequencies that more readily attenuate. It is therefore may be difficult to find coefficient of attenuation and acoustic impedance of layers by analyse reflected signals. On the other hand, low frequency signals are less attenuative. In order to use them, we decided to analyze time-integral of the received signals, which enhances low-frequency components.

Time-intergal $I(t)$ of the received signal is shown in Fig. 2 is plotted in Fig. 3. Its value increases until arrival of the first signal. After integrating this first signal, the value of I reaches some constant level A_0. Then reflection from the object arrives, and I continues to rise, and reaches level $A_1 = (1 + R_{10})A_0$. Here R_{10} is reflection coefficient:

$$R_{10} = \frac{A_1 - A_0}{A_0}$$

Impedance of the investigated material could be calulated using R_{10}:

$$Z_1 = Z_0\frac{1 + R_{10}}{1 - R_{10}} \tag{1}$$

Let us consider a structure that has two layers. We will suppose that the proximal layer properties are known (e.g. obtained from the measurements described above). We will now calculate impedance of the distal layer. Its impedance could be calculated from the levels of flat portions of the integral signal $I(t)$:

$$M = \frac{A_2 - A_1}{A_1 - A_0} = \frac{T_{01}R_{21}T_{10}}{R_{10}},$$

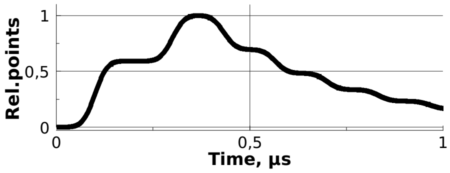

Fig. 3. Time-intergal $I(t)$ of the received signal is shown in Fig. 2

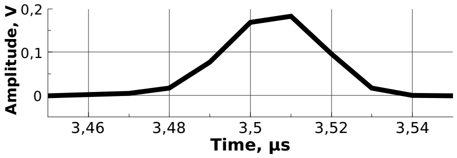

Fig. 4. Probe signal.

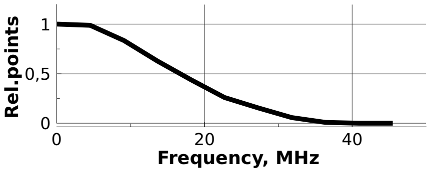

Fig. 5. Spectrum of probe signal

where A_2 and A_1 are values of $I(t)$ that correspond to reflections from the proximal and distal sides of the first (known) layer.

Acoustic impedance of the second (distal) layer can be expressed as:

$$Z_2 = Z_1\frac{4Z_1Z_0 + M(Z_1^2 - Z_0^2)}{4Z_1Z_0 - M(Z_1^2 - Z_0^2)} \tag{2}$$

Similarly, structures with larger number of layers can be analyzed. However, this approach in practice is limited by diffraction effect, which results in significant decrease of low-frequency components. Due to that the described approach could be applied only to a few layers.

III. EXPERIMENTAL SETUP

Scheme of laser-ultrasonic transducer is shown in Fig. 1 and it was described in the theoretical part.

A short light pulse of 10 ns duration is emitted by a Q-switched laser. The pulse energy 60 μJ. The pulse is delivered to the generator through an optical fiber. Electrical signal of the acoustic receiver is digitized by an analog-to-digital converter (frequency of sampling - 100 MHz, 12 bits, analog bandwidth 70 MHz). Filtering and deconvolution of the signals were made on a computer.

Probe ultrasonic signal has smooth waveform (see Fig. 4). Its half-amplitude duration is approximately 50 ns. Spectrum of the probe signal displayed in Fig. 5. Lateral distribution of acoustic beam is the same as for the optical one, and has approximately Gaussian shape. Because the absorbing layer is flat, the acoustic wavefront is plane. Diameter of the beam is approximately 3 mm.

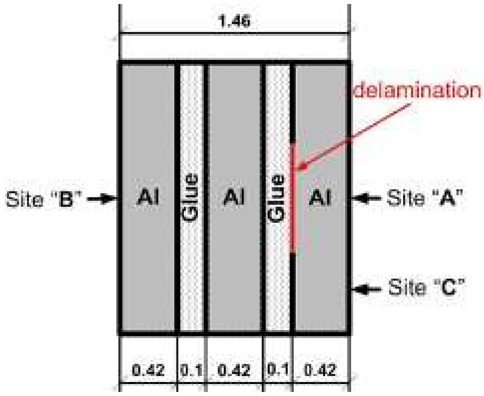

Fig. 6. Scheme of sample

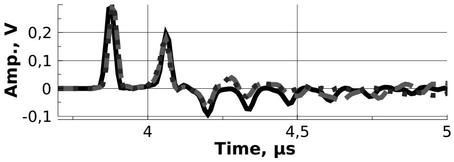

Fig. 7. Signal in site “A” (solid line), “B” (dashed line) and “C” (doted line).

IV. OBJECTS

Composite material, which was used as an object, consists of three aluminum sheets glued by a polymer. Thickness of the aluminum sheets is approximately 0.42 mm, and the glue layers have thickness of 0.08 mm (Fig. 6). This sample has a defect - a delamination in one of the glue layers. The sample was investigated in three sites. In the first site “A” there was a delamination between the first and the second aluminum sheets, for the second site “B”- between the second and the third sheets. In the third site “C” there was no delamination.

V. EXPERIMENTAL RESULTS.

The CLUE signals in the three sites of the composite A-C are presented in Fig. 7: A - delamination between the first and the second aluminum sheets (solid line), B - delamination between the second and the third aluminum sheets (dashed line), and C - without delamination (doted line).

The probe pulse and signal reflected from the front surface of the first layer have the save waveform for all three sites. Pulse that follows is the reflection from the rear surface of the first layer. Pulse from rear surface of the first layer has negative polarity, that corresponds to soft acoustic boundary. Signals from sites B and C have smaller amplitude of the reflection from this boundary, as compared to that for the site A. It means that impedances of the following layer for the sites B and C are greater than for the site A. Ultrasonic paths through the first and the second aluminum layer for the sites B and C are the same. The difference in these signals is manifested after time of arrival of the pulse reflected from the rear surface of the second aluminum layer (t>4.45 μs).

Integrals of the signals show a difference between reflected signals in sites A-C (Fig. 8) very clearly. First rising slope corresponds to the partial displacement in the probe signal. The following rising slope corresponds to the partial displacement in the signal reflected from front surface of the first aluminum layer. Using measured time-of-flight in each layer and coefficient of reflection at each boundary one can calculate the ultrasonic wave velocity and acoustic impedance of layers. The result of such calculation for the first layer gives (1.8096 ± 0.0024) g/(μs mm^2). Sound velocity can be calculated by using thickness of the layer and formula:

$$c_l = \frac{2h}{t_2 - t_1},$$

where h - thickness of layer, t_2 - time of receiving signal from far bound, t_1 - time of receiving signal from near bound. Thickness of the first layer is (0.42 ± 0.01) mm and sound velocity is (6.462 ± 0.014) mm/μs. Density is calculated from impedance and sound velocity and its value for the first layer is (2.800 ± 0.028) g/cm^3. As one can see, aluminum has closer parameters. Impedance of next layer is calculated by using formula 2 and it is equal to (0.6382 ± 0.0015) g/(μs mm^2) (thickness of this layer is (0.07 ± 0.01) mm, velocity - (2.89 ± 0.11) mm/μs, density - (2.20 ± 0.10) g/cm^3).

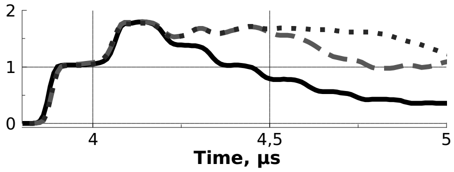

Fig. 8. Integrals of signals. In side “A” (solid line), “B” (dash line) and “C” (dotted line)

Low transmition coefficient of interface aluminum-glue is a one of a few reasons of errors in determining layer parameters.

Computer simulation was used to study influence of diffraction. Layers in our model have parameters equal to investigated parameters of the real object. Pressure on the back surface of the light-absorbing layer was calculated by two methods: finite-difference method and transfer matrix method. Integrals of these signals are shown in Fig. 9. Finite element approach correctly accounts for diffraction, which is neglected in analytical transfer matrix method. However, the latter approach has very small error: it is seen from Fig. 9 that the two signals are very close to each other. The corresponding error of the transfer matrix method in regard to the value of impedance for first layer is 2%, for second - 9% and for third is 23%. If we want to have result with errors less then 10% we should use result for first and second layer.

VI. CONCLUSIONS

Contact laser-ultrasonic testing is applied to the investigation of layered structures. The temporal trace of reflected ultrasonic pulse provides the information on the time-of-flight and coefficient of reflection for each peculiar layer. The results of theoretical treatment, numerical simulation and experimental investigation are in good agreement for a sandwich structure consisting of three aluminum layers. Contact laser-ultrasonic

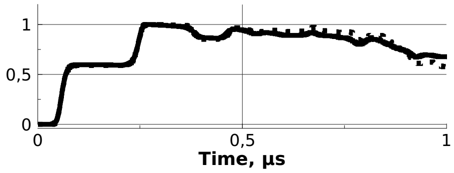

Fig. 9. Integrals of pressure on back surface of light-absorption layer. They were calculated by transfer matrix method (dots) and finite-difference method (solid line).

testing makes it possible to measure the ultrasonic wave velocity and density of several upper layers. Contact laser-ultrasonic testing can be effectively explored for the detection of delamination in a layered structure.

VII. ACKNOWLEDGMENTS

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