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About Possibility of using the Reverberation Phenomenon in the Defectoscopy Field and the Stress-Strain State Evaluation of Solids

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Abstract

The work assesses the possibilities of using the reverberation phenomenon for defectiveness testing and stress-strain state of solid dielectrics on the mechanoelectrical transformations method base. The principal reverberation advantage is that excitation acoustic wave repeatedly crosses the heterogeneities zones of testing objects. This causes to distortions accumulation of wave fronts which is revealed in the response parameters. A comparative responses analysis from the sample in uniaxial compression conditions at different loads in two areas of responses time realizations was made: deterministic ones in the initial intervals and pseudo-random intervals in condition of superposition of large numbers reflected acoustic waves. For deterministic temporal response component it was made difference analysis. As a statistical analysis it was selected the pulse flow distribution. The responses calculation by the mathematical model in a changing of sound speed conditions simulating the sample heterogeneity change under load was made. The calculation showed qualitative similarities with responses changes in the re al experiment. According to the obtained results it was concluded that the using deterministic and pseudo-random responses components in reverberation condition to control changes the heterogeneity degree under the mechanical load influence on the sample.

Keywords: acoustic wave, reverberation, mechanoelectrical transformations, defectoscopy, stress-strain state.

INTRODUCTION

The reverberation phenomenon is observed in the case when a sound wave of excitation, arising in the limited space of the investigation objects, comes to the signal receiver experiencing multiple reflections from its boundaries.

The phenomenon has found application at researching the auditorium acoustic characteristics in terms of its sounding quality as a whole and in the local distribution of the sound spectral characteristics [1, 2]. It used in the defectoscopy of solids and for 3D visualization [3-5]. Reverberation studies as a factor of noise are also relevant in radiolocation and sonar, when it is necessary to emphasize the reflected signal from the testing object from the summation responses conditioned the multiple reflections from natural and artificial interference [6-8].

The reverberation phenomenon is also used in the mechanoelectrical transformations (MET) method for investigation the defectiveness and stress-strain state (SSS) of dielectric composite materials [9]. The essence of the MET-method is that the test sample is subjected pulse acoustic excitement, as a result of which an acoustic wave propagates in it. Waves fronts repeatedly reflecting from the boundaries crosse defective and local inhomogeneities zones.

Part of the acoustic energy waves converted into electromagnetic signal on the MET sources. Double electrical layers at the boundaries of heterogeneous materials, as well as natural piezoelectric inclusions (quartz sand in concrete, for example) are MET sources. The electromagnetic signal is recorded capacitive receivers, external to sample.

Therefore, in the base of the MET-method is the electromagnetic signal reproducing the superposition of acoustic excitation waves, which are reflected from the boundaries of the TO, and whose fronts undergo distortions during the passage of defective zones and local inhomogeneities zones.

The important is also that the response duration is long enough than is provided multiple passage of the acoustic excitation wave through the inhomogeneity zones. So, for concrete samples at excitation duration in tens of microseconds the response duration reaches on low frequencies of tens of milliseconds that provide more than 60 reflections at linear sample sizes of 100 mm.

When developing the MET-method it was established that at the given excitation pulse shape and the unchanged internal state of the TO the response determinacy is very high [9]. It allowed considerably to increase the method sensitivity by multiple excitation of the sample with using a precision generator.

The MET-method showed high sensitivity to SSS degree of the material under uniaxial loading, to a changing surface and volume defectiveness of the samples just due to the reverberation phenomenon [10-14].

For further improvement nondestructive testing methods on based the reverberation phenomenon it is necessary to analyze processes occurring during the acoustic wave propagation in the TO.

Advantage of an acoustic wave multiple reflection in comparison with a single reflection in ultrasonic testing methods is that the wave front repeatedly crosses the defective zones of the TO and the inhomogeneities regions conditioned by the SSS. Therefore, despite on the relatively small effect of microcracks or local inhomogeneities on the excitation wave fronts, the distortions of fronts accumulate. This leads to noticeable change of the response form and ensuring the finding such parameters, which are uniquely linked with a degree of defectiveness and SSS of TO.

It is accepted to divide the time implementation due to reverberation on two parts. The one part which is formed as the sum of relatively small number of reflected waves is considered the determinate. The other part, representing a superposition of a large number of such waves, is considered a pseudo-random and to it is an applied analysis statistical method.

In order to assess the possibility of using phenomenon the reverberation phenomenon for defectiveness testing and SSS the experimental studies and calculations using a mathematical model were carried out.

MATERIALS AND EXPERIMENTAL PROCEDURE

For the experiment an epoxy sample with sand filler with size of 100x80x60 mm was used.

The sample was placed in a press and subjected to a stepwise uniaxial compression with a step of 3 MPa to the level of 59.6 MPa.

The sample excited in a series of 80 pulses with an interval of 3.5 ms at each loading step and then the responses were recorded. For each responses series the average value and standard deviation at each sampling point was calculated. The frequency of digitization was 1 MHz. At the initial time interval for differences preliminary assessment a difference signal was used. Fig. 1 shows the response under load of 1.3 MPa as well as the residual signal regarding next step (4.3 MPa).

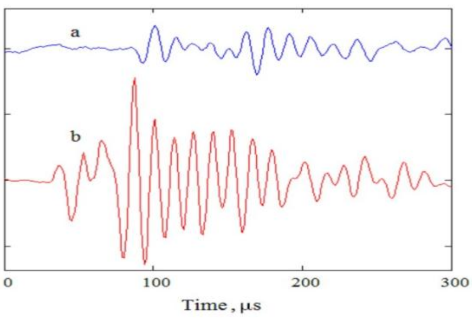

Figure 1: Experimental responses: a response at the initial load; b a residual response.

It follows from the figure that an appreciable difference signal is observed after the response signal appearance with a delay of approximately 50 μs. This can be explained by the changes accumulation of sound wave front owing to the scattering of acoustic waves by heterogeneity, as well as by the change in the sound speed in the sample in conditions of its SSS.

Fig. 2. shows a responses fragments at loads of 1.3 MPa (a) and 4.3 MPa (b) on time intervals from 0.8 ms to 1.8 ms.

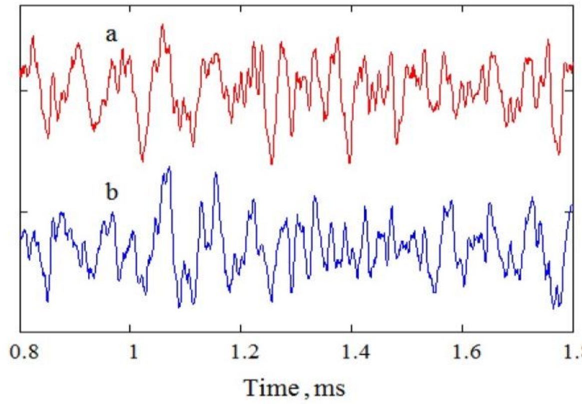

Figure 2: Responses temporal realizations of pseudo-random region

As seen in Fig. 2 the responses look noise-like.

To significance evaluation of differences such responses the Student's t-test was used. The significance levels as well as the critical level at a significance level of α=0.001 and the freedom degrees number of 158 were calculated.

In Fig. 3 shows the temporal significance levels and the critical level (illustrated as the bold line parallel to the abscissa axis).

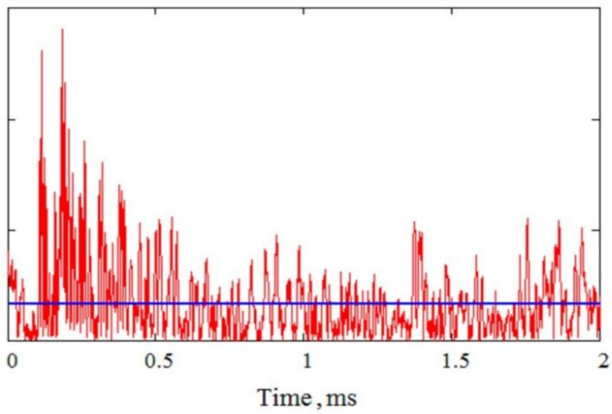

Figure 3: Testing the differences significance by the Student's test

As can be seen from Figure 3, throughout the range of realization of the difference is meaningful responses with a probability of 99.9%.

As an example of differences evaluation on a "tails" of the responses in this paper the method of pulse flows distributions is used. The pulse flow was formed as follows. Cut-off level was set below which the temporary implementations were assumed to be zero and then local highs the responses absolute values were found. Then distribution bar chart was constructed.

In Fig. 4 as an example the pulse flows distributions at loads of 4 MPa, 25 MPa, and 51 MPa are given.

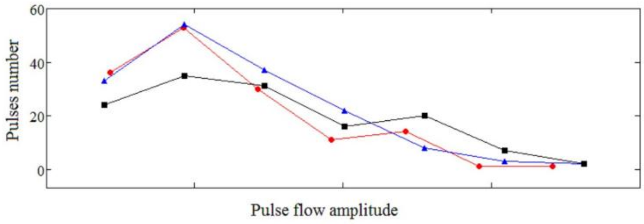

Figure 4: Pulse flow distribution at the loads 4 MPa (-●-), 25 MPa (-▲-), 51 MPa (-■-).

As seen from figure 4 there are significant differences in the pulse flow distribution from the mechanical stress level on the sample.

CALCULATION BY THE MATHEMATICAL MODEL

To confirm the assumption about influence of the excitation sound wave speed on responses calculation by the mathematical model was made [15]. The mathematical model is based on the ray approximation of excitation acoustic wave propagation.

To facilitate calculation the sample model is represented as repeating structures with sample geometry as a parallelepiped with mirror symmetry locating in it fictitious sources of MET and fictitious signal receivers.

This allows to represent the excitation acoustic wave front as a hemisphere surface with the center at the excitation point. A similar model was used in [1] to evaluate the reverberation influence on auditoriums acoustic properties with the difference that it uses the concept of excitation fictitious sources.

Fig. 5 shows a two-dimensional display of substitution scheme. Points display fictitious sources of MET, triangle indicates the sample excitation point and semicircles represent two-dimensional projections of wave fronts.

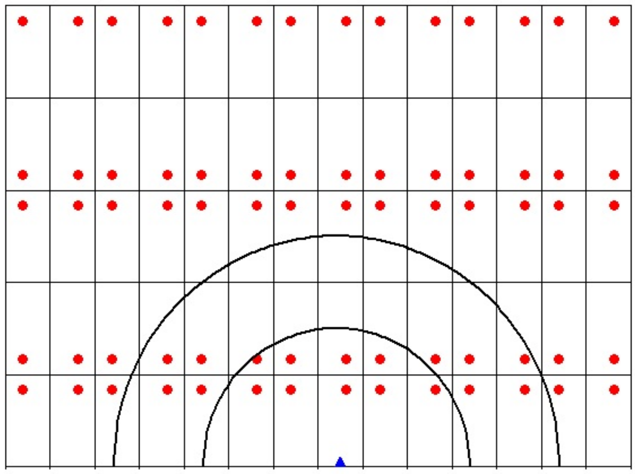

Figure 5: Two-dimensional scheme of a sample substitution in the periodic structure form

For a more adequate display of a response in reverberation conditions and consequently passing an excitation acoustic wave enough large a way it is necessary to take into account its frequency-dependent attenuation. It is known, that in a solid an attenuation of a harmonic acoustic wave occurs due to internal friction by exponential law with a time constant back proportional to the frequency square. Therefore, in indicated the mathematical model of calculation was added refinements, which accounted for frequency-dependent attenuation of the excitation pulse [15].

In Fig. 6 shown (a) the excitation pulse initial amplitude-frequency characteristic (AFC) and (b) its calculation AFC after 1 ms after passage in the sample.

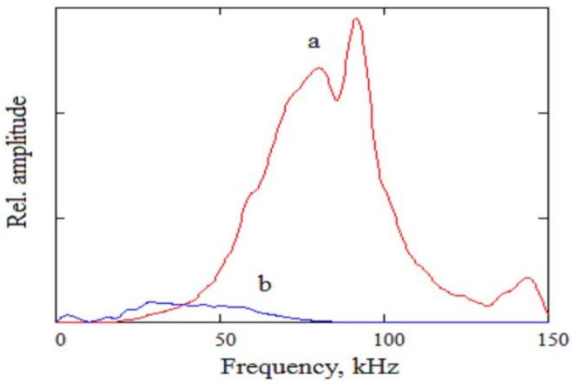

Figure 6: The excitation pulse AFC

At given sample geometric dimensions as well as the positions of the pulse mechanical excitation source and a signal receiver relative to faces of the sample the response pulse characteristic h_i was calculated. For this on the model input a single pulse was given, a distance to each of the fictitious sources was determined, the response level from the source taking into account the angle of incidence on it the ray was calculated, as well as its level which for a spherical wave decreases inversely proportional to the path traveled.

To account for the frequency-dependent attenuation the time sample decomposition of a real excitation pulse was produced in the Fourier series and then the attenuating harmonic signals $s_{i,k}$ were formed in as:

$$s_{i,k} = a_k \cdot \sin(2 \cdot \pi \cdot f_k \cdot i \cdot \Delta t + \varphi_k) \cdot \exp(-i \cdot \Delta t / \tau_k),$$

where a_k is the k-th harmonic amplitude; φ_k is the harmonic phase; $\tau_k = K/f_k^2$ is the frequency-dependent time constant; K is the constant factor; $i = 0 \ldots n$ (is the sample length); $k=0 \ldots m$ (m is the harmonics number); f_k is the k-th harmonic frequency; Δt is the digitization interval (1 µs).

Then the r_i response representing the derivative convolutions sum of the calculated pulse characteristic with harmonics of the excitation pulse was calculated.

$$r_i = \sum_k \sum_{i=0}^{i} h'_j \cdot s_{i-j,k} \, .$$

The response calculations at a sound speed ν=2100 m/s and with a change of 0.1% were made. In Fig. 7 shown calculated response at the ν_1-speed and the difference response signal at different sound speeds.

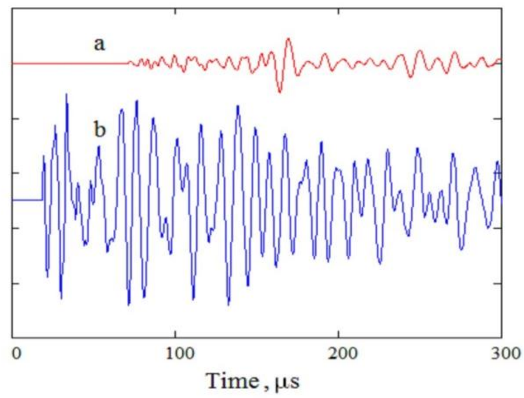

Figure 7: Calculated responses: a) a response at a sound speed 3000 m/s; b) responses difference at a change of sound speed at 0.1%.

As seen from the figure 7 the difference signal of calculation response has specific oscillatory components similar to those that were obtained from the experiment (Figure 1). In addition, in the calculated difference response, as in the real experimental response a delay in time is observed.

The average speed of an acoustic wave in a sample at changing the defects concentration is changed due to lengthening its way due to rounding defects. A speed of acoustic wave propagation also changes in SSS conditions by changing test material local density.

The natural reverberations feature is the imposition reflected excitation waves from the boundaries. In this case, those responses, which lie in the time interval equal to the excitation pulse duration, are folded.

To assess the characteristics of the responses in the specified time intervals calculation was performed according to a mathematical model as follows. Pulse response characteristics were calculated in spherical layers, width of 50 µs, which corresponds to the normal duration of the excitation pulse.

It has been calculated the number of fictitious sources inside each spherical layer. In Fig. 8 shown the dependence of fictitious sources number from the spherical layers number (the layer number correspond to the ascending wave front radius).

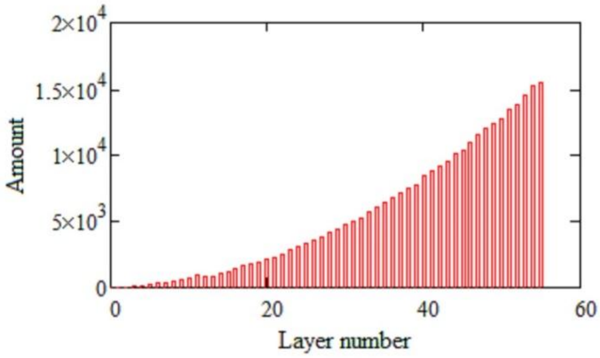

Figure 8: Dependence of number of fictitious sources from the spherical layers number.

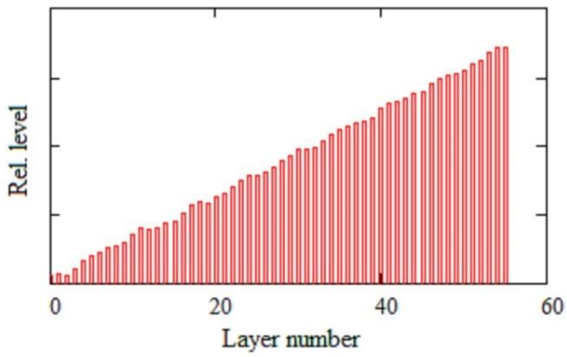

Figure 9: Dependence a pulse response level from a spherical layer number.

As seen the figure 8 the sources number increases according on a quadratic law that is natural as on the same law the spherical layer volume given thickness increases. Calculation of the pulse characteristic average intensity in each layer shows a linear growth (Fig. 9) which is explained by decrease excitation signal inversely proportional distance to the source.

CONCLUSIONS

Based on the conducted experiments and also from the mathematical model calculations we can make the following conclusions.

The response signal can be divided into two components: deterministic and pseudo-random. At analysis the deterministic component it can be used the whole signal processing tools arsenal of such kind. For pseudo-random components it needs to involve statistical control methods.

The results obtained in the paper allow to hope on receiving regularities linking the change in defectiveness and SSS degree with responses parameters. Thus, using the reverberation phenomenon at nondestructive testing of defectiveness and stress-strain state of materials is promising.

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