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METHOD FOR SEPARATION OF ELECTROMAGNETIC RESPONSES OF MECHANOELECTRICAL TRANSFORMATIONS UNDER THE IMPACT OF EXTERNAL NOISE

Anatoly Surzhikov[1], *Anatoly* Bespal'ko[1,*], *Anna* Demikhova[1], *Aleksandr* Bombizov[1,2], *Anton* Loschilov[2]

[1]National Research Tomsk Polytechnic University, 634050, Tomsk, Russia
[2]Tomsk State University of Control Systems and Radioelectronics, 634050, Tomsk, Russia

Abstract. The paper addresses the diagnosis of the presence of defects in concrete, cement-sand and other building and structure mixes using mechanoelectrical transformations. The problem of high levels of electromagnetic noise and interference affecting the correct interpretation of the data to diagnose presence of defects is considered. A version of the electromagnetic response from the unit heterogeneity is proposed, and the assumption of the total electromagnetic signal is suggested. The experiment on acoustic excitation of the sample was conducted and the electromagnetic responses were recorded and filtered using the correlation analysis. The obtained result was compared to the model one to confirm the single response model.

1 Introduction

During production and operation of concrete structures, there is a high demand for their reliability, since it is directly related to life safety. Deterioration of strength characteristics of concrete blocks can be largely due to the emergence of defect-containing areas that may appear during the manufacturing process due to imperfect processes and under the attack of the aggressive environment. In this regard, the development of a rapid diagnostic method suitable for quality control of construction materials both in the laboratory and on site and to analyze the reliability and strength of structures and supporting structures is an important task.

Different approaches to diagnosing of the dielectric material defects have been studied. Ultrasonic methods based on the study of ultrasonic wave propagation in the test product have gained widespread use in inspection of building materials. The easiest way to detect defects and concrete inhomogeneity are methods based on measurement of the speed of sound [1–4]. However, the accuracy of these methods depends on the accuracy of this measurement, which depends on the presence and amount of inhomogeneities. In case of one-sided access to the product, the echo method is commonly used to detect defects and

* Corresponding author: besko48@tpu.ru

their coordinates of different orientation [5]. The method implies product sounding with short ultrasonic pulses and recording the intensity and the arrival time of the echo signals reflected from discontinuities and inclusions. The methods of nondestructive testing of concrete defects that have been developed in recent years employ Rayleigh waves which are most sensitive to the near-surface cracks oriented vertically to the surface as compared to longitudinal waves [6, 7]. In [8], an approach to assess the real size of the defects using the shadow method of ultrasonic testing is proposed. The authors performed the input of ultrasonic vibrations at different angles using several independent pairs of transducers, thereby eliminating the measurement ambiguity. In the defect-containing region, each converter exhibited the amplitude signal envelopes, and the coordinates of the defect boundaries were recorded. These approaches are based on the principle of elastic (ultrasonic) wave propagation in the medium.

Apart from the existing physical phenomena, mechanoelectrical transformation is used for defects analysis. This is the transformation of the mechanical field energy in structural inhomogeneities or defects in dielectric structures [9]. This approach employs different techniques to conduct the study: short-pulse broadband excitation with subsequent analysis of the recorded responses [10], which increases the signal to noise ratio due to the probing signal energy; excitation by narrowband signals [11–13] and separation of responses from inhomogeneities with filters of high selectivity based on the principles of the test sample linearity.

This approach provides more information on the recorded signals of the mechanoelectrical transformation compared to that obtained by acoustic methods. The main problem encountered is high level of external electromagnetic interference from household and other devices that complicates the analysis and interpretation of responses.

The objective of this research was to search and use approaches to expose the test sample to a narrowband deterministic acoustic signal, and to develop the technique to separate the electromagnetic response during mechanoelectrical transformation in conditions of external electromagnetic interference.

2 Theory

The test sample, assume it is a sand-cement block, is a homogeneous medium with inclusions of empty cavities that represent defects. The equivalent electrical circuit of this sample can be represented as a serial connection of resistance-capacitance circuits. If this sample is exposed to short acoustic pulses, the length of which is less than the time of signal propagation through the sample, it can be considered as a distributed transmission line. In this case, the signal formed is a sum of electromagnetic responses from individual defects and geometric boundaries of the sample. As the sand-cement block is taken as a test sample, the speed of the acoustic wave propagation in the sample will be V=2500 m/s. If the thickness of the test sample is l=0.1 m, the signal path to the opposite boundary of the sample and its return to the exposure source will take $t=2\cdot l/V=1\cdot 0.1/2500=80$ μs. In this regard, it is appropriate to use the probe signal of the duration less than 80 μs to separate and interpret the electromagnetic responses.

For more noise-resistant electromagnetic response, the test sample should be exposed to the acoustic signal in the form of a radio pulse with the carrier frequency f.

As the test sample is a simplified form of the RC-circuits, a short radio pulse induces transient phenomena in each RC-circuit, which can be described by the following formula:

$$A(t)=\begin{cases} A_0\sin\left[\omega(t-t_0)\right]\left[1-e^{\frac{(t-t_0)}{\tau}}\right], t<T \\ A_0\sin\left[\omega(t-t_0)\right]\left[1-e^{\frac{(t-T)}{\tau}}\right]\left[1-e^{\frac{(T-t_0)}{\tau}}\right], t\geq T \end{cases} \quad (1)$$

where A_0 is the pulse envelope amplitude;

ω is angular frequency ($\omega = 2\pi f$);

t_0 is the pulse signal time;

τ is the time constant of the pulse rise and fall;

T is the time when the pulse envelope reaches its amplitude maximum.

On this assumption, the detected response signal should contain a set of signals:

$$S=\sum_{i=1}^{N} A_i(t) \quad (2)$$

where N is the number of imhomogeneities in the test sample.

Assume that an ideal test sample is free of defects. Initially, N equals to two responses: 1 is the response from the surface through which the sound travels; 2 is the response from the opposite surface of the sample. If a defect is in the middle of the sample, response 3 will be formed.

The difference in time between responses 1 and 2 should be about 80 μs for the sample thickness of 100 mm. Response 3 is to be recorded over 40 μs after response 1. All the responses recorded after 80 ms can be the result of multiple reflections of the acoustic wave that do not bear any useful information on sample defects.

In conditions of external noise effects, most acceptable approach is selective filtration through the correlation analysis of the recorded signal and the model radio pulse. It is known that the duration of the base signal during correlation affects the time and frequency characteristics of the recorded signal. In case of insufficient interference elimination, short signal duration retains time characteristics better. Long signal duration provides the opposite result. In this research, in conditions of high external noise, the base signal and the exposure signal of similar duration are used as a compromise derivative.

3 Experimental results

The studies were performed using the experimental setup, which excites the sample by a series of acoustic pulses and records the electromagnetic responses of mechanoelectrical transformations. Figure 1 shows the block diagram of the experimental setup.

The unit of exposure and measuring (UEaM) consists of a piezoelectric emitter, which induces a series of acoustic pulses of a predetermined shape towards the test sample (test sample SC) and a differential capacitive sensor to receive the electromagnetic response. The differential capacitive sensor has two inputs: measuring and control ones. The measuring input receives a useful signal and electromagnetic interference. The control input is located 12 mm above the measuring one and receives mostly noise but not the signal. Positioning of the UEaM over the test sample is performed with a plotter. The generation and digitization device (GaDD) based on the multi-channel data-acquisition unit NI PXIe-1071/PXI-5412/PXI-5105 generates excitement and digitizes electromagnetic responses. The measuring channel of the analog-to-digital converter is equipped with an auxiliary amplifier and low- and high-frequency Butterworth analog filters to limit the path of the analog bandwidth up to 1 kHz–1 MHz. The digital-to-analog converter output is connected to the input of the high-voltage amplifier (HVA) Tabor Electronics 9200A for 50-fold amplification of the 8 V signal and its transfer to the piezoelectric emitter to excite the sample.

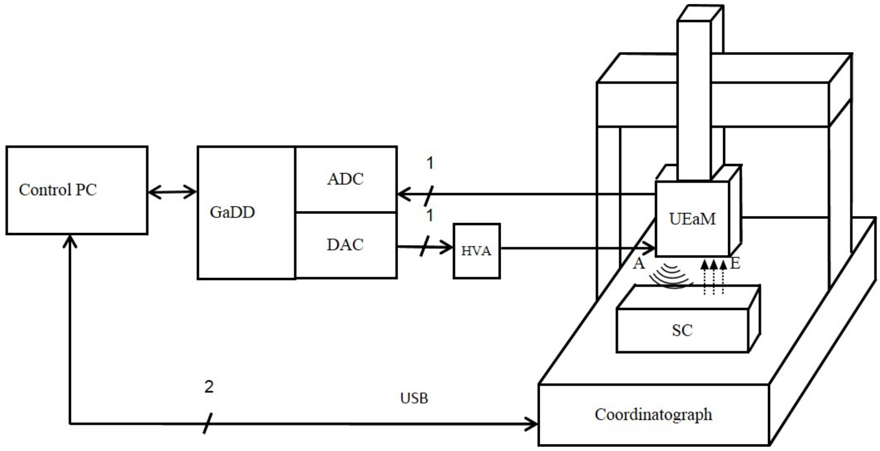

Figure 1. Block diagram of the experimental setup.

A sand-cement sample of 350×200×115 mm with two inclusions located in the center of the sample at a distance of 60 mm from the edge and 150 mm to each other was made for the experiments. The inclusions were foam cubes of 10×10×10 mm and 20×20×20 mm. The diffraction pattern of the test sample is shown in Figure 2.

Figure 2. Diffraction pattern of the test sample.

The experimental studies were conducted in several stages.

At the first stage, the electromagnetic responses were measured. Two sample regions (defect-containing and defect-free ones) were chosen to obtain responses. To record the response from the defect, the UEaM was placed above the 20×20×20 mm inclusion using the plotter. To investigate the defect-free region, the UEaM was moved to the area equidistant to both defects. The waveform of the signal to sound the object was a radio pulse with carrier frequency of 122 kHz and duration of 75 µs. The results of multiple exposures of the sample and response recording were averaged. That minimized the stationary electromagnetic interference and noise. Figure 3 shows the averaged recorded responses for 128 measurements, where *A1* is a defect-containing region and *A2* is the region free of defects.

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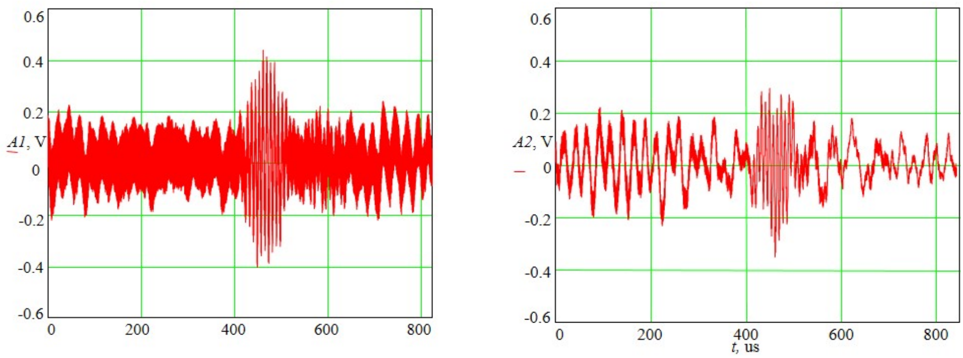
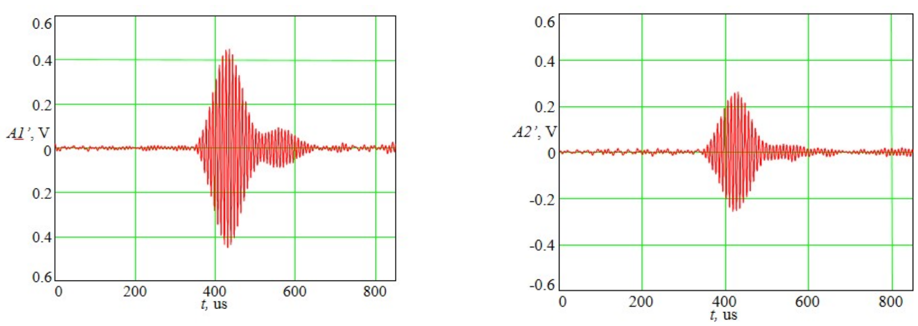


a b

Figure 3. Recorded response 1 (a). Recorded response 2 (b).

Figure 2 indicates that after averaging, the stationary interference and noise are minimal. At the next stage, the response was separated through filtering using the correlation analysis for the recorded averaged signal and the initial radio pulse. Figure 4 shows the electromagnetic responses after the correlation analysis (*A1'* is the defect-containing region; *A2'* is the region free of defects). The values were amplitude normalized to compare the result with those obtained previously.



a b

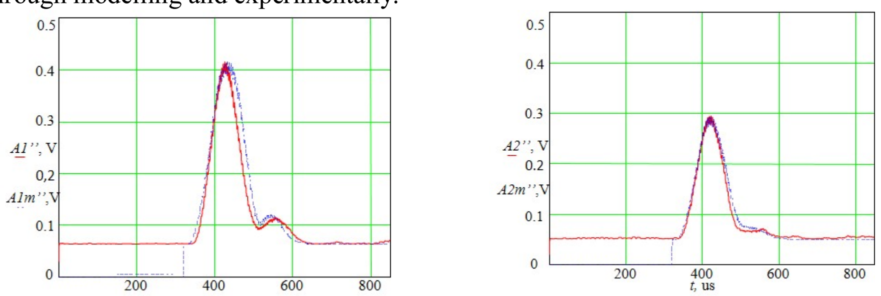
Figure 4. Correlation of response 1 from the defect-containing region and the acoustic signal (a). Correlation of response 1 from the defect-free region and the acoustic signal (b).

After filtering, the obtained signals consisted of the responses from the boundaries of the test sample and the defect (Figure 4, *a*). To verify the results, the response from the defect-free region is shown in Figure 4, *b*.

4 Discussion of the results

During the analysis of the obtained results, the parametrization of the recorded signal was performed using formulas (1) and (2). The pulse time was chosen based on the speed of acoustic wave propagation (2500 m/sec), and the distance the defect (60 mm) and the lower boundary (115 mm). The parameters of the electromagnetic signals obtained for the defect-containing sample region were as follows: for the first response, A_{01}= 0.46 V; t_{01}= 400 μs; f = 122 kHz; $T1$= 475 μs; τ = 34 μs; for the second response, A_{02}= 0.24 V; t_{02}= 450.2 μs; $T2$=525.2 μs; for the third response, A_{03}= 0.12 V; t_{03}= 503.8 μs; $T3$=578.8 μs. For the defect-free region of the sample, the following parameters were obtained: for the first response, A_{02}=0.27 V; t_{02}=400 μs; f=122 kHz; $T1$ = 475 μs; τ=34 μs; for the second response, A_{02}= 0.05 V; t_{02}= 503.8 μs; $T2$=578.8 μs. After model correction, it was found that the response from the defect returned after $t=t_{02}-t_{01}$=50.2 μs and the depth was 2500×50.2 μs=62.75 mm, while the response reflected from the lower boundary of the sample indicated 129.75 mm depth. The differences in the depth can be attributed to the error of the acoustic wave propagation measurement in the sand-cement block, which may be caused by irregularities of the sample cavities.

The envelopes for signal modules are shown in Figure 5 to compare the results obtained through modelling and experimentally.



a b

Figure 5. Envelope of the correlation of response 1 with the sounding signal and model signal envelope (a). Envelope of correlation of response 2 with the actuating signal and model signal envelope (b).

The Figures exhibit the coincidence of the model and the experimental results. This confirms the correctness of the model chosen for this experiment.

5 Conclusions

A setup to study the imperfection of concrete, sand-cement mixes and other samples used in the construction industry has been designed. The setup is equipped with digital equipment to process and analyze the measured signals. The analysis of the results obtained in measurement of the electromagnetic response under acoustic effect showed that the correlation analysis allows separation of the useful signal component from electromagnetic interference signals and noise. The designed electromagnetic signal model can be used to test both defect-containing and defect-free regions of the sample. It can also be used to separate responses in conditions of external electromagnetic interference.

Further research will focus on the development of algorithms for parameterization of the recorded signal to decompose it into individual responses and to define the time and amplitude characteristics of these responses. This will allow estimation of the imperfection of the investigated region.

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