Fracture Detection by Electro-Ultrasonic Spectroscopy

Pavel Tofel, Tomas Trcka

Dept. of Physics, Faculty of Electrical Engineering and Communication, Brno University of Technology, Technicka 10, 616 00 Brno, Czech Republic
tofel@feec.vutbr.cz

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Abstract. This paper describes the possibility to verify the electro-ultrasonic spectroscopy method validity. This new approach is based on the combined usage of two modern nondestructive testing methods, the electro-ultrasonic spectroscopy and the diagnostics of mechanically stressed solid dielectric materials by the electromagnetic (EME) and acoustic (AE) emission signals. The granite sample was measured by the electro-ultrasonic spectroscopy. Then mechanical load (provided by hydraulic press) was applied on this sample. Generally, an application of mechanical stress leads to micro-cracks formation in stressed solid dielectric materials. Cracks generation is accompanied by generation of the electromagnetic (EME) and acoustic (AE) emission signals, which can be measured by appropriate sensors. Continual measurement and real-time processing and evaluation of these signals can be used for quantitative sample damage estimation. After mechanical load application the sample measuring was conducted one more time by means of the electro-ultrasonic spectroscopy.

Introduction

Electro-ultrasonic spectroscopy is closely related to electro-acoustic effects, which are known since 1933 [1]. These effects are resulted from a coupling between acoustic and electric fields. This phenomenon mostly occurs when ultrasound actuates on the fluid which contains electrically charged ions. Ultrasonic signal moves with ions and then this motion generates an AC electric signal. In general, it is a phenomenon, when mechanical wave influences electrical carriers directly. It takes place when mechanical wave has shorter wave length then mean free path of electrons. In other words, electric potential is measured due to mechanical wave on the material [2-4]. Audio devices are described by electro-acoustic effect also, where acoustic signal is converted to electric signal and conversely.

Electro-ultrasonic spectroscopy is based on interaction of ultrasonic signal and electric signal in conductive materials [5]. Ultrasonic signal changes the contact area between conducting grains in the sample, thus resistance of the sample is modulated by frequency of ultrasonic excitation. Defects and cracks in the sample structure are the sources of new intermodulation signal. The frequency of this signal is given by superposition or subtraction of exciting frequencies. This method is very sensitive because helps to evaluate the intermodulation signal on the frequency different from exciting frequencies of electrical and ultrasonic signals.

More information about electro-acoustic effect can be found in [6-7].

Ultrasonic signal with frequency higher then 1 MHz is widely used in non-destructive testing. Electro-ultrasonic spectroscopy applies ultrasonic signal with frequency about 30 kHz. Thus the signal does not influence the electrical carriers directly. Standing waves are created on the sample by mechanical vibrations and sample’s geometry is changing in elastic range of deformations.

Resistance of the sample is changing due to deformations, similarly like piezo-resistive effect. If the sample contains defects or cracks, then the resistance change is more significant. Many types of standing waves may be created. Generally, it is longitudinal waves, transversal waves and torsion waves. Longitudinal wave is created on the metal sample, which has air bubbles inside the structure, see Fig. 1. Air bubbles are equally disposed from each other. This model was created in program COMSOL. In the area with minimal displacement the more volume's deformation occurs and vice versa. This helps to create a map of the sample's deformations and therefore deform any part of the sample. If the crack will be situated in minimal displacement area, then it will be more stressed, and resulting resistance change will be more significant.

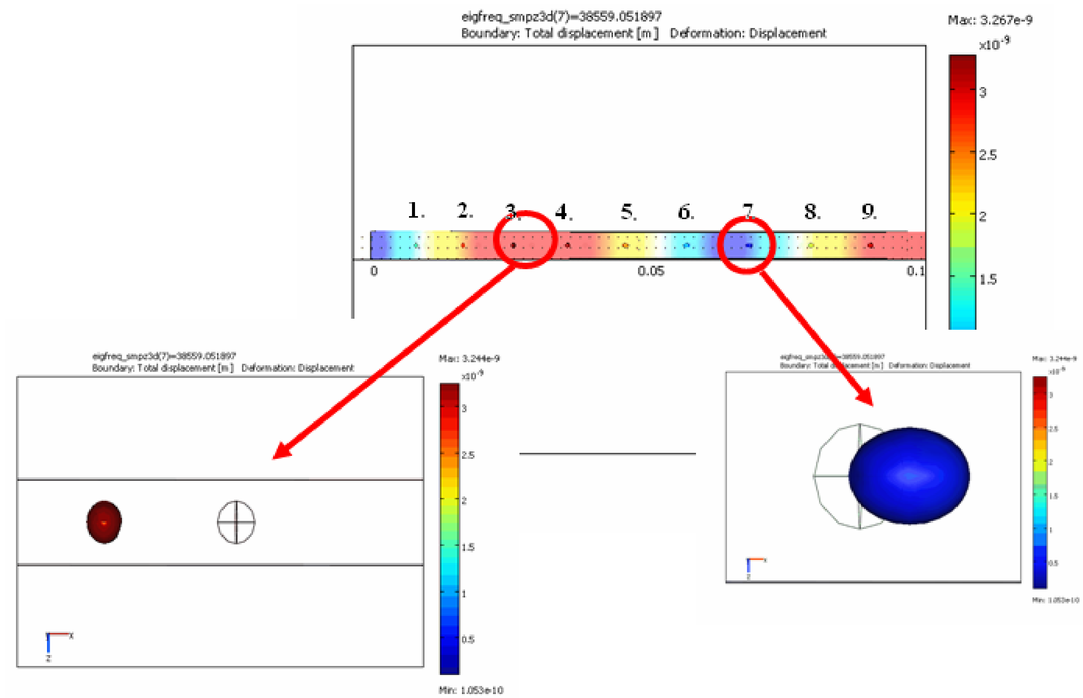

Fig.1. Longitudinal wave created on the metal sample

Generally, resistance change has very low value due to ultrasonically induced geometry change. Resistance change of homogeneous materials and sample without cracks is measurable also. It depends on the measurement setup and background noise.

Wheatstone bridge is the most sensitive method for measuring of a very low resistance change. If the electric current is flowing through the sample and ultrasonic signal induces resistance change (Fig. 2), then the resulting electric spectrum is given by an equation (1):

$$V_T = (R_{DUT} + \Delta R)\cdot i_{AC}\cos(\omega_E t) = [R_{DUT} + \Delta R\cos(\omega_U t)]\cdot i_{AC}\cos(\omega_E t) = \tag{1}$$
$$R_{DUT}\cdot i_{AC}\cos(\omega_E t) + \frac{1}{2}\Delta R\cdot i_{AC}[\cos(\omega_E t - \omega_U t) + \cos(\omega_E t + \omega_U t)]$$

where: R_{DUT} is the sample resistance, i_{AC} is amplitude of the electric current, ΔR is a resistance change, ω_E and ω_U are angular frequencies.

Mechanical vibrations created by ultrasonic actuator induce a resistance change ΔR of the sample, with frequency f_U.

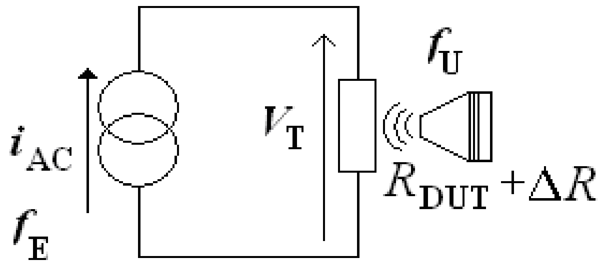

Fig.2. Electric circuit and ultrasonic transducer which influence the sample resistance

The resultant voltage spectrum is given by voltage at frequency f_E which consists of the sample resistance R_{DUT} and AC current flowing through the sample. Sideband voltages are created by resistance change ΔR and AC current flowing through the sample structure also. The resultant spectrum is shown in Fig. 3.

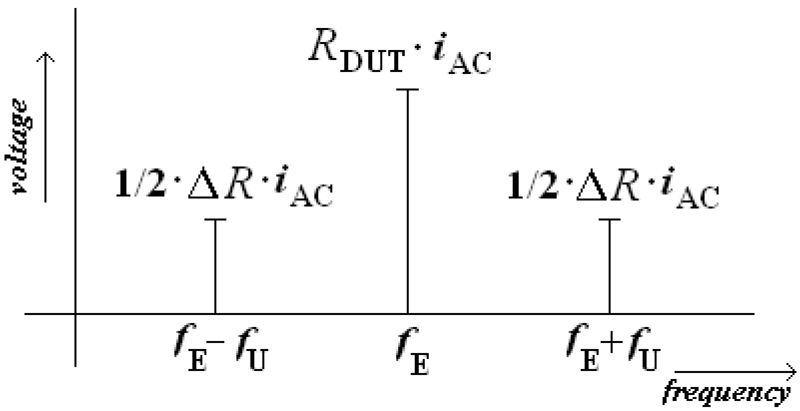

Fig.3. The theoretic resultant spectrum of the electro-ultrasonic spectroscopy

Electromagnetic emission (EME) and acoustic emission (AE) are promising methods for studying the generation and behavior of cracks [8, 9, 10]. EME and AE signals appear during cracks generation when a solid is exposed to mechanical loading (tensile, compressive, shear, torsion etc.). Generation of electromagnetic emission is related to an electric charge redistribution during cracks creation and development and it is in the frequency range from tenths of Hz up to the gamma radiation. For the time being, the EME method is the only method suited for studying the time development of the crack growth (crack propagation speed, crack face movement speed, crack length and size, etc.). Acoustic emission appears due to releasing of elastic energy during this process and it is in frequency range of ultrasonic waves. Application of the EME and AE methods for studying the material and structure behavior provides valuable information on other physical and technological parameters (porosity, rigidity, inhomogeneity, occurrence. etc.), which in turn contributes a great deal to a further development of the non-destructive testing methods [11, 12].
Next modern technics for non-destructive testing of defects in material can be based on luminescence techniques and laser/electron beam induced current techniques [13, 14, 15]. But this method cannot be applied on the granite samples.

Experimental

Non-destructive testing by the ultrasonic wave was applied on rock samples in many papers, for example [16, 17]. This material is supposed to have a lot of un-homogeneities in its bulk structure that is why the amplitude of intermodulation voltage is supposed to be very high. Nevertheless an electric resistance of our sample named Z01, of shape of prism 50 x 50 x 11 mm3 (Fig. 4), was of the order of R = 10 MΩ on a frequency of 33 kHz. The high value of electric resistance causes the low values of intermodulation voltage measured on the sample. Therefore, the measured part of an electric circuit must include low-noise preamplifiers which alow to magnify the signal of intermodulation voltage versus background noise. Electric contacts were fixed on the sample by dipping silver, as it is shown in Fig 4.

Fig.4. The rock sample of granite with an electric contact on the sample fixed by DiAg paste

Sample was fixed on the ultrasonic transducer HTP05 by beeswax. Resonant frequency of all system (ultrasonic transducer and granite sample) occurs when the frequency f_U= 31.7 kHz. Electric signal which was applied to the sample was of a frequency f_E = 33.7 kHz. Intermodulation voltage was measured on the frequency f_i=2 kHz, as it is shown in Fig. 5.

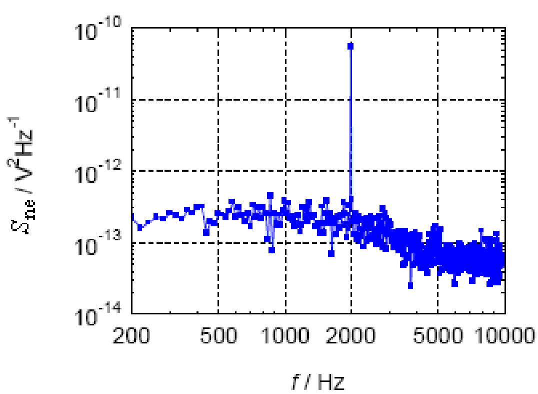

Fig.5. Noise spectral density of the granite sample Z01 on a frequency range from 200 Hz to 10 kHz. Frequency f_E = 33.7 kHz and f_U = 31.7 kHz

Figure represents the noise spectral density of the granite sample measured in the frequency range 200 Hz to 10 kHz. These data were acquired during simultaneous application of ultrasound and electric signals. Analog filters cut off the frequencies higher then 3 kHz and excited frequencies of electric and ultrasonic signals. Background noise is of the order of 10^{-13} V^2Hz^{-1}.

Results

In this work intermodulation voltage of a frequency f_i is evaluated which is shown in Fig. 6. The intermodulation voltage V_i of a frequency f_i increases linearly with an electric signal V_E.

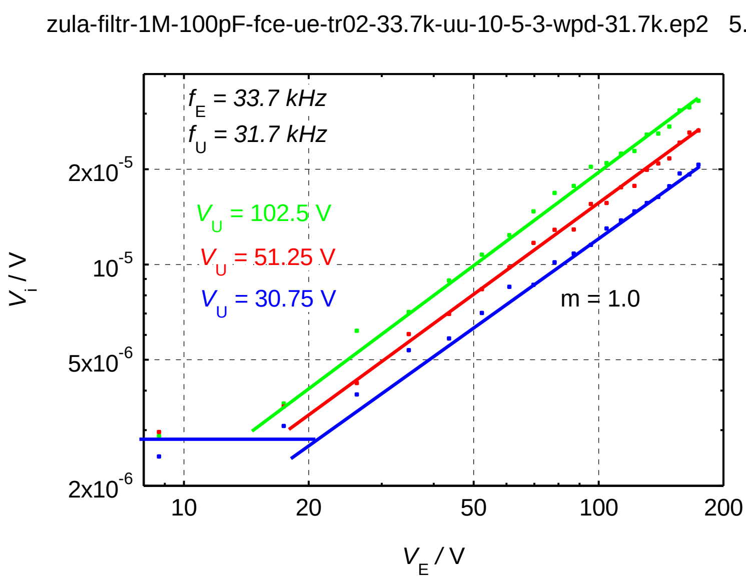

Fig.6. The intermodulation voltage V_i vs. electric voltage for constant ultrasonic excitation V_U = 102.5, 51.25 and 30.75 V.

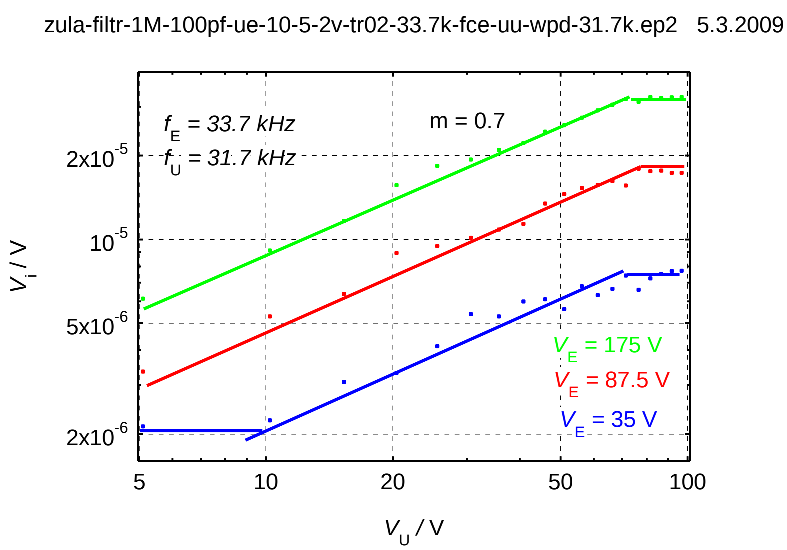

Fig.7. The intermodulation voltage V_i vs. ultrasonic excitation for constant electric voltage V_E = 175, 87.5 and 35 V

The second step was an applying the AC voltage to the sample with the same frequency f_E = 33.7 kHz with constant level for amplitudes of electric signal. Intermodulation voltage was measured for different levels of amplitudes of the AC voltage applied on the ultrasonic transducer of a frequency f_U = 31.7 kHz also. The intermodulation voltage V_i depending on ultrasonic excitation for constant electric AC voltage is shown Fig. 7. It is obvious that the intermodulation voltage V_i is increasing in increments of 0.7 for ultrasonic excitation. The saturation of ultrasonic excitation appears for amplitudes V_U = 70 V and higher voltages applied on the ultrasonic actuator.

The force of mechanical load applied on the granite sample and events intensity after time are shown in Fig. 8 and Fig. 9 for the first and second mechanical load relatively. Events intensity represents micro cracks generation in the structure of the granite sample during mechanical load.

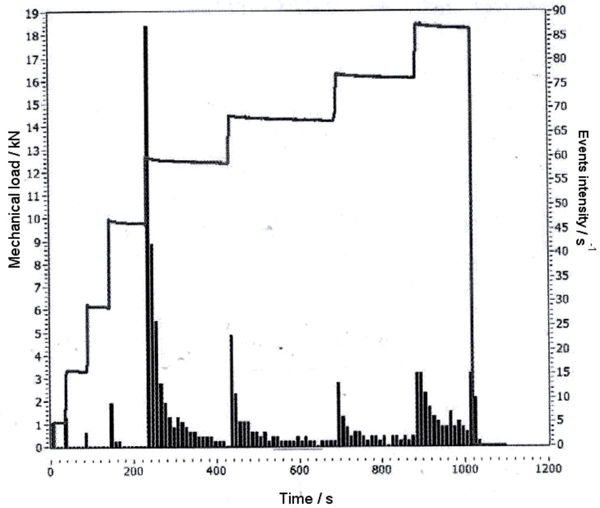

Fig.8. The force of the first mechanical load applied on the granite sample and events intensity after time.

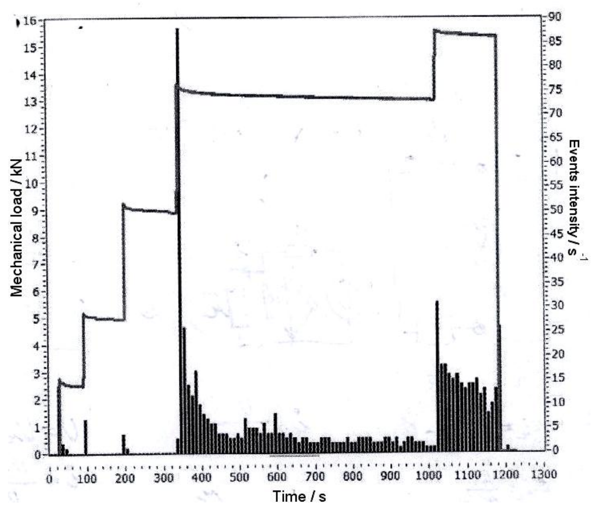

Fig.9. The force of the second mechanical load applied on the granite sample and events intensity after time.

The voltage V_i (measured on intermodulation frequency f_i) depending on the granite sample damage is shown in Fig. 10. It is obvious that intermodulation voltage V_i increases due to the cracks which occurs in the sample structure.

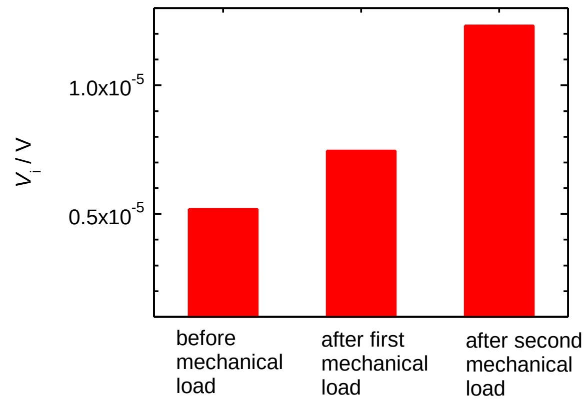

Fig.10. Intermodulation voltage V_i increasing with number of cracks in the granite sample.

Summary

The rock sample of granite named Z01 was tested in the experiment. This sample had a shape of prism with dimensions of 50 x 50 x 11 mm^3.
The voltage V_i depending on ultrasonic excitation increases approximately in increments of 0.7 for ultrasonic excitation till achieving the saturation when the ultrasonic voltage V_U = 70 V.
The intermodulation voltage V_i vs. ultrasonic excitation were measured for constant electric voltages V_E = 175, 87.5 and 35 V. The results indicates, that intermodulation voltage V_i increases with the number of damages of the granite sample.

Acknowledgements

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