PHYSICAL MODEL OF ELECTROMAGNETIC EMISSION IN SOLIDS

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Abstract

Cracks creation in solids can be accompanied by electromagnetic emission (EME). On the faces of new created crack electric charges constitute electric dipole system and due to crack walls vibration an EME signal is detected with frequency from 1 to 10 MHz corresponding to crack length 0.1 to 1 mm. The second source of EME signal is later activated due to whole sample mechanical vibrations with a frequency given by sample boundary conditions, which are in the range 50 to 500 kHz.

KEYWORDS: non-destructive testing, electromagnetic emission, acoustic emission, cracks creation

1. INTRODUCTION

Electromagnetic signals can be observed when solids, especially non-metallic materials, are mechanically stressed. Micro- and macro-cracking processes are often accompanied by electromagnetic emission (EME). This phenomenon is apart from NDT also studied in geophysics as a earthquake precursor [1] – [3]. The origin of EME from fractured materials is still not well understood. Several mechanisms were suggested [4] - [9], based on separation of electric charges at crack formation, dislocation movement or piezoelectric effect. It was observed [1], that charges moved simultaneously with the crack tip motion and then EME was excited by a dipole, consisting of the charges in the two crack tips and of the length equal to entire length of the crack. Acceleration of the crack tips during propagation increased the length of the dipole arm and consequently gave rise to EME.

Laboratory experiments, carried out on rock structures have proved that the failure process is more complicated. Two type of EME signals were observed: (i) corresponding brittle failure, (ii) shear failure or compressional displacement. From our previous experiments follows that electromagnetic emission signal precedes AE signal. EME signal has higher damping coefficient and lower relaxation constant than AE one. Signal of EME sensor depends on crack dimension and for the time interval less than 20 μs frequency of EME signal is given by boundary condition of crack eigen functions. AE signal is correlated with EME signal, but only with component, for which wave velocity is perpendicular to crack face area. Sample electrical conductivity and mechanical damping of crack wall vibrations determine EME signal damping constant in the first period after crack creation. Electrical conductivity is responsible for electric charge equilibration and this time when crack faces are charged is given by the low frequency EME signal. When crack faces are discharged, EME signal disappear, whereas AE signal is still measurable. EME signal depends on crack face orientation with respect to EME sensor. When the crack face is parallel to EME sensor, the signal has maximum value.

2. EXPERIMENTAL

A standard experiment set-up was used which allowed loading the samples up to 100 kN, to record the total deformation and the time evolution of the load. Samples of granite of size 8 × 4 × 1 cm^3 were provided with conducting sheets placed symmetrically, thus making up a plate capacitor whose dielectric is the material under test. The measuring set-up diagram was described in [3]. To eliminate interference arising from the ambience, the sample and the preamplifier were shielded electrically and magnetically. Two types of EME signals can be observed as are shown in Fig.1 and 2.

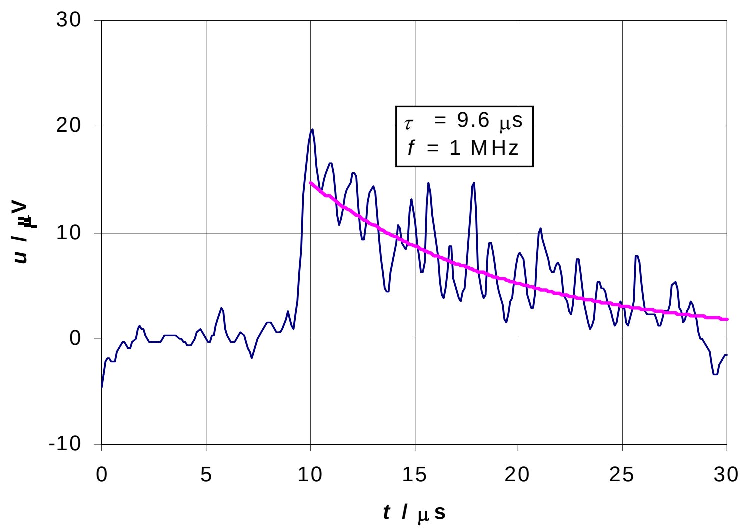

Fig.1. Time dependence of electromagnetic emission signal for brittle sample

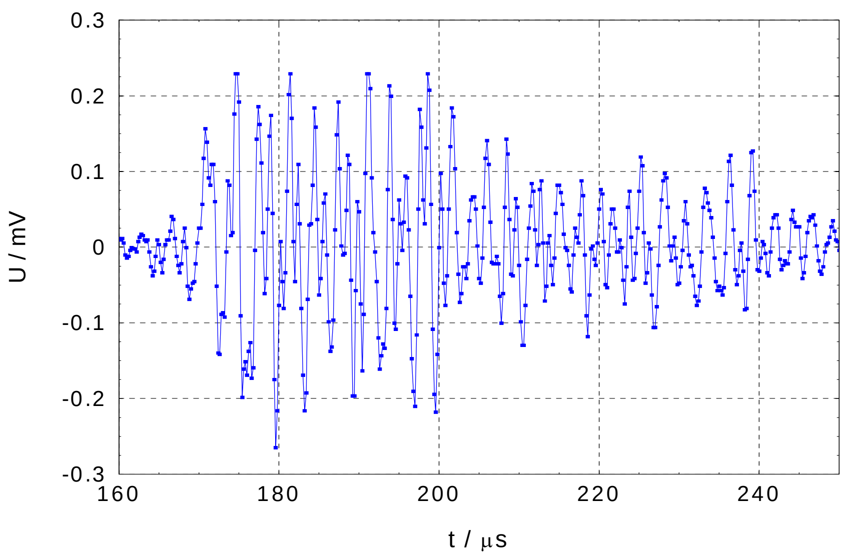

Fig. 2. EME signal time dependence with constant average value

3. MODEL OF AN EME SIGNAL CREATION

The electric charges $+q$ and $-q$ appear at the faces of the crack when the crack is produced. Their motion with the velocity $\vec{v}$ in the electric field $\vec{E}$ changes the voltage u on the parallel plate capacitor and the electric current i flows over the load resistor R (see Fig. 3).

Our model is based on the energy conservation law

$$\vec{E}\left(\sum_{k=1}^{N} q_k \vec{v}_k\right)\mathrm{d}t = Ri^2\mathrm{d}t + Cu\mathrm{d}u \quad (1)$$

where $\vec{E}\left(\sum_{k=1}^{N} q_k \vec{v}_k\right)\mathrm{d}t$ is the electrical energy created by charged crack walls motion, Ri^2dt is the electrical energy dissipated on the load resistance, $Cu\mathrm{d}u$ is the electrostatic energy of the capacitor sensor and N is a number of electric charges between the plates of the capacitor C.

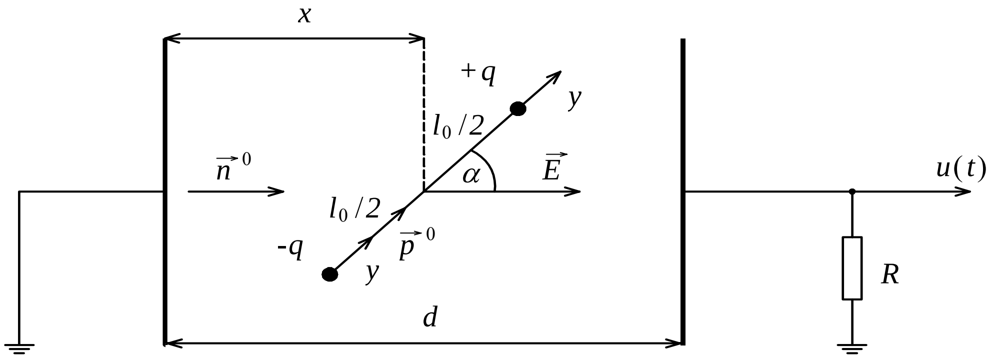

Fig. 3. A model for a crack

Then the differential equation for the voltage $u(t)$ is in the form

$$\frac{\mathrm{d}u}{\mathrm{d}t} + \frac{u}{\tau} = \frac{1}{C}\vec{E}_1 \cdot \sum_{k=1}^{N} q_k \vec{v}_k \quad (2)$$

where $\vec{E}_1 = \frac{\vec{E}}{u} = \frac{1}{d}$ for the parallel plate capacitor and $\tau = RC$ is the time relaxation constant.

The crack walls vibrate and the crack width is a function of time. The time dependent displacement of the crack faces results in an AC electromagnetic signal component whose frequency corresponds to that of mechanical vibrations of the specimen. The charges $+q$ and $-q$ are at the equilibrium distance l_0 and their displacement $y(t)$ is given by

$$y = y_0\, \mathrm{e}^{-\delta t} \sin \omega t \quad (3)$$

where δ and ω are damped harmonic motion constants.

The electrical conductivity is discharging the elementary capacitor representing crack walls. We will suppose the electric charge exhibits exponential time dependence in the form

$$q = q_0 \mathrm{e}^{-\beta t} . \tag{4}$$

The dipole moment $\vec{p}(t)$ is given by

$$\vec{p} = q_0 e^{-\beta t}(l_0 + 2y_0 e^{-\delta t} \sin \omega t)\,\vec{p}^{\,0} \tag{5}$$

The velocity of the damped harmonic motion of charges on the crack walls is given by

$$\vec{v}^{\,+} = v_0 \mathrm{e}^{-\delta t} \sin(\omega t + \varphi)\,\vec{p}^{\,0} \tag{6}$$

$$\vec{v}^{\,-} = v_0 \mathrm{e}^{-\delta t} \sin(\omega t + \varphi)(-\vec{p}^{\,0}) \tag{7}$$

where $v_0 = y_0 b$, $tg\varphi = -\dfrac{\omega}{\delta}$, $b = \sqrt{\omega^2 + \delta^2}$.

Then the form of the differential equation (2) is in the form

$$\frac{du}{dt} + \frac{u}{\tau} = g\mathrm{e}^{-\gamma t} \sin(\omega t + \varphi) \tag{8}$$

where $g = \dfrac{2q_0 v_0 \cos\alpha}{Cd}$, $\gamma = \delta + \beta$, v_0 is the velocity amplitude, *d* is the parallel plate capacitor thickness and α is the angle between the electric field intensity $\vec{E}$ and the electric charge velocity $\vec{v}$.

Its solution is in the form

$$u(t) = u_1(t) + u_2(t) = U_0 \mathrm{e}^{-\frac{t}{\tau}} - \frac{g\mathrm{e}^{-\gamma t}}{\sqrt{\omega_0{}^2 + \omega^2}} \sin(\omega t + \varphi) \tag{9}$$

where U_0 is an integration constant and $\omega_0 = \gamma - 1/\tau$ is a cut off angular frequency.

This electric voltage $u(t)$ on the capacitor *C* is given as a sum of two components. The first component $u_1(t)$ (DC component) characterizes the discharging of the capacitor *C* over the load resistor *R*. It will be dominant if crack walls are collinear to the plates of the measured capacitor *C*. The second component $u_2(t)$ (AC component) characterizes the damped harmonic motion of charges on the crack walls.

4. DISCUSSION

Experimentally we have observed two different type of signals like damped harmonic motion with: (i) constant average value and (ii) exponentially time dependent transient value as is shown in Fig. 4. Electrical signal of EME is given by superposition of the DC transient component and AC high frequency voltage. Time constant for DC voltage relaxation is given by amplifier input RC circuit: for R = 1 MΩ and C = 20 pF we have time constant τ = 20 μs, which is in good agreement with experiment.

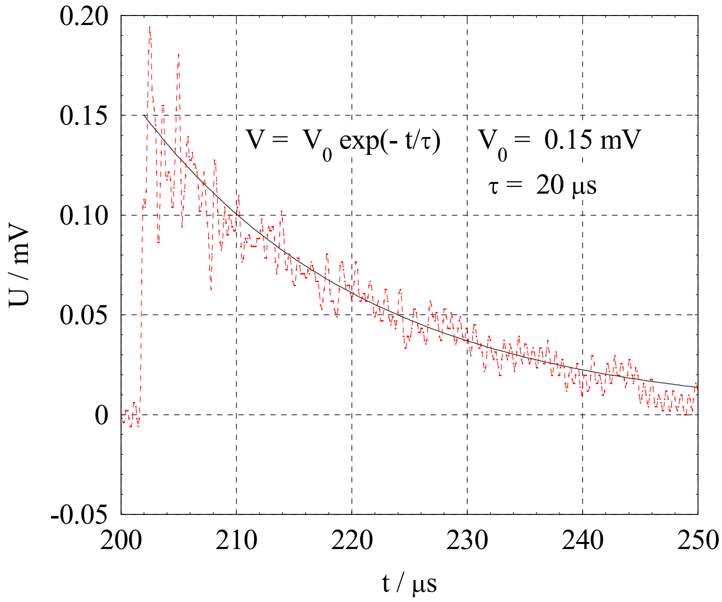

Fig. 4. Electric voltage time dependence

4.1. The EME signal model

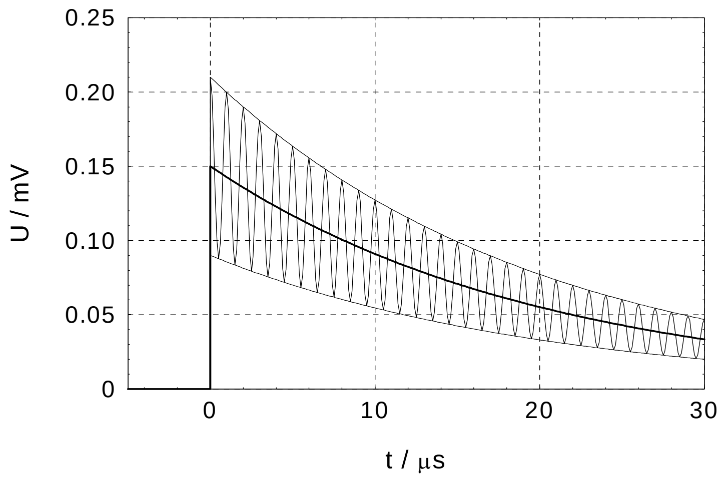

Fig. 5. Electric voltage time dependence

We will give a list of parameters corresponding to our model in Fig. 5: $V_0 = .15$ mV, $R = 1$ MΩ, $C = 20$ pF, $q_0 = 1.28{\cdot}10^{-14}$ C, $u_0 = 1.5{\cdot}10^{-5}$ m, $v_0 = 10^2$ ms^{-1}, $\alpha = 0$, $d = 10^{-2}$ m, $\gamma = 5{\cdot}10^4$ s^{-1}, $\omega = 6.28{\cdot}10^6$ s^{-1}, $\varphi = \pi$. Then ω_0 is much less than angular frequency ω. In this case equation (9) can be written as

$$V(t) = V_0 e^{-t/\tau} - \frac{g e^{-\gamma t}}{\omega}\left[\cos(\omega t + \varphi)\right] \tag{10}$$

EME sensor will detect AC component, which is proportional to g/ω.

5. CONCLUSION

From eq. (10) follow, that AC component of EME signal is proportional to crack face electric charge q_0 , crack wall velocity amplitude and crack area orientation with respect to EME sensor area. EME signal will be not detected, when crack area is perpendicular to EME sensor plates. AC component of EME signal is inversely proportional to the distance between EME sensor plates d. Thin samples are more suitable for this experiment. The last is dependence on capacity. EME sensor will have high sensitivity for low total capacity C, it is the sensor capacity including preamplifier input capacity and montage capacity (coaxial cable).

Acknowledgement

This research has been supported by grants GA CR 205/03/0071, GA CR 102/02/D073 and also as a part of a research project VZ MSM 261 100007 and VZ MSM 2622 000 22.

6. REFERENCES

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