ELECTROMAGNETIC EMISSION CAUSED BY FRACTURING OF PIEZOELECTRIC IN ROCK

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ABSTRACT

An electromagnetic emission caused by fracturing of piezoelectrics in rocks is analyzed. The source of the emission is a transient polarization current created by alternative deformation in a vicinity of the crack in piezoelectrics. Such a current source can be presented as an effective transient magnetic moment. The types of crystal symmetry where an effective electromagnetic emission is possible are pointed out. The maximal radiation takes place at frequencies $\sim 10^6$ s^{-1}, when the sizes of the crystal are about 1 cm. The corresponding effective transient magnetic moments are estimated. The considered problem is important for investigations of natural hazards.

INTRODUCTION

There exist various electromagnetic effects called precursors during seismic and volcano activity in the lithosphere, such as an electromagnetic emission (EME) caused by fracture of solids. This emission is very promising for investigations of natural hazards. There are a lot of different mechanisms of occurring electromagnetic wave (EMW) emission. Dominating mechanisms are an excitation of polarization of internal surfaces caused by fracturing of solids and an appearance of charged dislocations. The non-uniform motion of bridges between cracks and the tips of the cracks are the sources of EMW. An influence of piezoeffect on the stimulation and an amplification of electromagnetic pulses due to fracturing are very important [1]. In details, this phenomenon has been not investigated yet.

ANALYSIS

We consider a piezoelectric plate to which the stress of the value $\vec{P}_0$ along axis OY (Fig.1) is applied. In the analysis and calculations, all sizes of the plate (L, H, h) are of the same order. The axis OZ is the optical one of the crystal. For calculations, as an example, we take quartz (SiO_2). First, piezoeffect causes the electric field in directions of piezo-axes OX and OY. Second, it is important that the fracturing of crystals occurs in the distinctive crystallographic planes. This type of fracturing is called the cleavage [2]. Hence the crack caused by $\vec{P}_0$ can expand, as shown in the Fig.1, along the axis OX. If the crack exists within the plate, it begins to move in the crystal under the certain value of the mechanic stress. Its velocity, for example, in quartz, is equal approximately to the transverse acoustic wave velocity. It is necessary to analyze the nonstationary problem because of following reasons. First of all, an electromagnetic emission could be as a result of the electron system relaxation on the created surfaces of any materials. Also, the motion of the unloading wave from crack occurs, and nonstationary local mechanical stresses around the crack in piezoelectric appear. We take into account the long-wave emission connected with the great scale processes in all the volume of the crystal only. All the theory is based on the equations of motion obtained by using the free energy Ψ of a crystal. This energy $\Psi = \Psi(u_{kl}, T, E_k, B_k, a_1, ..., a_N)$ is a function of deformation tensors u_{kl}, the temperature T, the external electric and magnetic fields E_k, B_k, and, perhaps, of some N internal parameters a_k. If the dielectric is situated under an influence of small deformations and small electric fields, the equations of motion can be derived in the linear theory approach. We do not take into account a dependence on the magnetic field, because it is not important for our case of elastic dielectric. Hence, it is necessary to expand Ψ into series. All these assumptions give us a possibility to analyze the emission phenomenon in a linear approach. We use the Maxwell's equations for the description of electromagnetic waves

$$rot\,\vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}, \; rot\,\vec{B} = \frac{1}{c}\frac{\partial \vec{D}}{\partial t} \qquad (1)$$

$$div\vec{B} = 0, \qquad div\vec{D} = 0,$$

and equations of motion within a piezoelectric

$$r\ddot{U}_i = \frac{\partial s_{ij}}{\partial x_j}, \quad s_{ij} = c_{ijkl}U_{kl} - e_{kij}E_k, \quad D_i = e_{ij}E_j + 4p\,e_{ikl}U_{kl}, \qquad (2)$$

where $\vec{D}$ is the electric induction, c is the velocity of light, s_{ij}, U_i are components of stresses and mechanic displacement tensors, respectively; c_{ijkl}, e_{ijk}, e_{ij} are components of tensors of elastic constants, piezoelectric constants, and the dielectric permittivity, respectively [2].

Substituting $\vec{D}$ from Eq. (2) into Maxwell's equations and taking into account the definition of the linear deformation tensor $U_{kl} = \frac{1}{2}\left(\frac{\partial U_k}{\partial x_l} + \frac{\partial U_l}{\partial x_k}\right)$, one can obtain the wave equation for the electric field $\vec{E}(\vec{r}, t)$, which can be presented as:

$$\Delta\vec{E}(r,t) - \frac{e_{11}}{c^2}\frac{\partial^2}{\partial t^2}\vec{E}(r,t) = \vec{S}_w(r,t) \equiv \frac{4p}{c^2}\, rot\,\dot{m}(r,t) \qquad (3)$$

The right hand part $\vec{S}_w(\vec{r}, t)$ of the Equation (3) is the source of the electromagnetic emission and it is connected with the mechanical displacement vector U_i. As our calculations demonstrate, this source is equivalent to effective transient magnetization vector.

It is possible to analyze three basic cases of fracturing (see Fig.2), which determine three configurations of the mechanical displacement vector U_i. In the static case, if the crack does not move, the vector U_i is determined only by coordinates, and the right part of Eq.(3) is zero. Hence the electromagnetic emission is absent. If the crack moves, the displacement vector $\vec{U}$ depends on the time t and coordinates $\vec{r}$. Under this condition, the right part of Eq.(3) is not zero, i.e. $\vec{S}_w(\vec{r}, t \neq 0$. The dynamic self-consistent problem for a crack in piezoelectric has not been solved yet. The most appropriate solution of a distribution of the elastic deformation for the uniformly moving crack is presented in [3]. This solution has been used to obtain the right part of Eq.(3). In this solution, an influence of the crystal structure and the electric field in the right part $\vec{S}_w(\vec{r},t$ is not taken into account. Using results of [3] we have found a distribution of deformation for the crack in the traveling polar coordinate system for different cases of fracturing (see Fig 2), and, hence, due to piezoeffect, the value of the vector $\dot{\vec{m}}(\vec{r},t)$, too.

First of all, let us discuss the source of electromagnetic waves. Once we have demonstrated that the effective magnetization currents $\vec{j} = rot\,\vec{M}$ exist in piezoelectric crystal [4], then the wave equation is the same as described in Eq.(3) where the term $4p\,c^{-2} rot\,\dot{\vec{M}}(\vec{r},t)$ must be in the right part. The source of the electromagnetic emission is the variable magnetization vector $\vec{M}(\vec{r},t) = \vec{m}(\vec{r},t) + \vec{m}_0(\vec{r})$. It is possible to calculate the vector $\vec{m}(\vec{r},t)$, and the vector $\vec{m}_0(\vec{r})$ is a constant, which can be found from an initial condition that a magnetization is equal to zero for the immobile crack. The direct calculations show that $\dot{\vec{m}}(\vec{r},t) \neq 0$ only in the case of moving crackwith a velocity *V ¹ 0*. Therefore, we have $\vec{m}_0(\vec{r}) \equiv 0$.

It can be shown that transverse electromagnetic wave having the velocity about $c/\sqrt{e_{11}}$, which is coupled very weakly with the acoustic wave, can expand in all directions in the quartz. Only this electromagnetic wave is excited by transient stresses from the crack. It is important that just polarization currents in the source have the vortical character and create the effective magnetic moment, i.e. analogous to magnetization currents. Our investigations show a possibility of a creation of such the moment by the propagating crack parallel to the optical axis in the crystals. These crystals belong to the symmetry group 422 and 622 for crack III; and $\bar{6}$ and $\bar{6}m2$ for cracks I, II. The cracks, considered above, have the unique ability to create circular vortical polarization currents and magnetic fields in crystals of the symmetry group 32 only. The solution of Eq.(3) gives us the electric and magnetic fields for three types of fracturing and the frequency-angle distribution of the radiated energy.

DISCUSSION OF RESULTS

For a numerical analysis of the simplest third case, we use the interatomic distance l_0 = 0.1 nm, the travel time of crack in the crystal $T_0 = L/V$, the width of crack about 1 μm in the crystal with the all the sizes about 1 cm. After integrating by time T_0 and in volume of crystal with the size *L* in the Eq.(3), we obtain the following results for the magnetic moment and corresponding effective current [2] for three cases of fractures (I, II,III, see Fig.2).

Considering *L*=1 cm, l_0 = 0.1 nm, V=2 km/s, $\tilde{n}_1$ =5.3 km/s, e_{14} = 2680 units CGS, e_{11}=4.6 [2], we obtain $M_{III} = 3.7 \cdot 10^{13}$ units CGS, or $M_{III} \approx 1.3$ A·m². In a vicinity of the crack, this moment is excited by means of effective circular current with a value $I_{III} \approx 1.3 \cdot 10^4$ A. Analogous calculation can be done for another parameters. For data $c_2 = 3.3$ km/s, e_{11} =-53500 units CGS [2], one obtains: $M_I \approx 27$ A·m², $I_I = 2.7 \cdot 10^5\ A$, $M_{II} \approx 5$ A·m², $I_{II} = 5 \cdot 10^4$ A. All effective magnetic moments are oriented along the axis OZ.

Let us discuss a frequency dependence of the radiation energy. After calculations of the Fourier mode of deformations and the frequency-angle distribution of the radiated energy, it is possible to determine its maximal value, which appears at the frequency $w = 2p \cdot 0.795\,V/L$, the corresponding wavelength is $l_{\max} \approx L\dfrac{c}{0.795\sqrt{e_{11}}V}$. The next maxima of the intensity of the EM radiation correspond to shorter waves. For a crystal with the sizes 1 cm, the frequency and wavelength are $w_{\max} \approx 10^6$ s⁻¹, $l_{\max} \approx 0.75$ km respectively at crack velocity 2 km/s. For the crystals with sizes 1 m, this wavelength increases to 75 km, and the frequency decreases 100 times, respectively. It should be noted that this electromagnetic emission can be registered during volcano eruptions, if a fracture is located at the surface of volcano. In the case of a deep fracture, the EM waves with higher frequencies dissipate, and only ELF (extremely low frequency) and VLF (very low frequency) waves are registered at the Earth's surface. It is necessary to use very sensitive sensors for a registration of high frequencies, because high frequency waves attenuate very quickly with a distance in the lithosphere. The angular distribution of the radiation has the sharp orientation along the normal to the front line of crack and locates in the piezo-active plane. For the cracks of types I and II, there is a dependence on the direction of the radiation in this plane possessing four directional lobes on the angle j ; for the crack of the type III, this dependence is absent. As the calculations of the total radiation energy show, this energy is proportional to mechanical one of stresses created by the crack.

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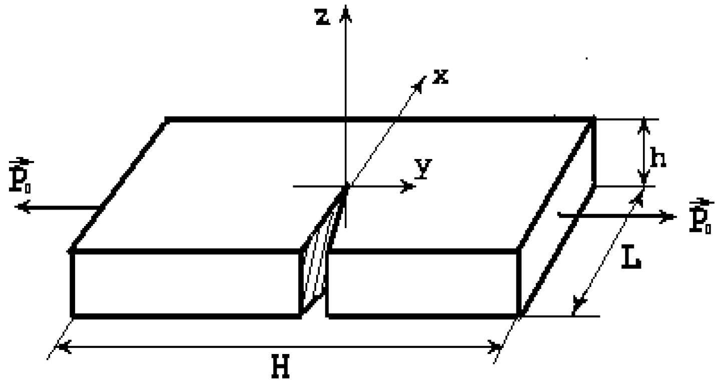

Fig.1. Model of moving crack.

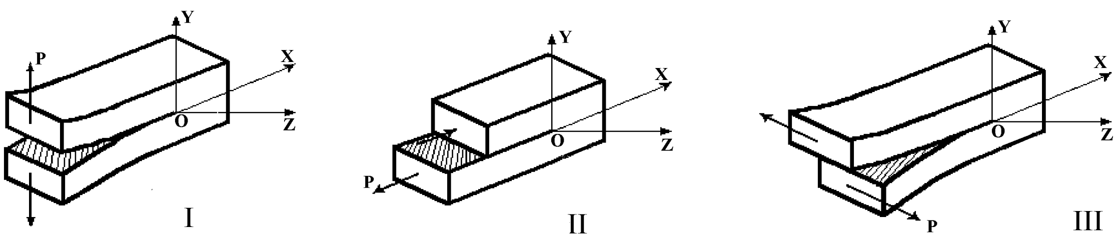

Fig.2. Model of the types of cracks.