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Piezoelectric Cut Exposed to Shock Wave

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Abstract: This paper deals with the problem of transformation and practical utilisation of explosion energy. A principle has been suggested and described that enables utilisation of detonation energy of condensed explosive used as energy source exerting shock wave strain upon piezoelectric sample cut prepared from the oxide system PbO-TiO_2-ZrO_2. The piezoceramic transducer used as generator of impulse electric charge is characterised by several favourable properties. In particular, they include readiness, large temperature and time ranges of functional parameters, variability of working regime, and relatively low price. The given system serves as efficient source of short-time prompt capacity electrical impulse, which can find application in a number of electro-physical disciplines.

Keywords: explosion energy, piezoelectric effect, shock waves

Introduction

Transformation of energy

Energy is a fundamental quality that every physical system possesses. Energy is defined as the amount of work required to change the state of a physical system, and it can be transformed from one form to another.

A detonation of explosive charge sets free the so-called detonation energy, which is divided into the shock wave energy and the expansion wave energy (i.e. the energy of expanding hot gaseous products of detonation). The liberated energy can be transformed into mechanical work and utilised in various applications, such as mass acceleration, welding of metals, forming of metals, pressing of porous materials (powders) etc.

Also such systems have been described that transform the explosion energy into electromagnetic impulse: (i) magneto-hydrodynamic (MHD) generators [1], which work on the basis of the principle of direct interaction of ionized products of detonation with a stationary magnetic field, and (ii) piezoelectric transducers [2], which make use of the direct transformation of energy of pressure-strain impulse into the piezoelectric effect.

Piezoelectricity

The phenomenon of electrical polarisation, in which electric charges of opposite polarity are created at opposite sites of crystal by mechanical deformation, is called the direct piezoelectric effect [3]. Above a certain critical temperature (Curie temperature) the crystal structure of material exhibits a centre of symmetry, and there exist no electric dipoles in the system. This situation is referred to as paraelectric state. Below this critical temperature, a phase transformation (change in crystallographic structure) takes place to give the ferroelectric state, which structure does not exhibit any element of symmetry, and in which electric dipoles are formed – see, e.g., Refs [4, 5].

Hence, the piezoelectric phenomenon only exists in crystalline materials lacking the centre of symmetry.

Piezoelectric materials and application

At present, the most frequently applied piezoelectric material, and by far the most significant commercially manufactured ferroelectric ceramic material is PZT [6]; it is based on solid solutions of oxides PbO – ZrO_2 – TiO_2. This easily commercially available ceramic material of perovskite structure has general formula ABO_3, where A = Na, K, Rb, Ca, Sr, Ba or Pb and B = Ti, Sn, Zr, Nb, Ta or W; it exhibits suitable piezoelectric and dielectric properties. Structure of substances of this group is derived from natural material called perovskite, which chemically is $CaTiO_3$.

Shock waves

A compression shock wave (SW) propagates through a medium at a velocity that is higher than the speed of sound in the same medium, and it represents compression of the medium with immediate increase in pressure, density and temperature at the wave front. Since the dynamically compressed medium represents an unstable system, an expansion wave is formed in opposite direction to the propagation of SW front, and this gradually reduces the load acting on the medium, which is accompanied by pressure decrease behind the SW front and volume increase of the medium hit by the propagation of waves. The shock wave increases adiabatically the temperature of the medium, being reflected at phase interfaces and interacting with all types of inhomogeneities in the medium [7].

The hydrodynamic effects of planar SW incident on a given object, e.g., a piezoceramic cut, are determined by several factors: the pressure P_1 at the front of incident SW, the velocity u_{P1} of particles of the medium and velocity D_I of propagation of SW front, the compression adiabatics of both the donor and the acceptor media (hereinafter differentiated by indexes 1 and 2, respectively). Important parameters of both media are their shock impedances $Z_i = \rho_i D_i$, where ρ_i means the density of the given medium. If the shock wave passes over an interface of materials with different impedance values, then it partly passes from medium 1 to medium 2, and partly is reflected by the impedance interface back into medium 1. The pressure P_2 at SW front behind the interface [8], in our case in the piezoceramic material, is defined by Equation (1):

$$P_2 = 2P_1 Z_2 / (Z_1 + Z_2) \tag{1}$$

Hence, the optimum working regime of generator depends, *inter alia*, upon the level of compression shock strain of the cut structure, which can vary within the range of 1-5 GPa. In this interval of pressures P_2 the structural changes of piezoceramic materials of any composition are irreversible, i.e. of destructive nature.

Experimental

Using piezoceramics based on PZT as the media capable of transformation of deformation forces into electric signal, and explosives suitable for generating shock waves of required parameters, we have suggested and then also practically verified a system of piezoceramic generator depicted in Figure 1. The experimental work was focused on optimization of construction of the whole system and determination of the optimum value of electric load of the cut, which allows obtaining the maximum of Joulean energy.

According to Figure 1, the used primary source of shock wave was a plastic explosive or its combination with loose explosive. The mass of the whole charge was from 6 to 14 g. The explosive was shaped to a cone form and inserted into a polyamide carrier. The whole system was placed into a cylindrical casing and initiated by means of electrical detonator.

After impact of detonation wave on the interface with barrier, a SW is formed here, the pressure at its front being defined by Equation (1).

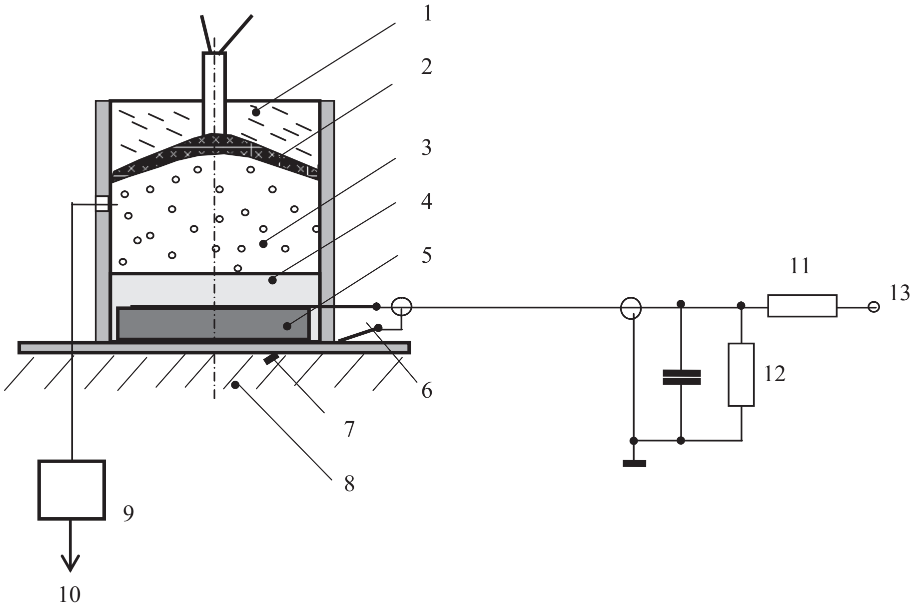

Figure 1. Scheme of piezogenerator: 1 – guide insert with detonator, 2 – plastic explosive, 3 – loose explosive, 4 – epoxide, 5 – piezoceramic cut, 6 – outlets from cut, 7 – cardboard or free surface, 8 – steel plate, 9 – RC switching-on circuit, 10 – external switching-on of time base of oscilloscope, 11 – high-voltage probe, 12 – generator load, 13 – input of oscilloscope.

Subsequently, this wave reaches the interface epoxide – piezoceramic cut, which will generate an energetic impulse. A typical time course of voltage at generator load 12 is presented in Figure 2. The time of impact of SW upon the cut in the lower picture (File 3) is denoted by symbol t_0. The negative polarity of this signal is due to the fact that the SW front travels in opposite direction to the vector of residual polarisation of cut and for practical reasons its more distant electrode is connected to ground. At the time $t = t_M$ the front of compression wave reaches the free surface of the cut, and the mechanism of charge generating at the collecting electrode causes the first voltage maximum to be observed at the load. According to (1), the compression wave is reflected at the free surface and returns back into the medium of cut as a wave of relief, and it gradually negates the compression effects of products until finally at a certain moment it starts to strain the medium of cut by tractive forces. Since at the test conditions it was only possible to attain a reversible, incomplete depolarisation of cut, we can also observe an increase in voltage of (+) polarity in the interval ($t_{OD} - t_Z$) as a demonstrable consequence of structure reversion of the cut. In the following time interval – in accordance with Equation (1) – the tractive strain of cut changes into pressure strain, which is probably accompanied by loss of cohesiveness of the whole system. From the given facts it is obvious that the mechanism of charge generating by shock wave is fundamentally different from the behaviour of quasi-statically loaded cut. A number of authors studied the shock loading of piezoelectric cuts in several variants, see, e.g., [2, 5, 9]. However, the use of explosives for initiation of mechanic energy has been mentioned rather exceptionally.

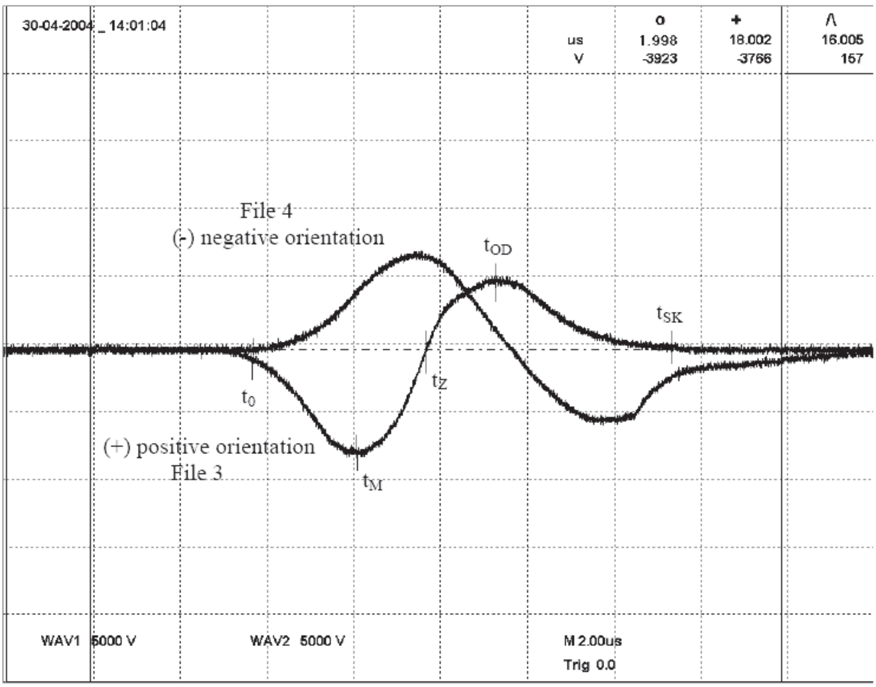

Figure 2. Effect of orientation of cut upon polarity of signal. Plastic explosive $m_P = 6$ g, $R_Z = 200\ \Omega$. File 3: Time t_0 – start of pulse generating, t_M – impact of SW on free surface, t_Z – compensation of voltage, t_{OD} – impact of expansion wave front on interface epoxide – cut, t_{SK} – impact of SW on free surface.

The cuts used in this series of experiments were made from a hard piezoceramic material that by its dielectric, electro-mechanic and physical properties corresponds (according to [10]) to type PCM 80. Dimensions of the cut: diameter $Ø$ = 3.8 cm; height h = 0.58 cm; active surface S = 10.7 cm^2; active volume V = 6.23 cm^3. Density of ceramic material $\rho_0 = 7.55$ g/cm^3.

The thickness of epoxide barrier, which serves as pressure modifier in shock wave, was chosen in the interval of 4-6.5 mm. The load resistance of system, R_Z, was varied in an interval of tens to hundreds ohm.

Figure 3 presents a pair of pictures, where File 1 was obtained with the detonation of a charge prepared according to Figure 1. The results of this type of tests are not sufficiently reproducible (probably because of not steady detonation of loose component of charge). In the second test (File 2) only plastic explosive was used.

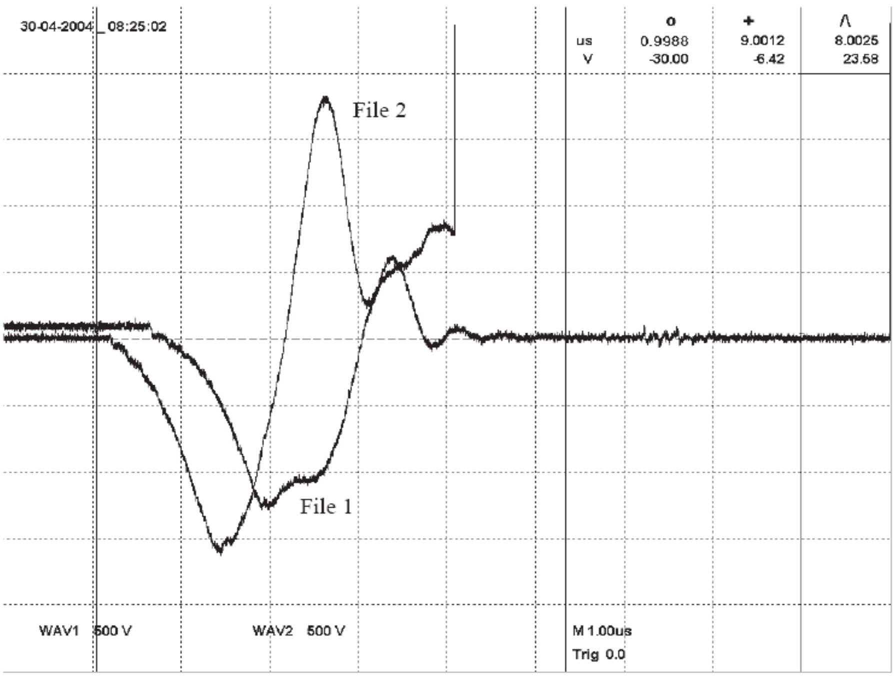

Figure 3. Effect of mass and type of explosive upon the signal of generator with a load of $R_Z = 20\ \Omega$. File 1 – 4 g plastic explosive + 10 g loose explosive, File 2 – 6 g plastic explosive.

Values of some parameters (see Table 1) were read from the graphs based on experimental results and calculated from Equations (2)-(7).

Table 1. Data evaluated from voltage-load dependences

Parameter	File 1	File 2	-	File 3	File 4	-
t_M [μs]	1.40	1.20	1.52	1.46	1.60	-
D [m/s]	4285	5000	3880	4041	3687	-
U_{max} [kV]	1.40	1.61	5.01	7.80	7.00	10.80
R_Z [Ω]	20	20	100	200	200	2000
Π_{max} [kW]	98	130	260	304	245	58
Q [μC]	112	140	116	89	93	6
Q^* [μC/cm^2]	10.40	13.10	10.70	7.57	8.69	0.58
E [mJ]	104	159	394	400	421	21
E^* [mJ/cm^3]	16.50	25.50	63.20	64.20	67.50	3.41
m_P [g]	4	6	6	6	6	6
m_X [g]	10	-	-	-	-	-
h [mm]	4.00	5.50	9.00	9.00	5.50	6.50

Analysis of records allowed the following parameters to be determined [11]:

$$D = \frac{h}{t_M - t_0} \quad [m/s] \qquad \Pi_{max} = \frac{U_{max}}{R_Z} \quad [W] \qquad (2), (3)$$

- where D is the velocity of SW front, h – height of epoxide, t_M – time for voltage maximum, t_0 – start of pulse generating, Π_{max} – the maximum performance, U_{max} – the maximum voltage, R_Z – resistance of load

$$Q = \frac{1}{R_Z}\int u(t)\,dt \quad [C] \qquad E = \frac{1}{R_Z}\int u^2(t)\,dt \quad [J] \qquad (4), (5)$$

- where Q stands for charge, E – energy, $u(t)$ – time course of voltage

$$Q^* = \frac{Q}{S} \quad \left[C/m^2\right] \qquad E^* = \frac{E}{V} \quad \left[J/m^3\right] \qquad (6), (7)$$

- where Q^* is specific charge, S – active surface of cut, E^*– specific energy, V – active volume of cut.

Discussion

The findings reported in literature show that the time course of voltage signal of piezoelectric pulse generator more or less depends on the duration and intensity of loading of the body of cut by the passing waves; on shock impedances of media adjoining the surfaces of cut; on resulting electric impedance of load; on ratio of main dimensions of cut; on electric fastness of the loaded cut; on the orientation of direction of propagation of wave with regard to the polarisation of piezoceramic material; on the resistance of structure to depolarisation factors; on the planarity of SW front and angle of deviation of this plane with regard to the axis of the system etc. The main assets of the series of experiments conducted out on the model represented by Figure 1 can be summarized as follows:

No effect of *orientation of polarisation vector* with regard to propagation of SW front upon the efficiency of energy conversion was proved.

Planarity of SW front represents a significant factor, but the small volume of charge did not allow its shape modification and, therefore, the cut was strained by a rounded SW front.

On the basis of the charge-rated yields of cuts it can be claimed that their *natural ageing* has no significant effect upon lowering of polarisation – see Ref. [2].

From the data of *the maximum performance and energy* generated on R_Z (Table 1) it can be deduced that the inner dynamic resistance of the generator designed according to Figure 1 is ca 150 Ω.

In *"short-circuit"* regime of loading of the generator (with $R_Z << 20\ \Omega$) the maximum current is obtained, at $R_Z = 20\ \Omega$ the current into load is ca 60 A.

In *"idle-running"* regime (with $R_Z \geq 2000\ \Omega$) the voltage at a cut of PCM 80 type, 0.58 cm high, reaches ca 10 kV, and thus it exceeds the electric fastness of medium.

The energetics of one cut can *inter alia* be raised by increasing its dimensions. Further increase in performance of system can be attained by the method of shock strain of a series of cuts with a single source of shock wave.

The *level of loading* of cut by shock wave was regulated on the one hand by the height of barrier – see Figure 2, on the other hand by the mass and type of the explosive used – see Figure 3 and the data of Table 1. After exceeding a certain critical limit of pressure strain, the inner structure of cut is extensively disturbed behind SW front, which results in irreversible depolarisation as well as formation of conductive channels through which the charges bound at the both surfaces of compressed zone are discharged. Then the current passing through the external circuit is lowered by escape of this discharge current – see Ref. [9].

However, gradual lowering of pressure P_M below the area of damage leads to lowering reversible depolarisation and, hence, to lowering efficiency of energy transformation.

Increasing *thickness of cut* increases the time of charge generation and, hence, also the interval ($t_M - t_0$), which is needed for re-polarisation of domains, which has a positive effect upon the efficiency of the system. However, the consumption of current by the load can lead to their permanent depolarisation. Another advantage of a higher cut is a weaker effect of sphericity of SW front upon the efficiency of system.

Conclusion

Practical tests carried out in recent years at the IEM proved that a shock-strained piezoelectric cut represents an efficient generator of short-term, prompt, easily synchronized energetic impulse, which can be applied in a number of electro-physical disciplines.

From the point of view of attainment of the maximum performance delivered into a real load, the optimum value appears to be $R_Z = 140\ \Omega$ for the given type of cut, which at the same time corresponds to inner dynamic resistance of the generator.

Acknowledgements

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