M.Sc. Jerzy KOWALEWSKI
Prof. Ph.D. D.Sc. Adam WIŚNIEWSKI
Military Institute of Armament Technology

PIEZOELECTRIC GENERATORS IN FUSES OF SHAPED CHARGE PROJECTILES

The composition, parameters and requirements, which should be fulfilled by piezoelements used in armament technology, have been described. The results of the tests of piezoelements (discs with the thicknesses of 1.2÷3 mm and diameters of 20÷25 mm with the holes and without them) as the voltage generators in fuses of shaped charge projectiles were presented. Electric parameters of piezoelements under dynamic loads as result of the drop of weights with the mass of 2 kg and 5 kg on them were determined. The generated minimum electrical energy of 0.002 J has been obtained, which is sufficient to the initiation of typical electro-spark detonators, used in fuses of these projectiles in the properly short time (4.4÷10.2 μs).

1. Introduction

The piezoelectricity or otherwise the piezoelectric effect was discovered by Pierre and Paul Curie in 1880. The piezoelectric effect means the appearance of heteropolar electric charges on opposite and asymmetric to each other, superficial elements some of crystals under the pressure or voltage. The phenomenon, presented above, is so called a simple piezoelectric effect. However, the creation of mechanical deformations of these crystals under the influence of electric field is so called inverse piezoelectric effect.

Piezoelectric are crystals in which the piezoelectric effect occurs. The crystals do not have the symmetry centre except of crystals which belong to the class of the pentagonal icositetrahedron. Piezoelectric are, among other things: quartz (SiO_2), Seignette salt ($NaKC_4H_4O_6 \cdot 4H_2O$) and titanate bar - ($BaTiO_3$).

The piezoelectricity makes possible the transformation of tensions and mechanical impulses into electric and vice versa. Piezoelectric crystals are used, among other things, to measure the pressure, in electro-acoustic transducers, in resonant circuits and in acoustic vibration generators. Due to their proprieties this crystals are used to produce the electrical energy for initiation of electric disruptive detonators of armour-piercing shaped charge projectiles [1].

Piezoelectric substances can be divided into several groups [2], and the most important ones are:

- Inorganic monocrystals of the substance which are characterized with the good mechanical and temperature durability, e.g. quartz and tourmaline. However, they are difficult enough to gain in the crystalline form in laboratory conditions.

- Monocrystals of substance of the lover mechanical and temperature durability, but easier to gain in the crystalline form, e.g. crystals of Seignette salt, of potassium tartrate, potassium dihydrogen phosthate, ethyldiamina tartrate.
- Policrystal substances of the ordered polarization with the external electric field or with direction voltage, so-called ceramic senetoelectric, e.g. titanate bar.

Basic requirements in relation to piezoelectric used in detonators are:

- the great piezoelectric effect,
- the high mechanical durability,
- the simple technology of producing of piezoelements of different shapes,
- the small time change of the polarization in the wide enough temperature range,
- the small temperature dependence on piezoelectric modules,
- the polarization in electric fields of low intensity.

The mentioned requirements are met, first of all, by ceramic piezoelectric. The production technology of the piezoelements usually consists in mixing of crumbled components and their burning. Piezoelectric properties of burned and cooled material are obtained with its activation in the electric field of the intensity of 2 kV/mm and its heating to the temperature higher than the Curie temperature, and then cooling its to the normal temperature.

Next the material must be protected against moisture by covering it with protective substances. Usually the following parameters of piezoelectric materials are determined: Q_V, g/cm^3 - density, ε - dielectric permeability, K^T_{33} - dielectric constant, tg δ, 10^{-4} - tangent of angle of dielectric loss, K_p, KV/mm - dielectric durability, k_p - coefficient of electromechanical coupling of radial vibration, t_c,°C - Curie temperature, N, kHz mm - frequency constant, Y^E_1, 10^{10}N/m^2 - elasticity modulus, k_{31} - coupling coefficient, k_{33} - coefficient of electromechanical coupling of thickness vibration, g_{31}, g_{33}, 10^{-3}Vm/N - piezoelectric modulus, d_{31}, d_{33}, 10^{-12}C/N - piezoelectric modulus, α - frequency change depending on the temperature change at the range of 0÷50°C.

2. Testing method of piezoelectric modulus

Existing testing methods of piezoelements during tests after of long standing warehousing of fuse mechanisms of shape charge projectiles, among other things, of WP-7, WP-7W and WP-9, consist in testing of so called piezoelectric modulus, ie. relation between deformation and obtained tension on the piezoelectric surface.

The determination of this modulus takes place on the stand which is equipped with the pressing device (hand press) and the loaded weight of 10 kg and the electrometer of entrance resistance with the parallel joint capacitor of the capacity C=1F assuring the unloading constant at least 10 s. The test consists in the placing of the piezoelectric transducer in the press and the loading it with the force of F=10 kG. Next the electrodes of the piezoelectric transducer are short-circuited and the circuit is opened, then the loading force is taken off violently. The electrometer shows the maximum value of voltage (U). The value of the piezoelectric modulus (d_{33}) results from the relation

$$d_{33} = 0.305 \cdot 10^{-4} \cdot \frac{C \cdot U}{F}\text{, cm/V}$$

3. The method of voltage measurement on piezoelectric

Choosing piezoelectric to produce the voltage and the current able to initiate the disruptive detonator in the fuse it is necessary to examine, what potential is cumulated on electrodes of the piezoelement under the influence of the mechanical impulse. The method should take into account real working conditions of the whole mechanism. That being so the measurement of voltage on piezoelectric under loading has to take place on the special test stand. Tested piezoelectrics are discs in shape of the diameter of 22 mm and 25 mm and thicknesses of 1.2÷3 mm.

This stand is equipped with the following equipments: the oscilloscope for the measurement and the registration of the high voltage courses in the time, the stand of fastening of piezoelement, drop device with weights of different masses in order to assure of the suitable impact energy, which deforms piezoelectric. The high voltage becoming on the piezoelement electrodes under impact of the weight, dropped from the definite height, is measured directly on the piezoelectric electrodes in real-time and the voltage course is registered on the oscilloscope. To lower the measuring range of the registering device the voltage divider, reducing the voltage 10 times, is used.

4. The test stand to examine piezoelements

Designed stand with the use of the Caste hammer to examine piezoelements (Fig. 1), intended to using them as the voltage generator in the fuse, consists of the aggregate of fastening of piezoelement, the guide, drop device of different weights and the voltage course register, measured on electrodes of piezoelectric. The guide is fastened over the fastening aggregate of piezoelement in this way that the axis of the piezoelement disc should be in the axis of dropped weight.

The piezoelectric disc is situated in the special isolated holder of the aggregate of fastening piezoelement and covered with the element, conical in shape, and which is impacted directly with the weight, guided exactly in the guide. The electrodes, on which the measurement of voltage takes place, are led out from the holder and from the cone. As a register of voltage courses the oscilloscope of the measuring range of 10 kV was used. The voltage courses were registered on the diskettes.

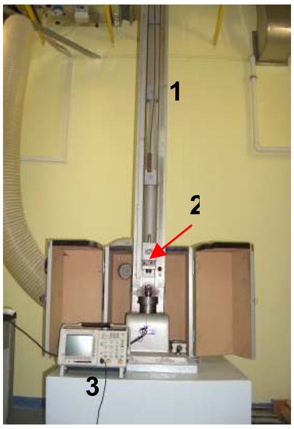

Fig. 1. The Caste hammer: 1 - the guide, 2 - the piezogenerator holder, 3 - the courses register, 4 - the weight

5. Research of chosen piezoelements

On the basis of the earlier researches [3÷6] it is known that the initiation of the electric spark disruptive detonator demands the energy of about 0.001 J, obtained from the piezoelement transducer. It results from calculations of the electric system that on the facings of the piezoelement transducer, it is required to obtain the voltage about 3 kV. The self-capacity of the piezoelements, prepared to use in the fuse, is of the order of 2 nF. Assuming that small electrical resistance of the disruptive detonator can be omitted, the required potential between facings was obtained, when the impact energy was 24.53 J (during the impact of the projectile with the speed of 5 m/s), i.e. it was considerably smaller than the energy which is obtained during the impact of the projectile with the speed of ~150÷230 m/s.

The obtaining of indispensable voltage and the initiation energy, the delay time of the initiation of the second warhead of the tandem shaped charge projectile, the required delay stability, the safety and the reliability and size limitations of the fuse, require the use of the electronic system with the energy transformation. This system lets accumulate and store the charge of the lower voltage and transform it to the demanding form in the determined time.

The electronic system of the energy accumulation is connected with the piezoelement. This system contains the capacitor battery cumulating the energy, the voltage limiter and the protection system against the destruction as a result of the electric breakdown of components. The capacitor battery is separated from the piezoelement by the diode, which protects against discharge of the capacitors after stopping of force action on the piezoelement or its mechanical destruction.

The forming system of the time delay of the energy transformation is powered by the capacitor battery. The control impulse, which closes circuit of unloading of the capacitor battery by the primary winding of the impulse transformer, is provided to the trip circuit after the determined time. The current, growing in primary winding of the impulse transformer, induces the magnetic flux, united with the secondary winding, causing the generating on it the induced voltage of determined magnitude.

On account of the accessible electronic components, the charge voltage of capacitors was limited to 400 V. Assuming that efficiency of energy transforming is 50%, the energy cumulated in the capacitors should not be less than 0.002 J. The energy consumption in the delay electronic system and voltage drop of 10%, resulted from that, should also be taken into account.

From reasons mentioned above the piezoelements were tested mostly in order to obtain the suitable voltage of capacitors charge of the component which initiates the disruptive detonator and accumulates enough quantity of the energy in the capacitors to initiate the disruptive detonator. The weights of 2 kg and 5 kg, dropped on the piezoelements from the height of 0.1÷2 m, were used in these tests. The examples of the voltage courses, obtained during the tests, are presented in Fig. 2 and 3, and the tests' results are shown in Tables 1÷4.

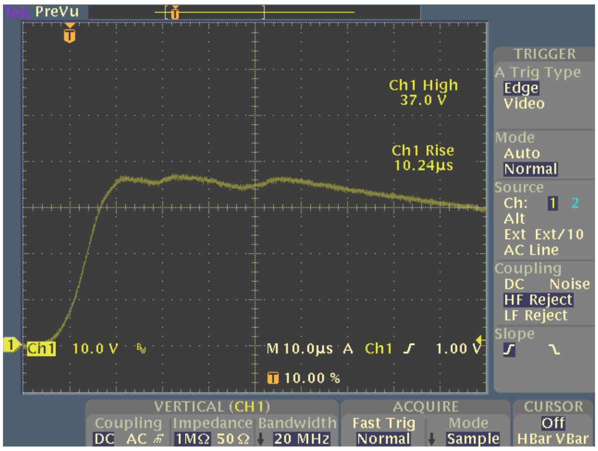

Fig. 2. The oscillograph of the voltage course tripped during the impact of piezoelement with the weight of 5 kg mass dropped from the height of 0.5 m (the measurement with the voltage limiter)

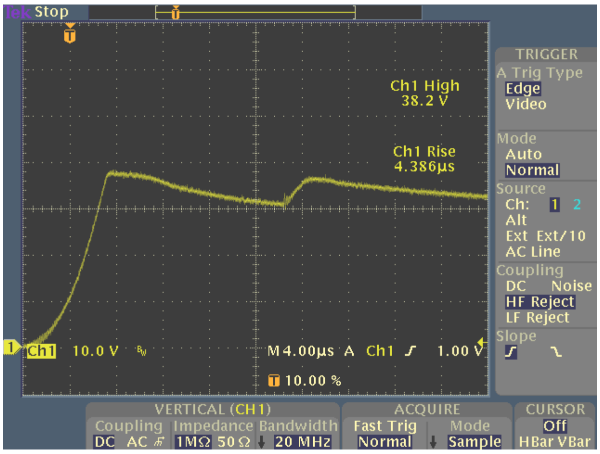

Fig. 3 The oscillograph of the voltage course tripped during the impact of piezoelement with the weight of 5 kg mass dropped from the height of 2 m with the registered secondary impact

The oscillographs show that after the impact of the weight into piezoelement the voltage on the capacitors of the system cumulating the energy grows very quickly to 400 V during 2.1÷12.8 µs. This time is sufficient to the quick initiation of the high voltage electro-spark detonator in the fuse of shaped charge projectile and this time of initiation is ~ 4 µs. The short initiation time of disruptive detonator, and after that - initiation time of the detonator and of the warhead together with the time of generation of shaped charge jet and its penetration into the armour is a guarantee that in this time the angle of penetration of the shaped charge jet into the armour will be equal to the angle of the impact of the shaped charge projectile into the armour. That is also a guarantee, that it will not be a ricocheting of the projectile or the change of its impact angle from the moment of contact of the projectile with the armour until the end of the piercing process of the armour.

There are several tops in the obtained graphs as a result of the secondary impacts of the weight into the piezoelement, and consequently its secondary deformations.

Table 1. The test results of the piezoelements (without the holes) with the diameter of 20 mm and of 1.2 mm thickness under dynamic loads

No.	Height of drop *h*, m	Mass of weight *m*, kg	Impact energy, *E*, J	Voltage on electrodes, *U*, V	Rise time, *t*, µs	Rise time to 400 V, *t*, µs	Remarks
1	0,1	2	1,96	600	24		without limiter
2	0,1	2	1,96	428	16		with limiter
3	0,1	2	1,96	600	24		without limiter
4	0,15	2	2,94	748	16	7,1	
5	0,2	2	3,92	840	16		without limiter
6	0,3	2	5,89	1050	16	6,4	with limiter
7	0,4	2	7,85	1006	15	5,6	with limiter
8	0,5	2	9,81	1250	15,2	5,4	with limiter

When the measuring system did not have the voltage limiter (Table 1), the voltage of 400 V on electrodes of the capacitor was obtained during the drop of the weight with the mass of 2 kg on the piezoelement (with the diameter of 20 mm and the thickness of 1.2 the mm) from the height of 0.1 m (the impact energy about 2 J).

However, when this energy was ~ 5 times greater (9.81 J during the drop of the weight from the height of 0.5 m) then the voltage generated on piezoelement was 3 times greater (1250 V). The lack of the voltage limiter did not permit to measure the voltage with the use of the greater impact energy in consideration of the danger of perforation and the damage of the capacitor cumulating the charge.

Accepting approximately the lineal dependence of voltage become on piezoelement on the impact energy of the piezoelement (Table 1), it can be assumed that the impact energy ~ 32 J (the drop of the weight of 2 kg from the height of ~ 1.6 m) will cause on the electrodes the obtainment of voltage 3 kV, indispensable to the initiation of the high voltage electro-spark disruptive detonator.

Table 2. The test results of the piezoelements (with the hole) with the diameter of 20 mm and of 1.2 mm thickness under dynamic loads

No.	Height of drop *h*, m	Mass of weight *m*, kg	Impact energy, *E*, J	Voltage on electrodes, *U*, V	Rise time, *t*, μs	Rise time to 400 V, *t*, μs	Remarks
1	0,1	2	1,96	424	15	12,8	without limiter
2	0,2	2	3,95	780	12,4	5,16	without limiter
3	0,4	2	7,85	1220	12,2	3,8	without limiter
4	0,8	2	15,70	1910	12,8	3,28	without limiter
5	1,59	2	31,20	2200		2,18	perforation of the capacitor at 2200 V
6	0,4	2	7,85	1060		2.1	
7	0,4	2	7,85	15		5.4	loading method
8	0,8	2	15,70	20,2		8,8	loading method
9	1,59	2	31,20	24,2		8,8	loading method

During the drop of the weight with the mass of 2 kg from the height of 1.59 m (the impact energy 31.2 J) on piezoelement with the hole, the voltage of 2200 V, obtained on the piezoelement surface, which caused breakdown of the capacitors cumulating the electric charge. In order to protect the electronic system against destruction, the further tests were carried out „with the loading method" in order to determine the time of loading of the capacitor to 400 V. It was obtained in the short time, i.e. ~ 8.8 μs, which is sufficient to the proper initiation of the electro-spark detonator in the shaped charge projectile.

Table 3. The test results of the piezoelements (with the hole) with the diameter of 25 mm and of 3 mm thickness under dynamic loads

No.	Height of drop *h*, m	Mass of weight *m*, kg	Impact energy, *E*, J	Voltage on electrodes, *U*, V	Rise time, *t*, μs
1	0,5	2	9,81	176	16
2	1	2	19,76	312	14
3	1	2	19,62	296	16
4	1,95	2	38,26	374	14,6
5	1,59	5	77,99	372	14,6
6	1,95	5	95,65	394	9

From Table 3 results that on the piezoelement of the diameter of 25 mm and the thickness of 3 mm with the central hole during the impact of the weight of 2 kg from the height of 1.95 m (the impact energy of 38.26 J) the voltage obtained on the capacitor was ~ 400 V. However, using the weight of 5 kg during the drop from the height of 1.95 m, and consequently of the higher impact energy (95.65 J), the shorter rise time (9 μs) of voltage of 400 V on the capacitors was obtained. This energy is much lower (345 times) than the impact energy of the PG-7 projectile into the armour (speed of 150 m/s), and the impact energy of the integrated fuse (mass of 0.125 kg impacted into the piezoelement) is minimum 14 times lower, so it can be supposed that in such case the rise time of voltage will be even lower than in the conditions of the laboratory tests, therefore these piezoelements can be useful in the fuses of the shaped charge projectiles.

Table 4. The test results of the piezoelements (with the hole or without the hole) with the diameter of 25 mm and of 3 mm thickness under dynamic loads

No.	Height of drop *h*, m	Mass of weight *m*, kg	Impact energy, *E*, J	Voltage on electrodes, *U*, V	Rise time, *t*, μs	Rise time to 400 V, *t*, ms
1	0,5	5	24,53	380	6	without hole
2	2	5	98,81	384	4.6	without hole
3	0,5	5	24,53	370	10.2	with hole
4	2	5	98,10	382	4.4	with hole
5	2	5	98,10	300	20	with hole destruction of the sample

During dropping down of the weight with the mass of 5 kg on the piezoelement and with the diameter of 25 mm and thickness of 3 mm with the central hole and without them (Table 4) the electric charge, generating the voltage of 400 V on the capacitors, was accumulated within the time of 4.4÷10.2 μs in dependence on the impact energy of 24.53÷98.1 J. From these tests results that the accumulation of the necessary energy on the capacitor occurs during the impact of this weight dropping down from the height of 0.5 m (the impact energy of 24.53 J).

The load of piezoelements in the fuse of the shaped charge projectile during the impact into the armour can be compared with the load of the piezoelement in laboratory conditions presented above. For example, the maximum kinetic energy of the shaped charge projectile (fired from RPG-7 launcher, with the speed of >150 m/s at the distance of 30 m, and with armed fuse) while the perpendicular impact into the armour ($\alpha=0^o$ to normal to the armour) carries out >33 kJ and it is 300 times higher than the impact energy of the piezoelement with the use of the weight during the laboratory tests. In this case so large reserve of the energy guarantees the generation of indispensable voltage on the piezoelement even in the case of the impact of the projectile, for example, at the large angle $\alpha=60^o$ from normal to the armour, when the impact energy causing the compression of the piezoelement will be considerably less than 33 kJ. Therefore, the piezoelements accepted to test can be useful as the electrical energy generators in the fuses (to initiate the electro-spark disruptive detonators) of the one-warhead and tandem shaped charge projectiles.

6. Conclusions

The tests carried out showed that:

1. In the shaped charge projectiles, especially tandem projectiles, with the fuses containing the piezoelements the specially designed electronic system should be used to:
   - accumulate and store the electric charge of the lower voltage, e.g. 400 V,
   - transform the electric charge into desirable shape,

- trip the voltage and obtain the suitable quantity of the energy to initiate the electro-spark disruptive detonators within the time of the order of the several microseconds.

1. Piezoelements during impact with the weight:
   - produce the required voltage 400 V in case of the use of much lower impact energy (~ 100 J) than the energy that occurs during the perpendicular impact, e.g. the impact of the RPG-7 projectiles into the armour (>33 kJ) or in case of the use of the integrated fuse with piezoelement (min. 1.4 kJ),
   - deliver the sufficient energy (0.002 J) to initiate typical high voltage electro-spark disruptive detonators (),

3. Tested piezoelements with the holes and without them have suitable electric and mechanical proprieties, suitable shapes and small sizes, now then they can be used in the fuses of the one-warhead and tandem shaped charge projectiles.

Bibliography

1. Derecki S., Blinds E.: *Bases of designing of artillery fuses*. Military University of Technology, Warszawa, 1983.
2. Perełkiewicz A., Wąsikowski P.: *The use of piezoelectrics in armament technology*. Military Institute of Armament Technology, Zielonka, 1975.
3. Wiśniewski A., Kowalewski J.: *The problems of using of different kinds of fuses in tandem shaped charges.* Problems of Armament Technology, vol. **82**, 2002, pp. 69÷82.
4. Kowalewski J., Wiśniewski A.: *The usefulness of different kinds of electric detonators in fuses of shaped charges*. Problems of Armament Technology, vol. **86**, 2003, pp. 35÷44.
5. Wiśniewski A., Kowalewski J. Podgórzak P.: *Research and constructional works of the integrated piezoelectric fuse of the shaped charge ammunition*. Military Institute of Armament Technology, Zielonka, 2001, not published.
6. Wiśniewski A., Kowalewski J., Podgórzak P., Jarzemski J.: *Research and constructional works and the tests at producer's place of the integrated piezoelectric fuse of the shaped charge ammunition*. Military Institute of Armament Technology, Zielonka, 2003. not published

Generatory piezoelektryczne w zapalnikach pocisków kumulacyjnych

Streszczenie

Opisano skład, parametry i wymagania stawiane piezoelementom stosowanym w technice uzbrojenia. Przedstawiono wyniki badań piezoelementów (krążki o grubościach 1.2÷3 mm i średnicach 20÷25 mm z otworami i bez otworów) jako generatorów napięcia w zapalnikach pocisków kumulacyjnych. Wyznaczono parametry elektryczne piezoelementów podczas obciążeń dynamicznych w wyniku spadku na nie ciężarków o masie 2 kg i 5 kg. Uzyskano generowaną energię elektryczną, która jest wystarczająca (min 0.002 J) do pobudzenia typowych spłonek elektroiskrowych, stosowanych w zapalnikach tych pocisków, w odpowiednio krótkim czasie (4.4÷10.2 μs).