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# SPARKLER PIEZOCERAMICS

## *General Information*

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## 1. Introduction :

Piezoelectricity from the Greek word "piezo" means pressure electricity. It is the property of certain crystalline substances to generate electrical charges on the application of mechanical stress. Conversely, if the crystal is placed in an electric field, it will experience a mechanical strain. Such materials are useful as transducer elements for transducting electrical energy into mechanical energy and vice versa. When an AC voltage is applied, it will cause it to vibrate and thus generate mechanical waves at the same frequency of the input AC field. Similarly, it would sense the input mechanical vibrations and produce the proportional charge at the matching frequency of the mechanical input.

Quartz is a well known single crystal material depicting such piezoelectric effects. However, strong piezoelectric effects can be induced in polycrystalline Lead Zirconate Titanate based ferroelectric ceramic materials. These materials are represented by the formula $ABO_3$ , Perovskite crystalline structure wherein A-site denotes large divalent metal ion such as Pb and B-site denotes smaller tetravalent ion such as Ti or Zr. This class of ceramic materials have several advantages over single crystals including : higher piezoelectric coeffs, ease of fabrication into components of any shape and size, mechanically hard and robust, chemically inert and completely unaffected by atmospheric humidity. In contrast, single crystals must be cut along certain crystallographic direction, thus limiting their possible geometrical shapes.

Sparkler manufactures piezoelectric ceramics based on the solid solutions of Lead Titanate ($PbTiO_3$) and Lead Zirconate ($PbZrO_3$) which are popularly known as PZT. The chemistry of $ABO_3$ perovskite in PZT compositions permit wide modifications by way of isovalent substituents or donor dopants at A or B sites. For example, A-sites modifications can be done by alkaline earths or rare earths cations whereas B-sites with trivalent or pentavalent cations of approximately matching ionic radii; thus allowing some tailor made properties of these class of materials. These are available in several grades, distinguished by their electrical and physical properties for well defined requirements.

## 2. PZT Manufacturing Process

These are manufactured from their respective oxides/carbonates of Pb, Zr, Ti, rare earths, alkaline earths, transition metals etc. to the specified compositions well tuned to the end properties, by mixing and solid state reactions. Typical production flowchart is given below :

WEIGHING RAW MATERIALS

⇓

MIXING - BALL MILL

⇓

OVEN DRY

⇓

SOLID STATE REACTION UPTO 1200 DEG. C.

⇓

MICRO-PULVERISATION TO A PRE-DETERMINED PARTICLE SIZE RANGE

⇓

FORMING PROCESSES

⇓

SINTERING 1300 DEG. C. - QC FOR SINTERABILITY

⇓

GRINDING / LAPPING / SLICING TO THE REQUIRED DIMENSIONS

⇓

FIRED - ON SILVER ELECTRODES

⇓

POLING. HIGH DC FIELDS; TIME-TEMP PROFILE

⇓

TESTING

## 3. Applications

These materials are available in a variety of shapes and sizes such as disks, plates, bars, rings, rods, tubes, etc. Some of the typical applications are:

* High Voltage Generators for gas lighters
* Fuzes for explosives
* Ultrasonic cleaners
* Ultrasonic welders
* Ultrasonic atomisers
* Nebulisers
* Strain and excitation gauges
* Accelerometers
* NDT transducers.
* Flowmeters
* Dynamic force and pressure measurement
* SONAR
* Deepwater hydrophones
* Piezoelectric actuators/translators

## 4. Definition of Terms and Relationships

**Polarisation and charge coefficients:**

With piezoelectric ceramics, the relationship between the applied stress and the resulting responses depend upon:

- Piezoelectric properties of the ceramic.
- Size and shape of the element, and
- Direction of the electrical and mechanical vector quantities.

To identify directions in a piezoelectric element, three axes termed as 1,2 and 3; which are analogous to the classical three dimensional orthogonal set of axes X, Y and Z are used. Material properties along the 1 and 2 axes are identical to each other but different from those along the 3 axis. For maintaining simplicity, references are made only to the 3 and 1 directions. The poling or 3 - axis is invariably taken parallel to the direction of polarisation within the ceramic ( Fig 1(A) ) . The polar axis is induced during the manufacturing process by treatment with a high voltage DC field applied between the pair of electroded faces to align the domains of the material in the direction of the field.

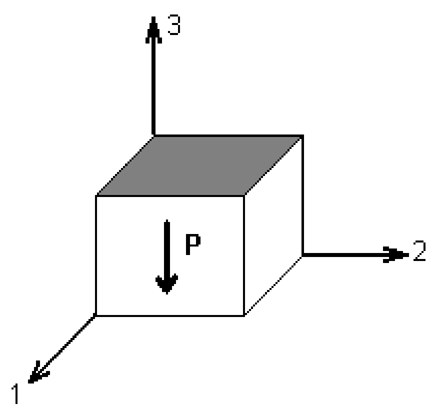



**FIG 1(A)**

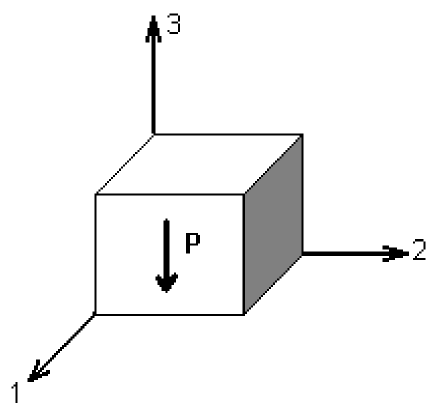



**FIG 1 (B)**

The polarisation vector P is represented by an arrow pointing from the positive to the negative poling electrode. In shear mode operations, the poling electrodes are later removed and replaced by a set of electrodes on the second pair of the faces. The 3-axis is not altered, but it becomes parallel to the new electrode faces as seen on the finished element ( Fig 1(B) ).

**Piezoelectric charge coefficient (d constant):**

The piezoelectric d constant is a measure of the charge density per unit stress or the strain per unit field

$$d_{ik} = \frac{\text{Coulombs/meter}^2}{\text{Newtons/meter}^2} = \frac{\text{Coulombs}}{\text{Newton}}$$

$$d_{ik} = \frac{\text{meter/meter}}{\text{volt/meter}} = \frac{\text{meter}}{\text{volt}}$$

Piezoelectric coefficients with double subscripts link electrical and mechanical quantities. The first subscript gives the direction of the electrical field associated with the voltage applied or the charge or the voltage produced. The second subscript gives the direction of mechanical stress or the strain.

The piezoelectric charge coefficient $d_{33}$ applies when the force in the 3-direction ( along the polarisation axis ) and is impressed on the same surface on which the charge is collected ( Fig 2(A) ) , whereas $d_{31}$ applies when the charge is collected on the same surface as before but force is applied at right angles to the poling axis (Fig 2( B) ).

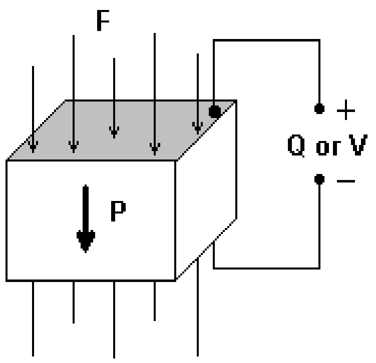



**FIG 2 (A)**

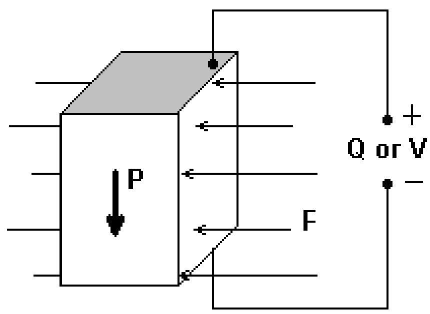



**FIG 2 (B)**

**Piezoelectric Voltage coefficient ( g constant):**

The g coefficient is a measure of the field per unit stress or strain per unit charge density.

$$g_{ik} = \frac{\text{Volt/meter}}{\text{Newton/meter}^2} = \frac{\text{Volt - meter}}{\text{Newton}}$$

$$g_{ik} = \frac{\text{meter/meter}}{\text{Coulombs/meter}^2} = \frac{\text{meter}^2}{\text{Coulomb}}$$

Output voltage is applied by multiplying the calculated electric field by the thickness of the ceramic between the electrodes. The first subscript indicates the direction of the generatedvoltage and the second indicates the the direction of the force. A "33" subscript signifies that the electrical field generated and the mechanical stress are both along the polarisation ( Fig 2(a) ). A "31" subscript signifies that the pressure is applied at right angles to the polarisation axis but the voltage appears on the same electrodes as in the "33" case ( Fig 2(b) ).

**Relative Dielectric Constant :**

$K^T_3$ expresses the relative dielectric constant of the material relative to that of vacuum in the 3 direction. Multiplying this by $\varepsilon_o$, the dielectric constant of free space yields the absolute dielectric constant ($\varepsilon_o = 8.85 \times 10^{-12}$ farads/meter). The superscript T applies to the mechanically free condition. $K^T_3$ therefore, expresses the relative dielectric constant measured in the polar direction under mechanically free condition. It is generally measured at 1 kHz, well below the mechanical resonance of the specimen.

**Relationship Between g and d coefficients**:

At frequencies far from resonance effects, piezoelectric ceramic transducers are fundamentally capacitors. Consequently, the voltage coefficient $g_{ik}$ are related to the charge coefficient $d_{ik}$ by the dielectric constant $K_i$ , as in a capacitor the voltage V is related to charge Q by the capacitance C.

$$Q = C \, . \, V$$

$$d_{33} = K^T_3 . \ \varepsilon_o \ . \ g_{33}$$

$$d_{31} = K^T_3 . \ \varepsilon_o \ . \ d_{31}$$

**Coupling Coefficients**:

Sometimes also referred as electromechanical coupling coefficients, these describe the conversion of energy by the ceramic element from electrical to mechanical form or vice-versa.

$$k = \frac{\text{Mechanical Energy stored}}{\text{Electrical Energy applied}}$$

$$k = \frac{\text{Electrical Energy stored}}{\text{Mechanical Energy applied}} .$$

Subscripts denote the relative directions of the electrical and mechanical quantities and the kind of motion involved. $\mathbf{k_p}$ signifies the coupling in a thin round disc polarised in radial expansion and contraction, whereas $\mathbf{k_{33}}$ is appropriate for a long thin bar or rod, electroded on the ends, poled lengthwise and vibrating in simple length expansion or contraction. $\mathbf{k_{31}}$ relates to a thin long bar, electroded on a pair of long faces, poled in thickness and vibrating in the longitudinal dimension. Since these coefficients are energy ratios, they are dimensionless.

**Young's Modulus**:

The mechanical stiffness property of a piezoelectric ceramic material is expressed as the ratio of stress to strain. Because mechanical stressing of the ceramic produces an electrical response which opposes the resultant strain, the effective Young's modulus with electrodes short circuited is lower than the electrodes open circuited. Furthermore, the stiffness is different in the 3 - direction from that in the 1 or 2 direction. Therefore, in expressing mechanical quantities both direction and electrical conditions must be specified.

$\mathbf{Y^D_{33}}$ is the equivalent with the electrodes open circuited in the 3 direction whereas $\mathbf{Y^D_{11}}$ is the modulus in the 1 or 2 direction. The superscript D points out the open circuit condition. The inverse of Young's modulus Y is the elastic compliance 's'.

**Dissipation Factor or tan $\delta$** :

This is also frequently called loss tangent and is a measure of the dielectric losses in the material, expressed as the tangent of the loss angle or the ratio of resistance to reactance of a parallel equivalent circuit of the ceramic element. It is measured directly at 1 kHz using LCR Bridge.

**Curie Point:**

It is the temperature at which the crystal structure of the material changes from a piezoelectric to non-piezoelectric state. It is also the temperature at which the dielectric constant peaks. Each ceramic composition has its characteristic Curie Point and in use the operating temperature must be kept substantially below the Curie Point.

**Aging Rate:**

The change or aging of the material parameters that occurs after the poling of the ceramic is called aging rate. The aging is a logarithmic function of time. The aging rate defines change in the relevant parameters per decade of time, for example 1 - 10 days, 10 - 100 days etc. The most parameters that age with time are: $K^T_3$, $k_p$, Freq. constant, $Q_m$, etc.

**Mechanical Quality Factor ($Q_m$) :**

The mechanical Q is a dimensionless number which gives the quality of the ceramic as a harmonic oscillator. It is the reciprocal of the damping factor. The electrical analogue ( in an equivalent electric series circuit, representing the mechanical vibrating resonance system) is the ratio of reactance to resistance. The shape of the part affects the value.

**Frequency Constants:**

The frequency constant, N, is the product of the resonance frequency and the linear dimension governing the resonance. It is also equal to half the sound velocity in the same direction. The constant can be used to calculate the resonant frequency at which an element would operate.

$N_p$ : Planar mode of thin disc

$N_t$ : Thickness mode of thin plate.

To calculate the resonant frequency of a given element in kHz, divide the frequency constant by the controlling dimensions as shown below.

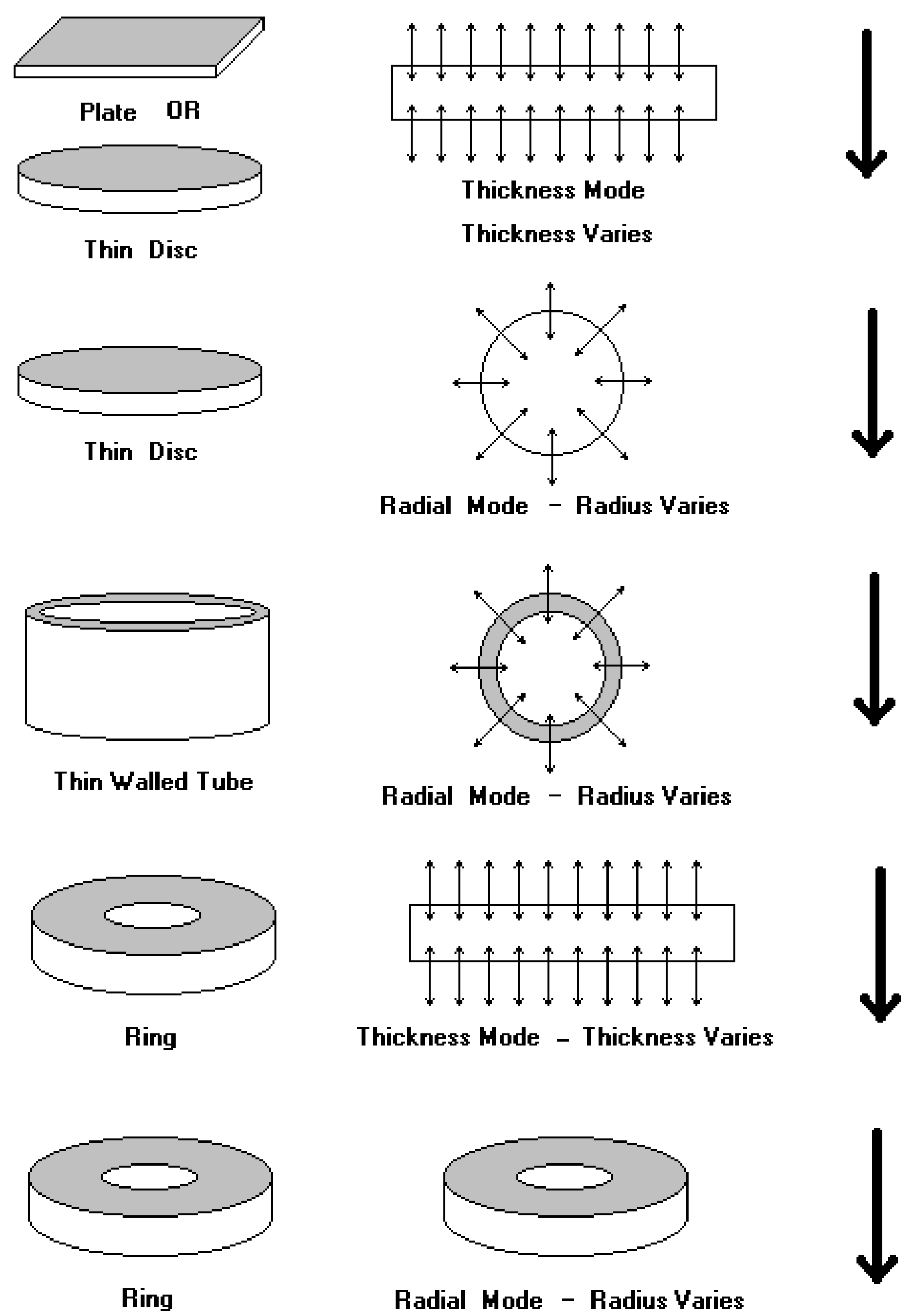
$$f_r = \frac{\text{Frequency Constant (Hz-m)}}{\text{Dim. (L,T,D) in m.}}$$

## 5. Vibrational Modes in Common Transducer Configurations

**Modes of vibration**:

Different shapes are capable of different modes of vibration - each having a natural resonant frequency corresponding to the minimum impedance condition and each characterised by a frequency constant as previously discussed. The various modes of vibration in the transducers are shown below:

| SHAPE AND ELECTRODE POSITION | MODE AND PRIMARY MOTION | DIRECTION OF POLARISATION |
|---|---|---|



## 6. Connections

Usually fired-on silver electrodes are provided on the ceramic body. The electrode quality is best defined by adhesion , cosmetic appearance and conductivity and the adhesion is tested from time to time.

Electrical contact to the elements may be made by soldering, bonding or clamping wire to the silver electrode. Suggested soldering procedure for lead soldering is given below:

**Soldering Iron** : About 15 Watts with copper tip.

**Soldering Iron Temp**. : 250 to 300 deg C.

**Preferred Solder** : 62 % tin, 36 % lead and 2 % silver.

**Flux** : Non corrosive rosin.

**Soldering wire dia.** : 0.3 mm or fine stranded flex or 2.5 mm dia. solid test wire.

**Soldering Time** : Maximum 5 seconds. Soldering time should be kept as short as possible; otherwise disk or plate may be partly depoled to an extent depending on the temperature and time exposure.

**Soldering Method** :

(a) Preheat soldering iron for about 10 - 15 minutes.

(b) The electrode surface should be made free from dust oil or grease and mildly abraded with a fine abrasive paper.

(c) Flux both ceramic silver and the test wire.

(d) Pretin the ceramic area and the wire avoiding excessive flow of the solder. Place the wire in the electrode area with mild pressure and start heating the lead wire about 2-3 mm above the silver electrode until the solder flows onto the surface. Hold lead stationary for about 5 seconds to allow the solder to solidify.

It would be preferred to make electrical contact at the vibration mode in the resonant devices. In some applications, pressure contact may serve the purpose.

## 7. Literature

For further information , the following literature is suggested: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