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PIEZOELECTRIC SENSORS

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***Abstract*- This paper reviews the current trends and historical development of piezoelectric sensors and sensor materials technology. Piezoelectric elements are used to construct transducers for a vast number of differentapplications. Piezoelectric materials generate an electrical charge in response to mechanicalmovement, or vice versa, produce mechanical movement in response to electrical input.**

This report discusses the basic concepts of piezoelectric transducers used as sensors and two circuits commonly used for signal conditioning their output. A piezoelectric sensor is a device that uses the piezoelectric effect, to measure changes in pressure, acceleration, strain or force by converting them to an electrical charge. The prefix *piezo-* is Greek for 'press' or 'squeeze'. Depending on how a piezoelectric material is cut, three main modes of operation can be distinguished: transverse, longitudinal, and shear. A piezoelectric transducer has very high DC output impedance and can be modeled as a proportional voltage source and filter network. The voltage *V* at the source is directly proportional to the applied force, pressure, or strain.[7] The output signal is then related to this mechanical force as if it had passed through the equivalent circuit.

***Index Terms*- piezoelectricity, sensors, PZT, piezoelectric crystals,compsites, connectivity**

I. INTRODUCTION

The word piezo comes from the Greek word piezein, meaning to press or squeeze.

Piezoelectricity refers to the generation of electricity or of electric polarity in dielectric crystalswhen subjected to mechanical stress and conversely, the generation of stress in such crystals inresponse to an applied voltage. In 1880, the Curie brothers found that quartz changed itsdimensions when subjected to an electrical field and generated electrical charge when pressurewas applied. Since that time, researchers have found piezoelectric properties in hundreds ofceramic and plastic materials.

Many piezoelectric materials also show electrical effects due to temperature changes andradiation. This report is limited to piezoelectricity. The basic theory behind piezoelectricity is based on the electrical dipole. At the molecular level,the structure of a piezoelectric material is typically an ionic bonded crystal. At rest, the dipolesformed by the positive and negative ions cancel each other due to the symmetry of the crystalstructure, and an electric field is not observed. When stressed, the crystal deforms, symmetry islost, and a net dipole moment is created. This dipole moment forms an electric field across thecrystal.In this manner, the materials generate an electrical charge that is proportional to the pressureapplied. If a reciprocating force is applied, an ac voltage is seen across the terminals of thedevice. Piezoelectric sensors are not suited for static or dc applications because the electricalcharge produced decays with time due to the internal impedance of the sensor and the inputimpedance of the signal conditioning circuits. However, they are well suited for dynamic or acapplications.

A piezoelectric sensor is modeled as a charge source with a shunt capacitor and resistor, or as avoltage source with a series capacitor and resistor

The charge produced depends on the piezoelectric constant ofthe device. The capacitance is determined by the area, the width, and the dielectric constant ofthe material

(I)Determination and Classification of Piezoelectric Sensors

This is devoted to piezoelectric transducers; therefore, it is necessary toagree on terminology. Transducers will transform one physical size or one type ofinformation to another physical size or another type of information. Therefore, asensor can be called a pressure transducer in an electrical signal, or a transducer ofelectric voltage from one level of voltage to another level (electric transformer).

In technical language there is also the concept “sensor”, which is equivalent tothe concept “primary transducer.”Piezoelectric transducers contain crystals or structures which electrosize underthe influence of mechanical pressure (a "straight-line piezoeffect") and deformedstructures in an electric field called "return piezoeffect."A feature of the piezoeffect is sign sensitivity, when a charged sign changes or when compression is replaced; this sign stretching and changing produces a directional field change. Many crystal substances possess piezoelectric properties: quartz, turmalin, niobium,lithium, segnet salt, etc. Artificial polycrystalline materials are also producedwhich polarize in the electrical field (piezoelectric ceramics), e.g., titanium barium, titanium lead, zirconium lead, etc. Piezoelectric transducers are used for measuring mechanical parameters (effort,pressure, acceleration, weight, angular speed, moments, deformations, etc.), thermalsizes (temperature, expense, vacuum, electric parameters, etc.) and for structurecontrol, gas concentration, humidity, and micro weights [28]. For accuracy, thesedevices in many cases surpass transducers based on other physical resolutionprinciples.Piezoelectric sensors can be divided into two large classes depending on theirbasic physical effects:

- Sensors in the first class use a straight-line piezoeffect. They are used formeasuring linear and vibrating accelerations, dynamic and quasistatic pressureand efforts, as well as parameters of sound and ultrasonic fields, etc.
- A second but no less extensive class of sensors concerns the so-called resonantpiezotransducerswhich use the return piezoeffect. They are resonantsensors from piezoelectric resonators, and they can also produce straight-linepiezoeffects. (These are resonant piezoelectric transformer sensors.) In addition,other physical effects can be used, e.g., tensosensitivity, acoustosensitivity, thermosensitivity, etc., allow utilization for measurement of static and/or dynamicpressure and efforts, linear and vibrating accelerations, concentration of gassubstances, viscosity, inclination corners, etc.

The largest class of piezoceramic sensors can be classified as follows:

1. Sensors on applied materials:
-Monocrystal materials (quartz, niobium lithium, etc.)
- Polycrystalline materials (piezoceramic)
2. by fluctuations:
– On the linear size
– On the radial
– On curving
– On torsion (rotation?)
– On the shift (shear modes)
– On surface acoustic waves
– On a combined configuration
3. by the physical effects:
– Thermosensitivity
– Tensosensitivity
– Acoustosensitivity
– Gyrosensitivity
– Contact (using contact rigidity and the actual contact area, etc.)
– Domain dissipative, etc.
4. by the quantity of the piezoelements:
– Monoelement
– Bimorph (symmetric or asymmetric)
– Threemorph, etc.
5. by destination:
– For measurement of dynamic pressure and efforts
– For measurement of linear accelerations
– For measurement of vibration parameters
– For measurement of static pressure and efforts
– For measurement of blow parameters
– For measurement of sound pressure
– For humidity measurement
– For viscosity measurement
– For hydroacoustics
– For gyroscopes
– For gas analyzers
– For temperature measurement
– For contact rigidity measurement
– For measurement of the actual area of contact
– For magnetic size measurement
– For optics measurement
– For micromoving measurement
– For dust concentration measurement
– In ultrasonic technology
– In electroacoustics
– In automatics devices
– In communication
– In electronic techniques and radio engineering
– In medicine:
– For ultrasonic tomographs
– For pulse measurement
– For tone measurement by Korotkov
– For urology
– For ophthalmology and others.

B.Properties and Descriptions of Piezomaterials

The piezoeffect's physical nature can be shown with quartz, the most commonpiezoelectric crysta shows the basic crystal quartz cell structure.

The cell as a whole is electrically neutral; however, it is possible to allocatethree directions which pass through the center and two different uniter ion polars. The polars are called electric axes or axes X, with polarization vectors *P*1, *P*2,and *P*3.

If force *F*xin regular intervals is distributed on the side, a perpendicular axisX results; the broken electric neutrality of the elementary cell is enclosed in aquartz crystal along the axis. As a result, thepolarization vector appears equally effective, and there are corresponding polarizing charges on the sides. Here the vector projection sum is equal to zero, for*P*2Y D *P*3Y.Polarizing charge formation on the sides and perpendicular axes X, with force on axis X, is called the *longitudinal piezoeffect*.

Mechanical pressure enclosed along one of the Y xes is called *mechanicalaxes*. The geometrical sum of vectors *P*2 and *P*3 on a Y axis projection is equal to zero. When the Y axis piezoelement sides are perpendicular, charges are not formed. However, vectors *P*2 and *P*3 on the X axis projection sum are not equal tovector *P*1. As a result, the bottom side forms positive charges and the top sideforms negative charges. The formation of side charges, perpendicular to the loadedsides, is called *transverse*.When uniformly loaded from different directions, as for example in hydrostaticcompression, the quartz crystal remains electrically neutral. When loading Z axisperpendicular to axes X and Y with a crystal optical axis, the quartz crystal remainselectrically neutral. When the geometrical sum of vectors *P*2 and *P*3 on X axis projections is equal tovector *P*1 directed on X axes and on the sides of perpendicular X axes, the charge does not increase. However, when vectors *P*2 and *P*3 on the Y axis are not equalprojections and the Y axis sides are perpendicular, there is a charge.

When considering the physical nature, the piezoeffect shows that intense quartzcharges can rise between three side steams. The polarizing quartz charge is a vectorthat can be described by three components. The intense condition is characterizedas a second-rank tensor with nine components.

A piezoelectric module defining charge dependences from an intense conditionis a third-rank tensor; it is defined by 27 components.

However, tensor mechanical pressure contains only six independent components,which are designated as _11 D _1, _22 D _2, _33 D _3, _23 D _4, _13 D _5, and_12 D _6.

With the piezo-module table, it is possible to calculate charge density on all three sides after any pressure.

The basic advantages of quartz are great hardness, insolubility in water, stabilitywhen exposed to some acids, small thermal expansion, extremely good mechanicalquality (105–106), and parameter stability (10_3–10_5%).However, the electromechanical communication coefficient of quartz is approximatelyten times greater, and the piezo-modules are less than the corresponding piezoceramic parameters. In addition, quartz has low dielectric permeability andits own plate capacity; therefore, the shunting capacity of the cable and entrancechains in the measuring devices considerably reduces transducer sensitivity. Theimportant constraining factor in pressure quartz transducer utilization is its highcost and production difficulties.

The most utilized piezoelectric materials are piezoceramics, which appearedonly in the early 1960s when industrial synthesized natural piezoelectric materialslike quartz were mastered. With high-sensitivity segnet salt, turmalin and others,the mechanical durability was raised by temperature stability. Now in domesticand foreign literature, many publications speak about piezoceramic elementapplications, so they have been introduced to the industry.

Transducer Research Methods

Piezoceramics possess many advantages.

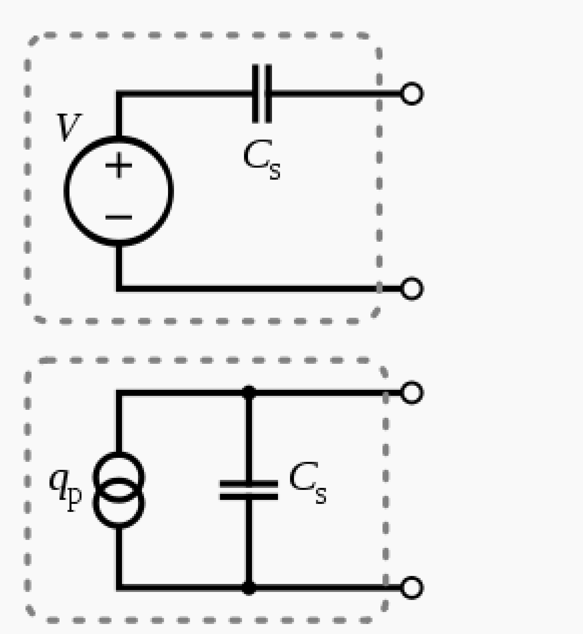
Piezoceramic elements are rather economical, and they possess high radiatingfirmness in various active environments.Onlyhydre fluoric acid is capable of havinga destroying effect on piezoceramics; thus, piezoceramic devices can be utilized inmany difficult chemical situations.When compared with quartz, piezoceramic material has a low Curie TK pointvalue. For quartz this TK value D 570ıC, while for piezoceramics with titaniumbarium the TK value is 100–200ıC. There are high-temperature piezoceramicmaterials with Curie points within quartz matter. Hence, some piezoceramicmadeelements of CTC (PZT) do not lose working capacity at temperatures of300–400ıC, e.g., CTC-21 has TK D 400ıC. With cobalt, they are able to maintaina temperature of 700ıC andmore.The wide temperature ranges allow piezoceramic sensor usage from 400 to270ıC. Moreover, special transducers can be used for pressure measurement ininternal combustion engine cylinders, where temperatures fluctuate from normal toC1;600ıC.Piezoceramic sensors with decimals increase the measurement range usage.Piezoceramic sensors have high resolution; as an illustration, if a 100 T locomotiveis put on piezoelectric scales and the measurement range on the panel of thecharging amplifier is switched, it is possible to measure the additional weight of apencil put on the locomotive’s footboard.Piezoelectric transducers can maintain high pressures, measuring pressures to10,000 bar. They have great rigidity; that is especially important when manufacturingmeasurement dynamometers in a wide range of frequencies.

3. Sensor [Physical Size] Descriptions;

Basic sensor characteristics are a range of measurements, sensitivity, a thresholdof reaction (sensitivity), errors, time of indication establishment, and reliability

1. *Range of measurements* – measured size values in which we normalize supposederrors. This range is subject to measurement limits, greatest and least values ofthe measurement range.
2. *Sensitivity* S – change relationship between an output sensor Y signal to thechange which caused it on the measured size X: S D Y=X.
3. *Errors* – with series graduation of the same sensors it appears that the characteristicsdiffer from each other. In the measuring transducer passport, some averagecharacteristics “nominal” are observed. Differences between the “nominal passport”and the real sensor characteristics are considered its “error.”
4. *Reliability* – transducer’s ability to keep characteristics in certain limits duringthe established time interval, under set operation conditions.

A detailed model includes the effects of the sensor's mechanical construction and other non-idealities.The inductance L_m is due to the seismic mass and inertia of the sensor itself. C_e is inversely proportional to the mechanical elasticity of the sensor. C_0 represents the static capacitance of the transducer, resulting from an inertial mass of infinite size.R_i is the insulation leakage resistance of the transducer element. If the sensor is connected to a load resistance, this also acts in parallel with the insulation resistance, both increasing the high-pass cutoff frequency.



In the flat region, the sensor can be modeled as a voltage source in series with the sensor's capacitance or a charge source in parallel with the capacitance

For use as a sensor, the flat region of the frequency response plot is typically used, between the high-pass cutoff and the resonant peak. The load and leakage resistance need to be large enough that low frequencies of interest are not lost. A simplified equivalent circuit model can be used in this region, in which C_s represents the capacitance of the sensor surface itself, determined by the standard formula for capacitance of parallel plates. It can also be modeled as a charge source in parallel with the source capacitance, with the charge directly proportional to the applied force, as above.

Based on piezoelectric technology various physical quantities can be measured; the most common are pressure and acceleration. For pressure sensors, a thin membrane and a massive base is used, ensuring that an applied pressure specifically loads the elements in one direction. For accelerometers, a seismic mass is attached to the crystal elements. When the accelerometer experiences a motion, the invariant seismic mass loads the elements according to Newton's second law of motion $F = ma$.The main difference in the working principle between these two cases is the way forces are applied to the sensing elements. In a pressure sensor a thin membrane is used to transfer the force to the elements, while in accelerometers the forces are applied by an attached seismic mass.Sensors often tend to be sensitive to more than one physical quantity. Pressure sensors show false signal when they are exposed to vibrations. Sophisticated pressure sensors therefore use acceleration compensation elements in addition to the pressure sensing elements. By carefully matching those elements, the acceleration signal (released from the compensation element) is subtracted from the combined signal of pressure and acceleration to derive the true pressure information.Vibration sensors can also be used to harvest otherwise wasted energy from mechanical vibrations. This is accomplished by using piezoelectric materials to convert mechanical strain into usable electrical energy.Two main groups of materials are used for piezoelectric sensors: piezoelectric ceramics and single crystal materials. The ceramic materials (such as PZT ceramic) have a piezoelectric constant/sensitivity that is roughly two orders of magnitude higher than those of the natural single crystal materials and can be produced by inexpensive sintering processes. The piezoeffect in piezoceramics is "trained", so their high sensitivity degrades over time. This degradation is highly correlated with increased temperature. The less-sensitive, natural, single-crystal materials (gallium phosphate, quartz, tourmaline) have a higher – when carefully handled, almost unlimited – long term stability. There are also new single-crystal materials commercially available such as Lead Magnesium Niobate-Lead Titanate (PMN-PT). These materials offer improved sensitivity over PZT but have a lower maximum operating temperatureand are currently more expensive to manufacture.

CONCLUSION

In this paper you have read about the basics of a piezeoelectric material and sensors. After decades of research and development, piezoelectric materials have been applied in a wide range of applications, ranging from household appliances to industrial equipments. In areas such as precision and acoustic engineering, piezoelectric material is well accepted to be one of the leading functional materials. Today, due to the high demand, particularly from the electronic, energy, and biomedical industries, researchers are driven to the exploration of new materials and device configurations for new applications. At the same time, engineers are making continuous effort to improve the existing technologies. As the scope of the area is vast, it is necessary to provide an overview on different branches of piezoelectric materials.

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