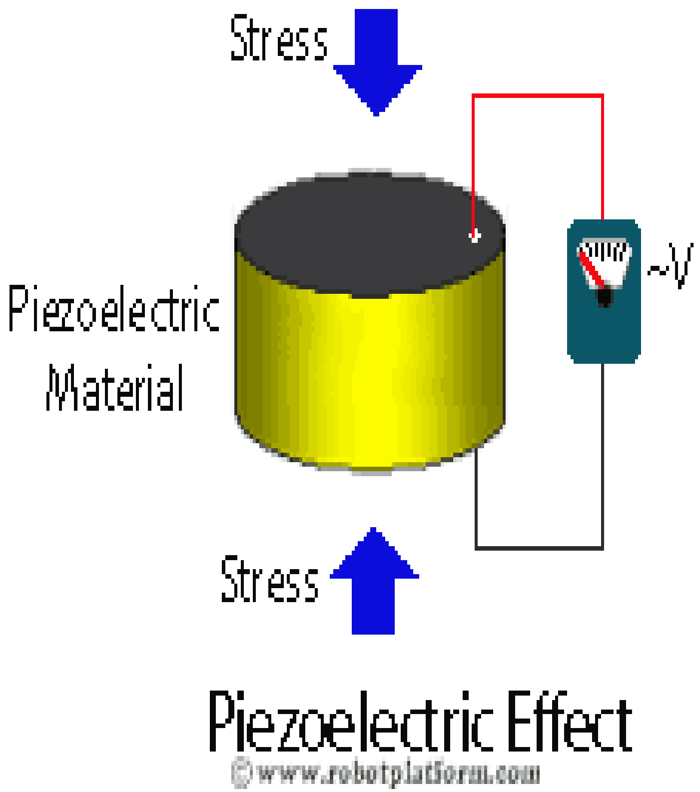
PIEZOELECTRIC EFFECT

- Appearance of an electric potential across certain faces of a crystal when it is subjected to mechanical pressure
- Conversely, when an electric field is applied to one of the faces of the crystal it undergoes mechanical distortion.



PieZOELECTRIC PHENOMENON

In 1880 Curie brothers discovered the direct piezoelectric effect in certain solid crystalline dielectric substances such as quartz.

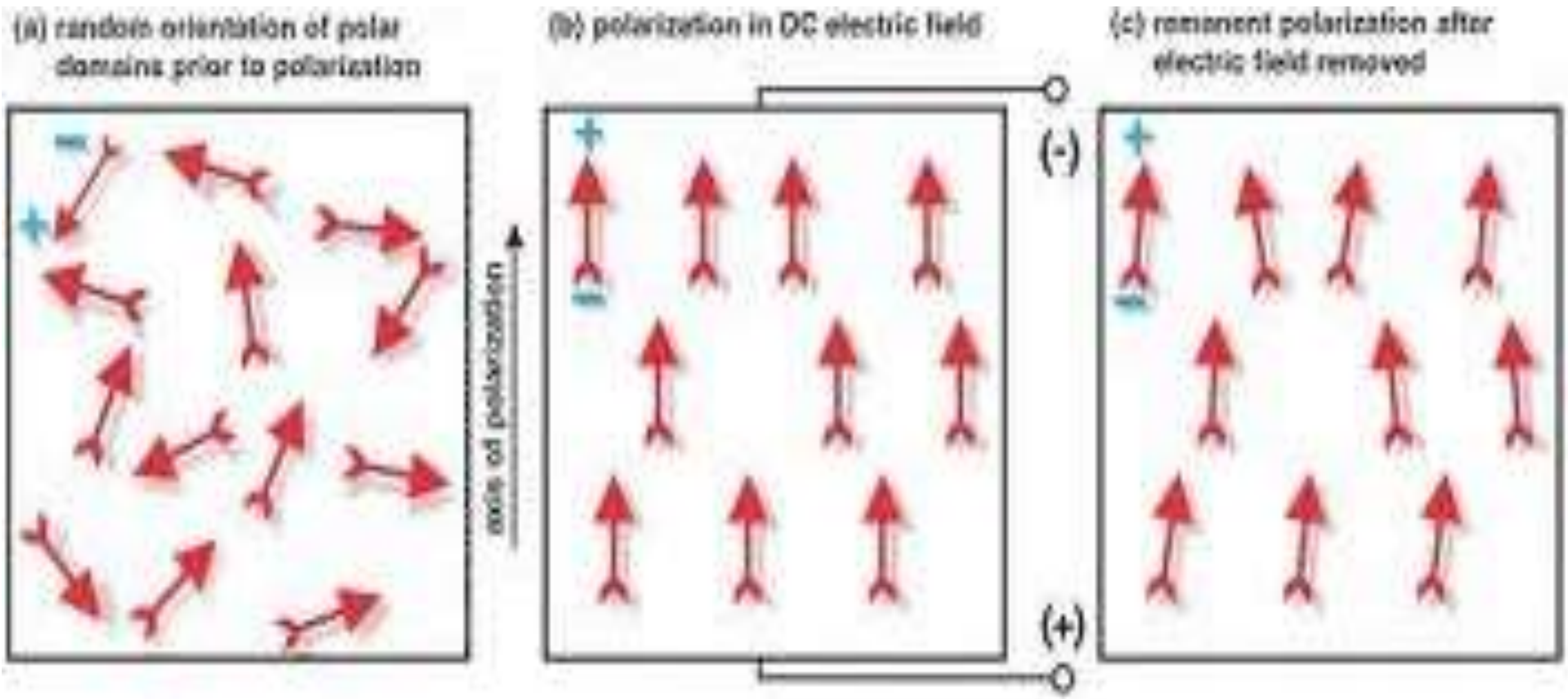
The word piezo originates from the Greek word “piezein”, which means “to press”

MATERIALS USED

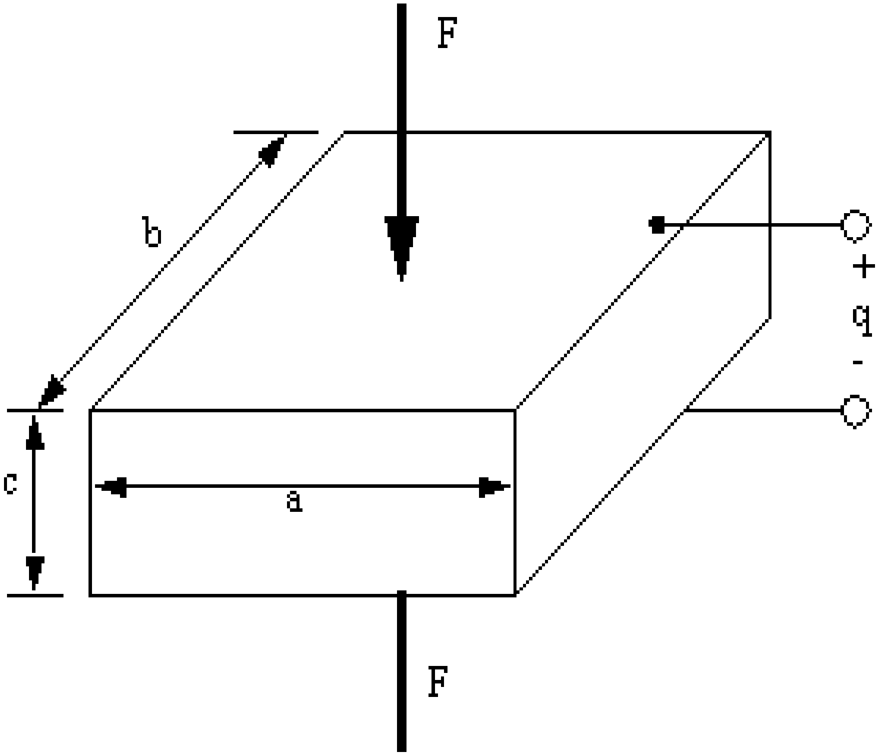
The material that show significant and useful piezoelectric effect fall under three main groups:

1. Natural, Eg: Quartz, Rochelle salt
2. Synthetic, Eg: Lithium Sulphate, Ammonium Dihydrogen Phosphate
3. Polarized Ferroelectric Crystals, Eg: Barium Titanate, Lead Zirconate-Titanate

- Because of their natural asymmetric structure, the crystal materials other than ferroelectric crystals exhibit piezoelectric effect without further processing.
- However for ferroelectric crystals, they need to undergo certain processing.
- They must be artificially polarized by applying a strong electric field to the material, while it is heated to a temperature above the Curie point of the material. They are then slowly cooled with the field still applied. When external field is removed they have a remnant polarization which allows them to exhibit the piezoelectric effect.


(a) random orientation of polar domains prior to polarization
(b) polarization in DC electric field
(c) remanent polarization after electric field removed
axis of polarization
(-)
(+)

PIEZOELECTRIC TRANSDUCERS



There are two families of constants which are used to describe the piezoelectric effect:

- g constant
- d constant

These are written as g_{ij} and d_{ij}

Where,

i= direction of electric effect

j= direction of mechanical effect

- **g constant is defined as:**

g_{33}=(field produced in direction 3)/(stress applied for direction 3)

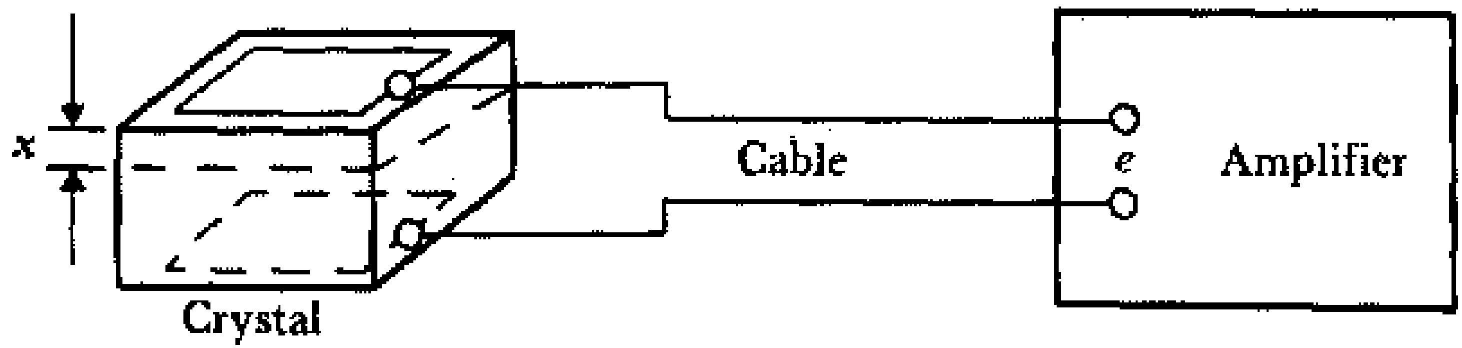
$$\frac{V/c}{F/ab}$$

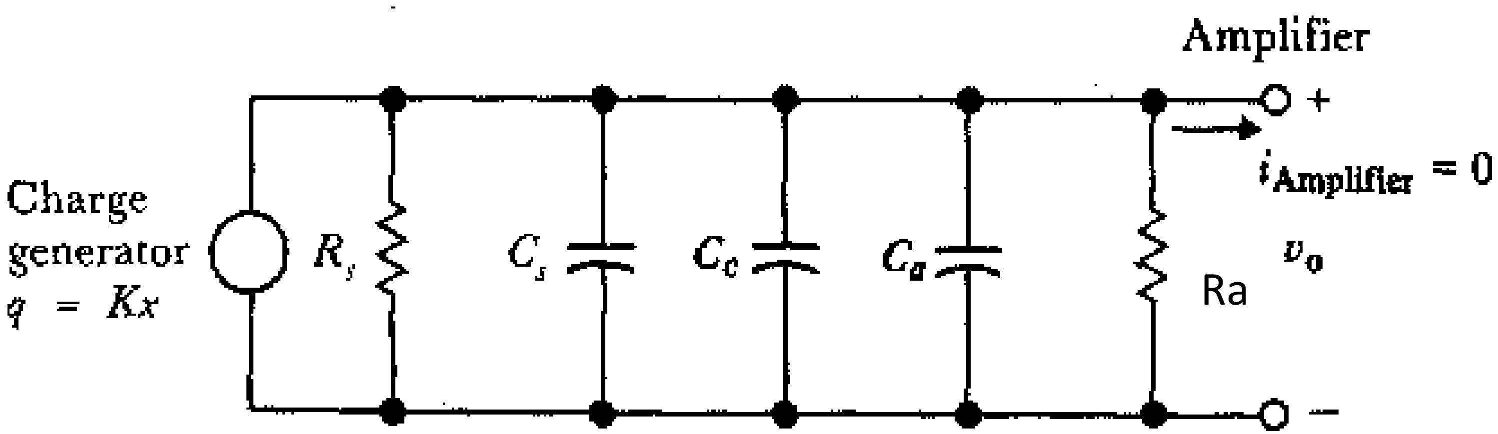
- **d constant is defined as:**

d_{33}=(charge generated in direction 3)/(force applied in direction 3)

$$q/F$$

Piezoelectric crystal can be represented as a charge generator *q in parallel with* a capacitance C_N





R_s=Resistance of the crystal

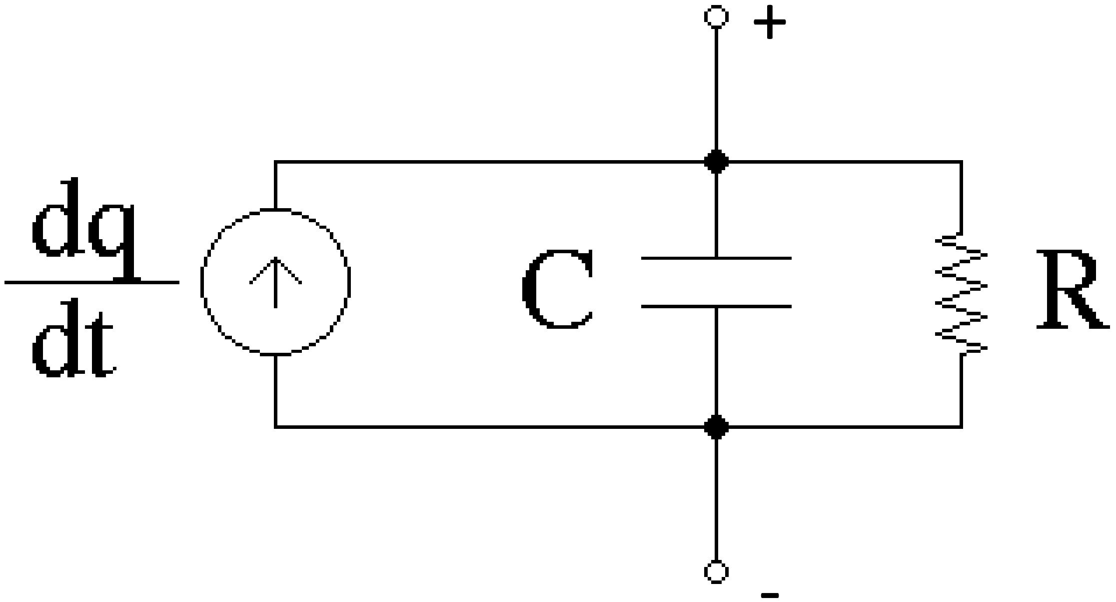
C_s=Capacitance of the crystal

C_c=Cable capacitance

C_a= Capacitance of the amplifier

R_a= resistance of the amplifier

Equivalent Circuit:



$C = C_s + C_c + C_a$

$R = R_s || R_a$

$V_o = iR = (dq/dt - C\, dV_o/dt)R$

Or, $RC\, dV_o/dt + V_o = R\,dq/dt$

By Laplace Transformation,

$V_o(s)/q(s) = Rs/(RCs+1)$

We know that, $q = d*F$

Therefore,

$$V_o(s)/F(s) = dRs/(RCs+1)$$

$$V_o(s)/F(s) = (d/C)RCs/(RCs+1)$$

$$V_o(s)/F(s) = (d/C)\tau/(\tau s+1)$$

- **The above represents the transfer function.**

- It is not possible to measure any static force with this circuit.
- Static Sensitivity (d/C) will change with the change in any of the values of C_c or C_a.
- For this reason we use Charge Amplifier.

Measurement using Charge Amplifier:

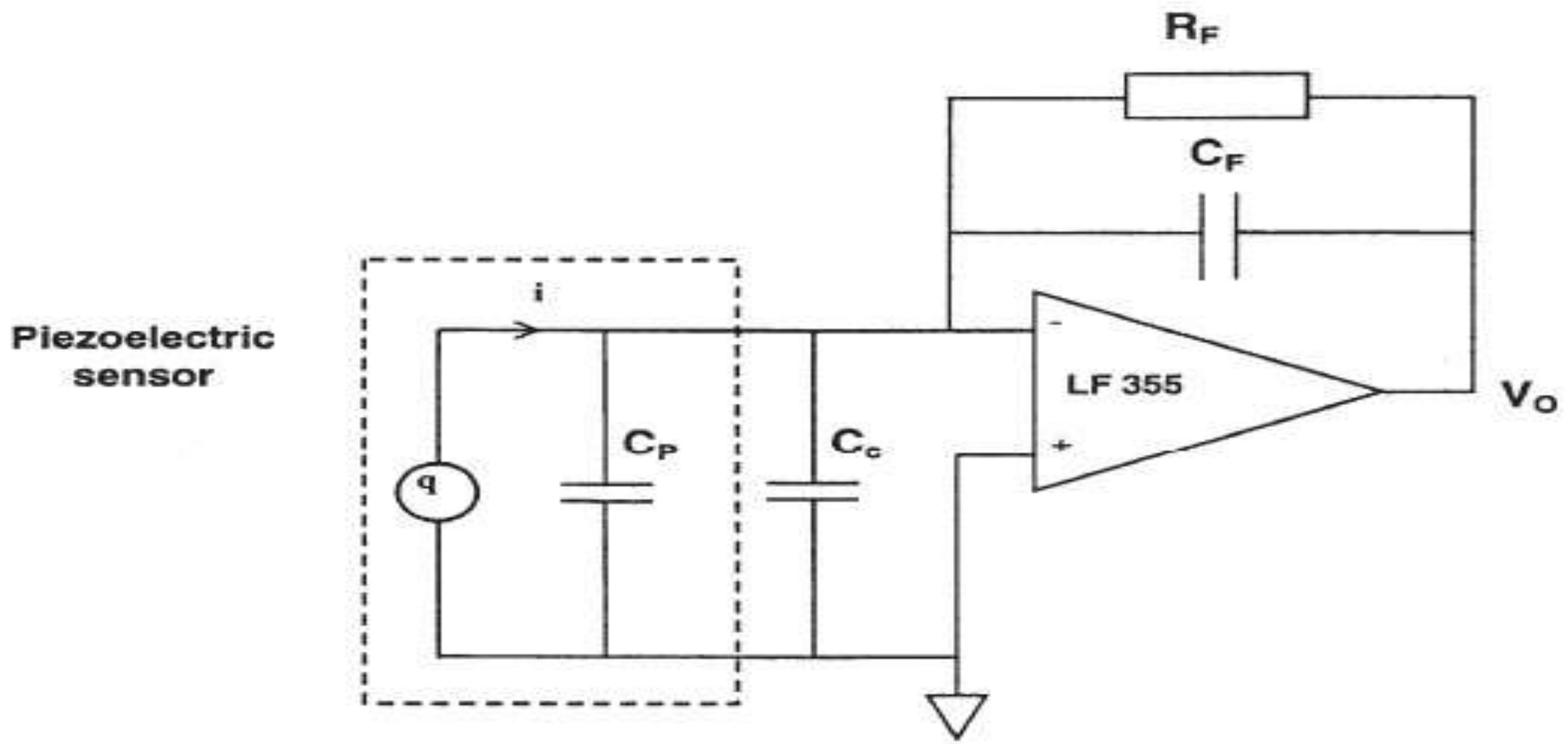


Figure 3. *Charge amplifier circuit.*

From circuit Analysis:

$$i = dq/dt = -V_o/R_f - C_f \, dV_o/dt$$

$$\text{Or, } R_f C_f \, dV_o/dt + V_o = -R_f \, dq/dt$$

$$\text{Or, } V_o(s)/q(s) = -R_f s/(R_f C_f s+1)$$

$$V_o(s)/F(s) = -(d/C_f)R_fC_fs/(R_fC_fs+1)$$

$$V_o(s)/F(s) = -(d/C_f)\tau_fs/(\tau_fs+1)$$

Where, $\tau_f = R_fC_f$

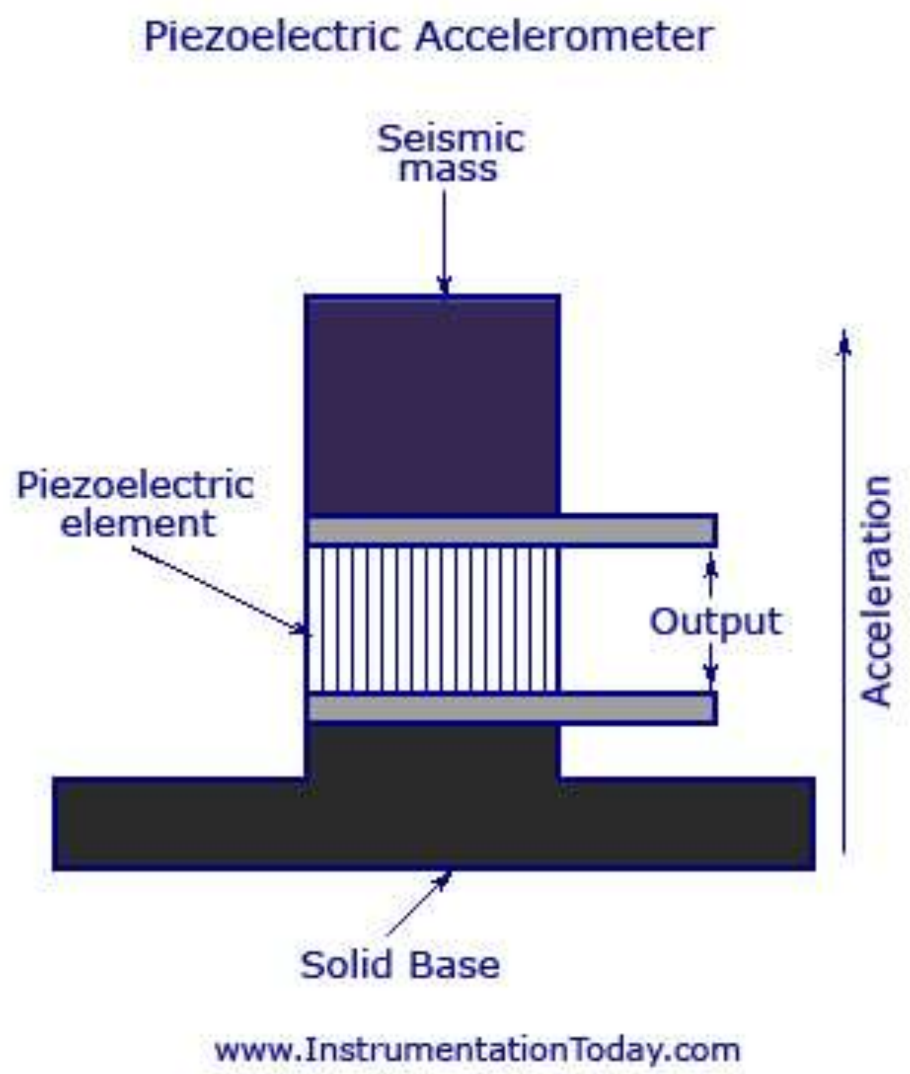
- **The above circuit also cannot measure static force but it removes dependencies on cable capacitance and resistances.**

APPLICATIONS

Applied Piezo: Applications
Piezoelectric materials are used in numerous applications.
The *direct* piezoelectric effect is used in e.g.
generators (e.g. gas igniters)
sensors (e.g. accelerometers, pressure sensors)
switches (e.g. in control panels)
ultrasonic transducers (e.g. in medical imaging)

The *indirect* piezoelctric effect is used in e.g.
actuators (for micropositioning, micropumps, microvalves)
motors (e.g. inchworm motors, SAW motors)
speakers, buzzers (e.g. in mobile phones)
ultrasonic transducers (e.g. sonar)
A *combination* of the direct and the indirect piezoelectric effect is found in
active vibration control (e.g. active damping)
smart structures (e.g. active shape control)
voltage transformers
quartz oscillators (e.g. for timing in microelectronics)

Accelerometers


Piezoelectric Accelerometer
Seismic mass
Piezoelectric element
Output
Acceleration
Solid Base
www.InstrumentationToday.com

Principle of Operation

- Physical Setup: Piezoelectric Material Sandwiched Between Base and Resonant Mass - Also Shear, Bender
- Motion Causes Resonant Mass to Move, Force to Move Mass Is Transmitted Through Piezoelectric Material (F = ma)
- Compression/Tension or Shear of Piezoelectric Material Causes Charge Buildup Proportional to Acceleration
- Equivalent Electric Circuit
  - Measures **Capacitance**
  - Depends On Cable

Characteristics of Accelerometers

- Dynamic Range: Should Be Able to Measure Low and High Level Vibration
  - Lower Limit is Noise
  - Upper Limit is Set By Accelerometer
- Frequency Range: Should Be Able to Measure Across a Broad Bandwidth
  - Accelerometer is SDOF system w/ Frequency Response
- Physical Dimensions
  - Weight
  - Size

Ultrasonics

Piezo Electric Generator or Oscillator

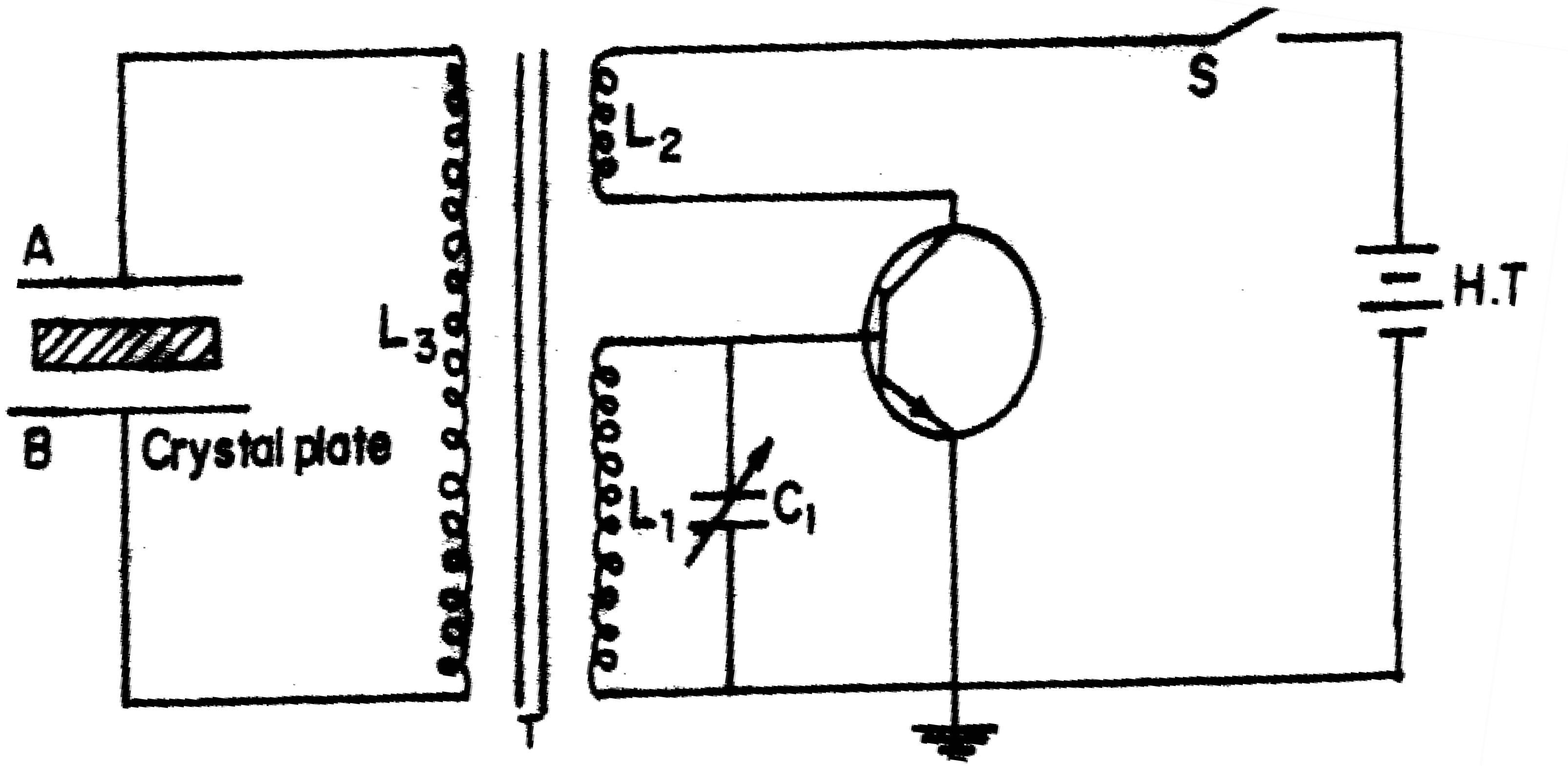
Principle : Inverse piezo electric effect

If mechanical pressure is applied to one pair of opposite faces of certain crystals like quartz, equal and opposite electrical charges appear across its other faces.This is called as piezo-electric effect.

The converse of piezo electric effect is also true.

If an electric field is applied to one pair of faces, the corresponding changes in the dimensions of the other pair of faces of the crystal are produced.This is known as ***inverse piezo electric*** effect or ***electrostriction***.

Construction



The quartz crystal is placed between two metal plates A and B.
The plates are connected to the primary (L_3) of a transformer which is inductively coupled to the electronics oscillator.
The electronic oscillator circuit is a base tuned oscillator circuit.
The coils L_1 and L_2 of oscillator circuit are taken from the secondary of a transformer T.
The collector coil L_2 is inductively coupled to base coil L_1.
The coil L_1 and variable capacitor C_1 form the *tank circuit* of the oscillator.

Working

When H.T. battery is switched on, the oscillator produces high frequency alternating voltages with a frequency.

$$f = \frac{1}{2\pi\sqrt{L_1 C_1}}$$

Due to the transformer action, an oscillatory e.m.f. is induced in the coil L_3. This high frequency alternating voltages are fed on the plates A and B.

Inverse piezo-electric effect takes place and the crystal contracts and expands alternatively.The crystal is set into mechanical vibrations.

The frequency of the vibration is given by

$$n = \frac{P}{2l}\sqrt{\frac{Y}{\rho}}$$

where P = 1,2,3,4 … etc. for fundamental, first over tone, second over tone etc.,

Y = Young’s modulus of the crystal and

ρ = density of the crystal

- The variable condenser C_1 is adjusted such that the frequency of the applied AC voltage is equal to the natural frequency of the quartz crystal, and thus resonance takes place.
- The vibrating crystal produces longitudinal ultrasonic waves of large amplitude.

Quartz Crystal Oscillator

One of the most important features of any oscillator is its *frequency stability*, or in other words its ability to provide a constant frequency output under varying load conditions. Some of the factors that affect the frequency stability of an oscillator generally include: variations in temperature, variations in the load as well as changes to its DC power supply voltage to name a few.

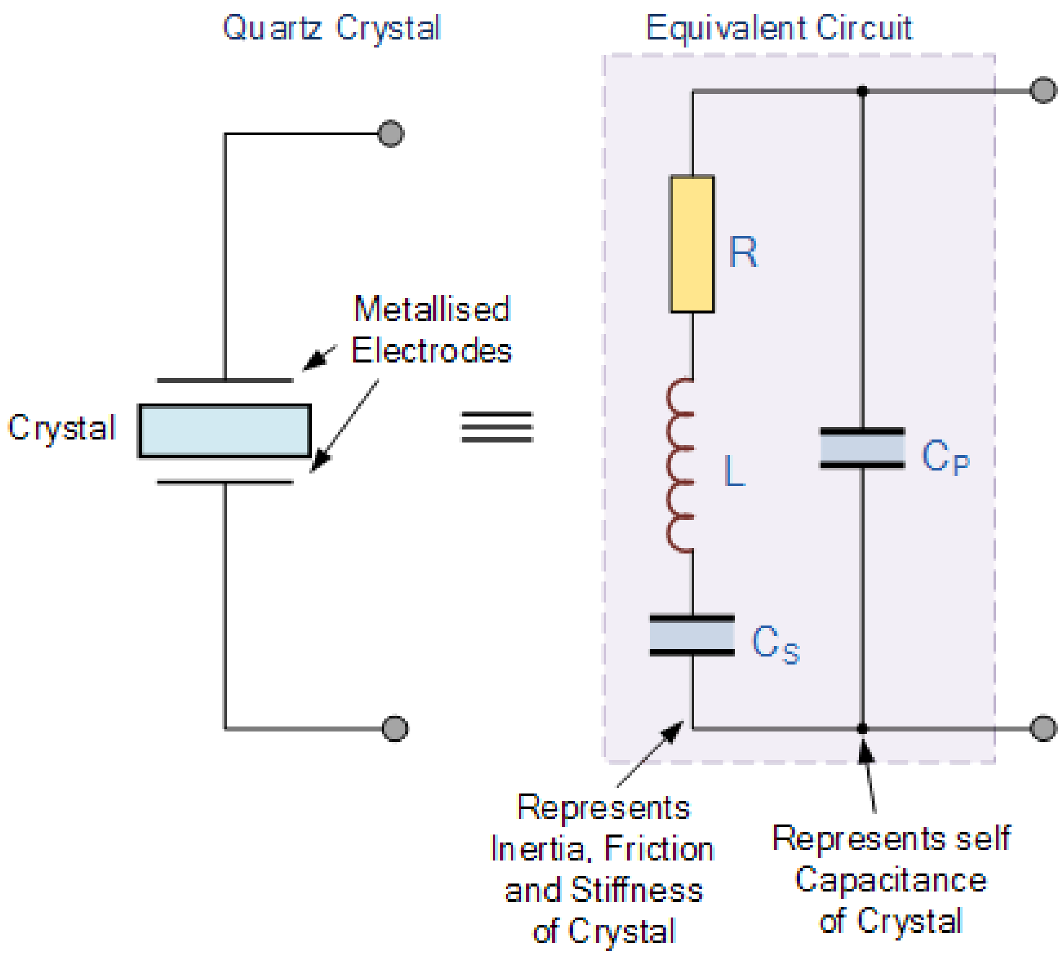
To obtain a very high level of oscillator stability a **Quartz Crystal** is generally used as the frequency determining device to produce another types of oscillator circuit known generally as a **Quartz Crystal Oscillator**, (XO).

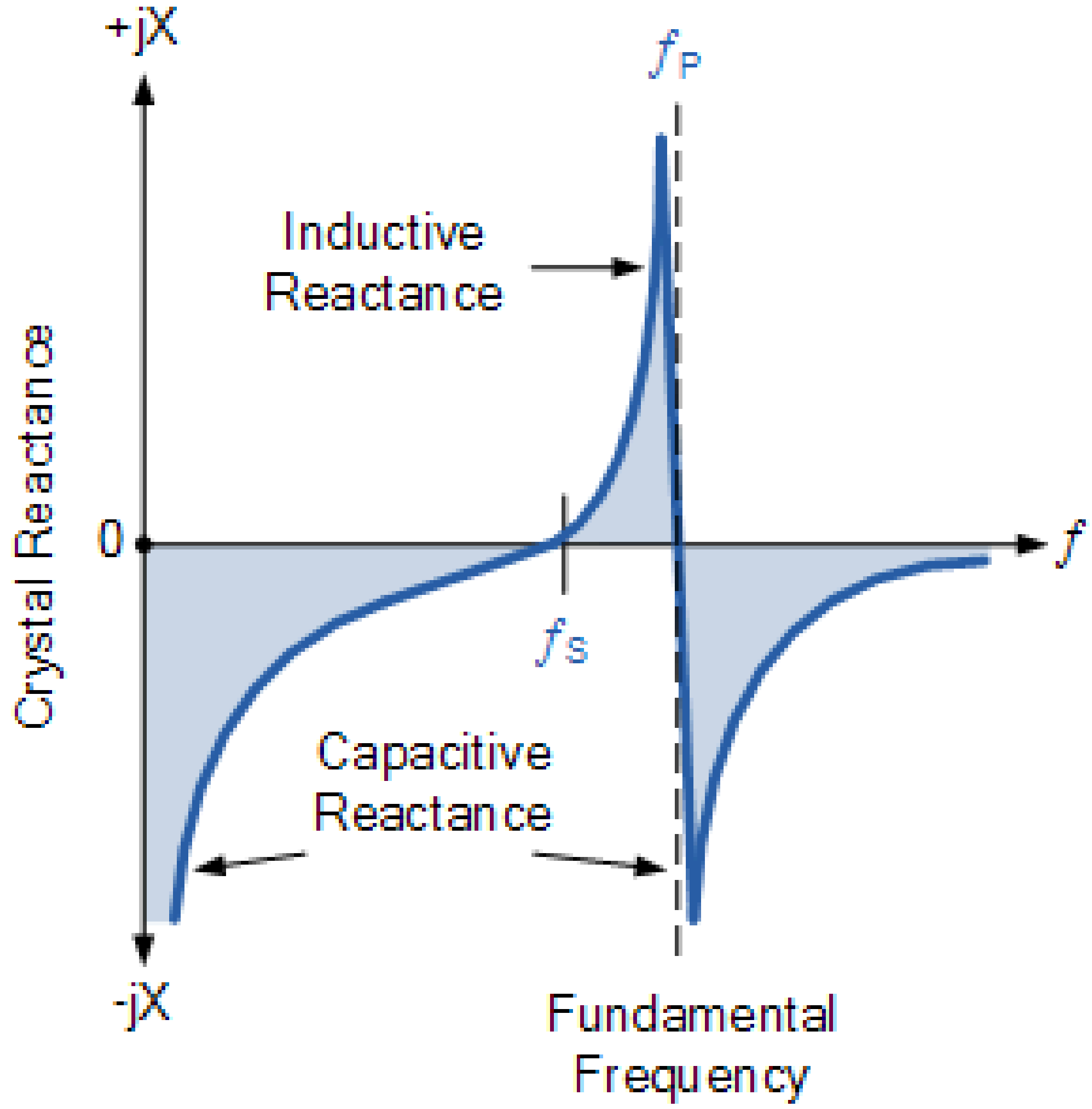
When a voltage source is applied to a small thin piece of quartz crystal, it begins to change shape producing a characteristic known as the **Piezo-electric effect**. This Piezo-electric Effect is the property of a crystal by which an electrical charge produces a mechanical force by changing the shape of the crystal and vice versa, a mechanical force applied to the crystal produces an electrical charge.

The quartz crystal used in a **Quartz Crystal Oscillator** is a very small, thin piece or wafer of cut quartz with the two parallel surfaces metallised to make the required electrical connections. The physical size and thickness of a piece of quartz crystal is tightly controlled since it affects the final or fundamental frequency of oscillations. The fundamental frequency is called the crystals “characteristic frequency”.

Then once cut and shaped, the crystal can not be used at any other frequency. In other words, its size and shape determines its fundamental oscillation frequency.

The crystals characteristic or resonant frequency is inversely proportional to its physical thickness between the two metallised surfaces. A mechanically vibrating crystal can be represented by an equivalent electrical circuit consisting of low *resistance*, large *inductance* and small *capacitance* as shown below.


Quartz Crystal
Equivalent Circuit
Metallised
Electrodes
Crystal
R
L
C_P
C_S
Represents
Inertia, Friction
and Stiffness
of Crystal
Represents self
Capacitance
of Crystal



+jX
-jX
0
Crystal Reactance
f_P
Inductive
Reactance
f_S
f
Capacitive
Reactance
Fundamental
Frequency

Limitations

Each piezoelectric material has a particular operating limit for temperature, voltage, and stress. The particular chemical composition of the material determines the limits. Operating a material outside of these limitations may cause partial or total depolarization of the material, and a diminishing or loss of piezoelectric properties.

Temperature Limitations

As the operating temperature increases, piezoelectric performance of a material decreases, until complete and permanent depolarization occurs at the material's Curie temperature.

The Curie point is the absolute maximum exposure temperature for any piezoelectric ceramic. Each ceramic has its own Curie point. When the ceramic element is heated above the Curie point, all piezoelectric properties are lost. In practice, the operating temperature must be substantially below the Curie point.

The material's temperature limitation decreases with greater continuous operation or exposure. At elevated temperatures, the ageing process accelerates, piezoelectric performance decreases and the maximum safe stress level is reduced.

Voltage Limitations

A piezoelectric ceramic can be depolarized by a strong electric field with polarity opposite to the original poling voltage.

The limit on the field strength is dependent on the type of material, the duration of the application, and the operating temperature. The typical operating limit is between 500V/mm and 1 000V/mm for continuous application.

It should be noted that alternating fields can have the same affect during the half cycle which is opposite to the poling direction.

Mechanical Stress Limitations

High mechanical stress can depolarize a piezoelectric ceramic. The limit on the applied stress is dependent on the type of ceramic material, and duration of the applied stress.

For dynamic stress (impact ignition) the limit is less severe; materials with higher energy output (high g constant) can be used.

For impact applications, the material behaves quasi statically (non-linear) for pulse durations of a few milliseconds or more. When the pulse duration approaches a microsecond, the piezoelectric effect becomes linear, due to the short application time compared to the relaxation time of the domains.

Energy Harvesting

Energy harvesting describes the process of changing parasitic mechanical energy, for instance of a vibrating structure, into electrical energy. This energy is used for other purposes. For example driving an electrical circuit or for storage in a battery or a large capacitor.

➢ Energy harvesting is the process by which energy is derived from external sources and utilized to drive the machines directly, or the energy is captured and stored for future use.

➢ Some traditional energy harvesting schemes are solar farms, wind farms, tidal energy utilizing farms, geothermal energy farms and many more. With the advent of technology, utilization of these sources has increased. When viewed on a large scale, energy harvesting schemes can be categorized as shown in Table.

Type of Energy Harvesting	Energy Source	Solution	Ultimate Goal
Macro	Renewable sources like solar, wind, tidal etc.	Energy Management solutions	Reduce oil dependency
Micro	Small scale sources like vibration, motion, heat etc.	Ultra-low-power solutions	Driving low energy consuming devices

Piezoelectric Energy Harvesting

➢ Piezoelectric Energy Harvesting comes under the category of Micro scale energy harvesting scheme.

➢ The energy harvesting via. Piezoelectricity uses direct piezoelectric effect. The phenomenon will be clear from the diagrams shown below.

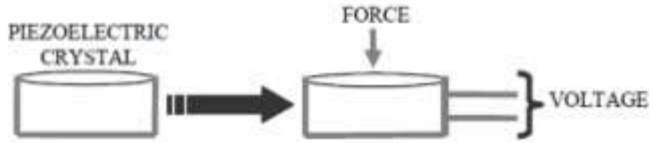


Fig 1. Principle of direct piezoelectric effect

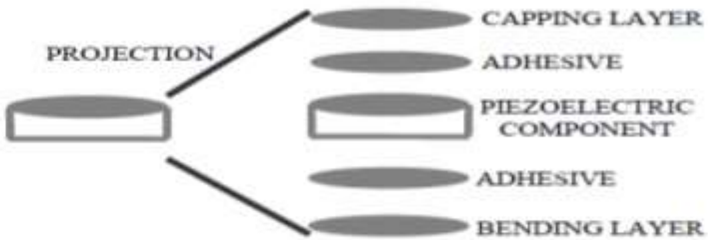


Fig 2. Structure of a piezoelectric component

➢The output voltage obtained from a single piezoelectric crystal is in milli volt range, which is different for different crystals. And the wattage is in microwatt range.

➢ In order to achieve higher voltages, the piezoelectric crystals can be arranged in series. The energy thus obtained is stored in lithium batteries or capacitors. This is the working principle behind piezoelectric energy harvesting system.

SOURCES OF VIBRATION FOR CRYSTAL

A. POWER GENERATING SIDEWALK

The piezoelectric crystal arrays are laid underneath pavements, side walks and other high traffic areas like highways, speed breakers for maximum voltage generation. The voltage thus generated from the array can be used to charge the chargeable Lithium batteries, capacitors etc. These batteries can be used as per the requirement.

ADVANTAGES

1. HIGH FREQUENCY RESPONSE
The parameter changing at very high speeds can be sensed easily.

2.HIGH TRANSIENT RESPONSE
Even the events of microsecond durations can be detected.

3.SELF GENERATING

4.SIMPLE TO USE

DISADVANTAGES

It is not suitable for measurement in static conditions.
The output may vary according to the variation in temperature of the crystal.
It is very difficult to give the desired shape to the crystals with sufficient strength

Since the device operates with small electric charge, high impedance cable is needed for electrical interface. So they have to be connected to the amplifier and the auxiliary circuit ,which have potential to cause errors in the measurement.

Output is low.

Piezoelectric Transducers

Electric Field

Interaction of charges.
Electric field , E = F/q ,
where F=force experienced by the charged particle of charge q.

Strain

Ratio of change in length by original length.
Dimensionless measure.
Material property of all elastic solids , Young’s modulus is defined as stiffness of material.
Y=(L/a)*(F/dL)
Used to determine equivalence spring constant of rod/plate of material i.e. in contact with piezo actuator.

Tensile Strength

Stress measured in Newtons per m^2 at which the sample of solid material will break from tension.

Damping: general tendency of vibrating materials or structures to loose some elastic energy to internal heating or external friction.

Why Piezoelectricity?

Some atomic lattice structures have essential unit or cell i.e. a cubic or rhomboid cage made of atoms and this cage holds a single semi mobile ion which has several stable quantum position states inside the cell.

They change by deformation or by application of electric field.

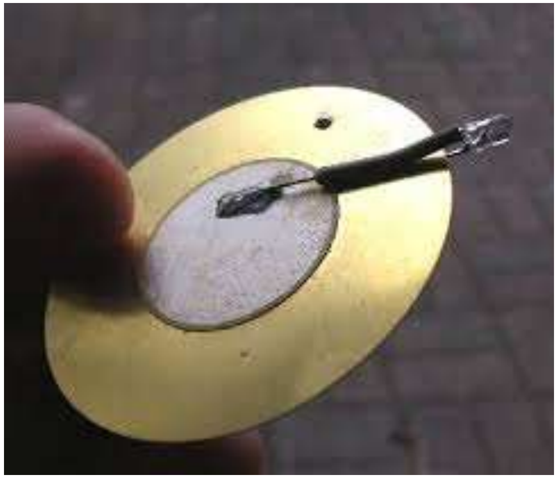
Poling and Depoling

Piezoceramic material is subjected to a high electric field for a short period of time to force the randomly oriented dipoles into alignment. This alignment of application of high voltage is called poling.

If electric field is applied in opposite direction, it exerts a dislodging stress on micro dipoles .Low level applied field result in no permanent change in polarisation.

Piezoactuators at cryogenic temperatures

Piezoelectric effect is due to interatomic electric fields and their electric effect is not affected by temperature at all. Quantitatively the piezo coupling of most piezo ceramics decrease as temperature decreases.



Pyroelectric effect

Tendency of some materials to exhibit a change in internal electric polarisation state in response to change in temperature.

Handling and preparation of piezo ceramics

Shaping to required size : Using a diamond saw ,razor blade OR straight edge to score a piezo surface and then making a controlled break.

Attaching /bonding a piezoceramic sheet :good quality temporary bonds maybe made with cyanoacrylate. E.g. :superglue.

An added benefit of this bond is that it easily achieves electrical contact.

The time span of bond is application dependent.

Should be handled with great care. Dropping them always results in shattered parts. This can be avoided by bondage with metal shim. The shim can be accessed by supporting the bender underneath by using a milling machine. Water is used as a lubricant.

Hooking up a bender element :this depends on how the two ceramic plates are polarised.

Properties

Etching of electrode :Chemically etch, sand blast , laser ablate or sand paper the electrode.
Elasticity :A sheet can be stretched to strain of approx. 500 micro strain in regular use.
Repoling of sheet : For a 5H material an electric field of 50-60 V/mil will restore nearly all lost polarisation.

Applications

- Frequency limit : No inherent frequency limit. Determined by resonances associated by shape and size of transducer designed.
- Highest voltage : 300volts
- Mechanical power obtained : One standard PSI -5A sheet used as an extender can do 0.00035 joules of work on the outside world in a quasi static cycle.
- Electrical power : Theoretical- 9 watts
  Practical – 3.6mWatts
- Static and dynamic application : Not suitable for static due to charge leakage. Used for transient force measurements lasting less than 0.1 s.
- Expected fatigue : Dependent on mounting and voltages.
- Detection of vibrations: Almost any size or shape can pick signals as when fastened somewhere on a machinery.

As a strain gauge: Most sensitive and self powered.
Repeatable outputs from piezo : Outputs from piezo are generally very repeatable and stable. Hysteresis and creep affects cause non repeatable motion if the cycle time is changed.
Temperature effects : Changes in temperature leads to voltage change across electrodes due to pyro electic properties of piezo electric.

Piezo technology

Found in watch beepers, smoke detector alarms ,fish finders, cigarette lighters and many gas grill igniters.

Vibration cancellation : Two sheets can be bonded directly to the surface of a structure close to one another at a site were unwanted bending occurs. The output from strain sensor is fed into a smart box, which in turn controls a power amplifier which drives the other piezo ceramic sheet. Finally the resulting mechanical contractions of the second piezo sheet injects a vibration into structure which is equal and opposite to initially detected so that the next vibration is cancelled.

Magnetic technology is based on force that arises at a distance without physical contact. Thus piezo cannot replace magnetic