Piezoelectric Transducer

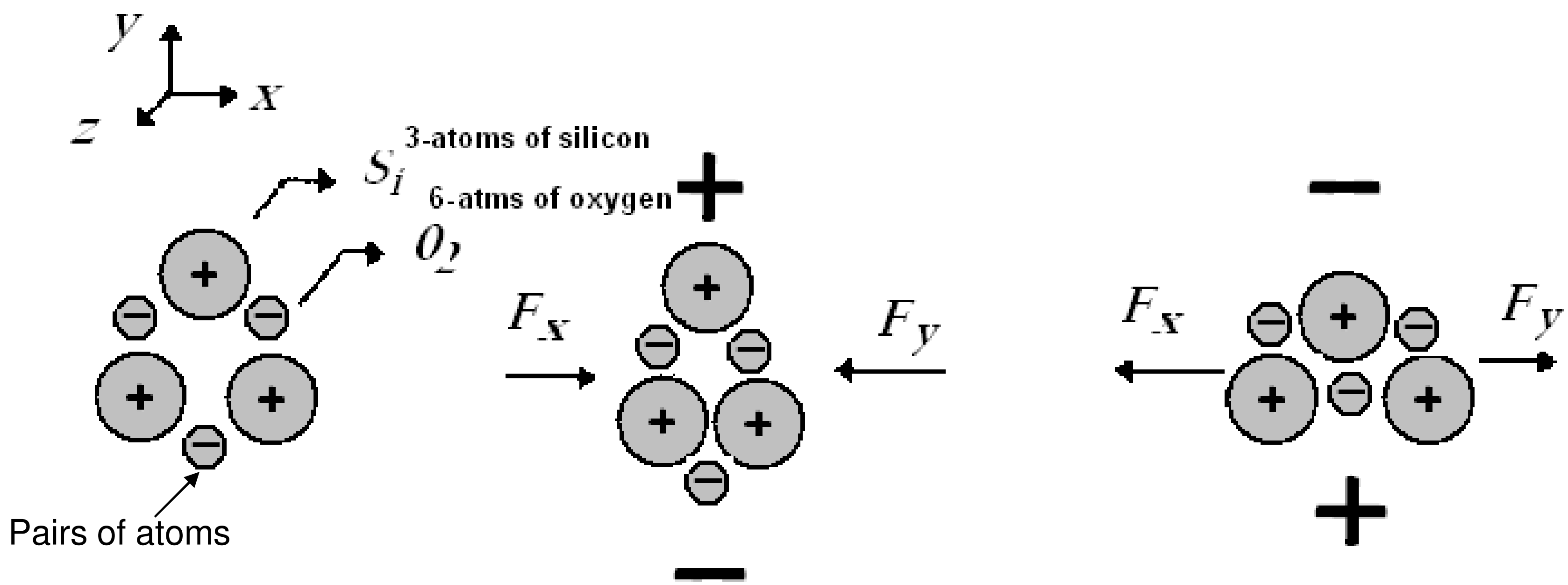
Certain material are characterized that they generate electric voltage when they are deformed by subjecting to mechanical force or stress.

The best known material is quartz crystal (SiO_2), Barium titanate, lead zirconium titanate (PZT) or poly vinylidene fluoride (PVDF)

Piezoelectric materials are characterized by their ability to output a proportional electrical signal to the stress applied to the material.
This property makes piezoelectric materials useful as a primary sensors.

Piezoelectric materials (piezo = pressure) possess the property that a voltage applied to them will produce a pressure field on the atoms in their lattice (a stress) with an accompanying overall contraction or expansion in one or more dimensions of the material (a strain).

These material can be cut along its axes in x, y and z directions.



View along the Z-axis

An asymmetric atomic structure will distort in an applied electric field. By the piezoelectric property of the material, electrical excitation is changed into motion and pressure, the necessary elements for acoustic waves.

The sensor is governed by Newton's law of motion $F = ma$.

- The force experienced by the piezoelectric crystal is proportional to the seismic mass times the input acceleration.

- The more mass or acceleration, the higher the applied force and the more electrical output from the crystal.

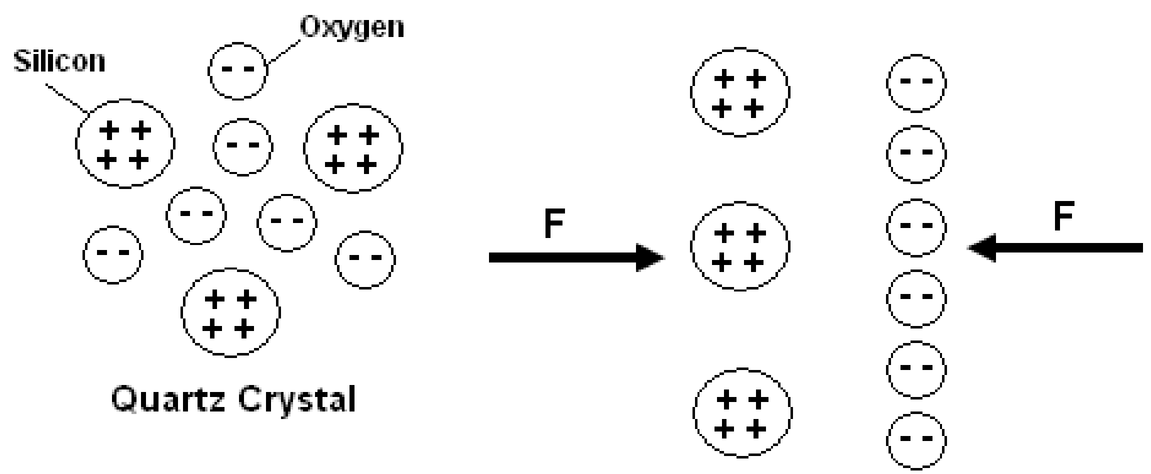
Voltage Generation

- In a single crystal cell there are three atoms of silicon and six atoms of oxygen.

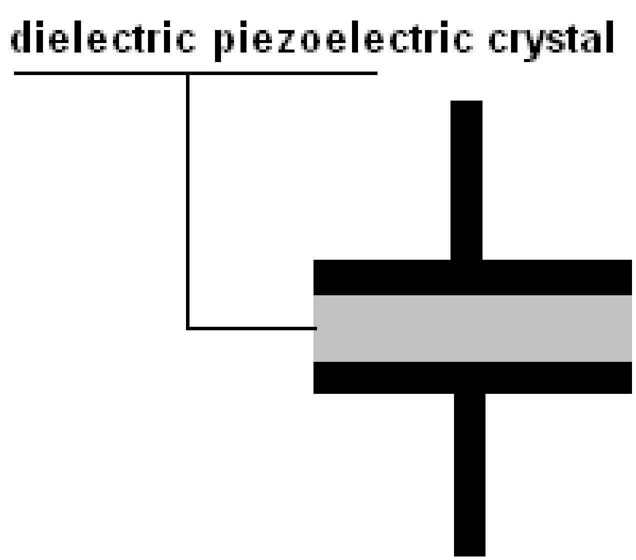
- Each silicon atoms caries four positive charges, and oxygen atom carry two negative charges.

- A pair of oxygen atom carries 4 negative charges , when there is no force applied on the quartz crystal, the quartz cell is electrically neutral.

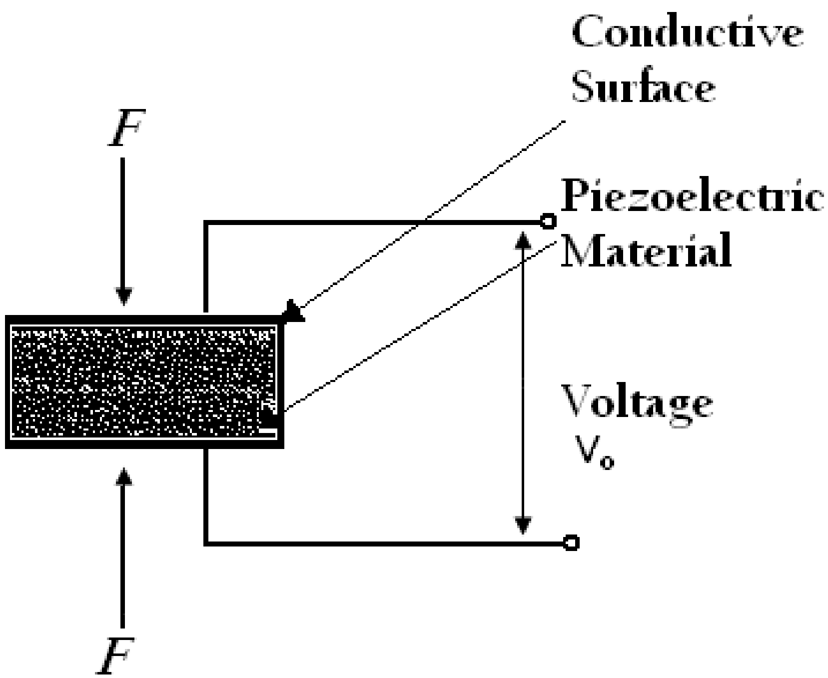
- When <u>compressive forces are applied along the x- axis</u>, the hexagonal lattices become deformed. The forces shift the atoms in the crystal in such a manner the positive charges are accumulated at the silicon atom side the negative charges at the oxygen pair side.



- The crystal tends to exhibit electric charges along the y-axis .
- If the crystal is subjected to a tension along the x-axis, a charge of opposite polarity is produced along the y-axis.
- To transmit the charge that has been develop, conductive electrodes are applied to the crystal at the opposite side of the cut.
- The piezoelectric material acts as a capacitor, with the piezoelectric crystal acting as the dielectric medium. The charge is stored because of the inherent capacitance of the piezoelectric material.

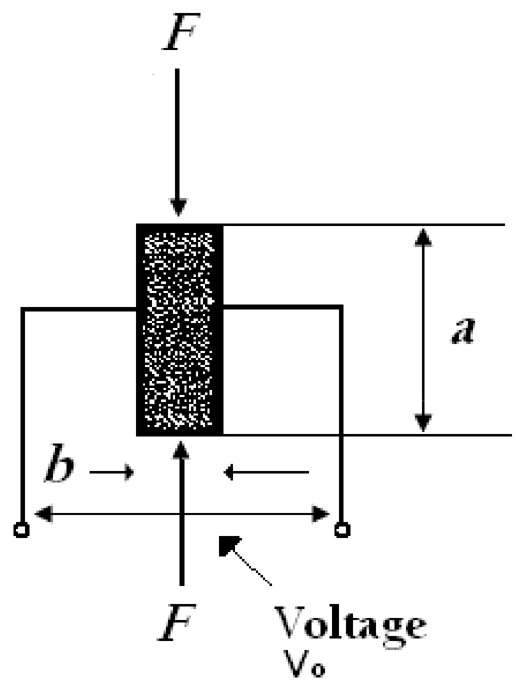


Two opposite faces of the transducer are plated with conductive metal films; a voltage generator V is attached to the electrodes to produce an electric field



longitudinal effect

$$Q = d \cdot F$$



Transverse effect

$$Q = d \cdot F \frac{a}{b}$$

The piezoelectric is reversible. If a varying potential is applied to the proper axis of the crystal, it changes the dimension of the crystal, thereby deforming it.

A piezoelectric element used for converting motion to electrical signal, thus though as both charge generator and a capacitor.

The charge appears as a voltage across the electrodes. The magnitude and polarity of the induced surface charges are proportional to the magnitude and direction of the applied force

The charge generated Q is defined as

$$Q = d \cdot F$$ (longitudinal effect)……………………………………………1

$$Q = d \cdot F \frac{a}{b}$$ (Transverse effect)……………………………………………2

d is the piezoelectric coefficient of the material, it is also known as the charge sensitivity of the crystal $d=2.3X10^{-12}$ F/N, F = applied force.

If the ratio of ***a / b*** is greater than 1, the transverse effect produces more charge than the longitudinal effect. The force ***F,*** results in a change in thickness of the crystal

If the original thickness of the crystal is ***t,*** and Δt is the change in thickness due to the applied force, then **<u>Young's modulus *E*</u>** can be expressed as the ratio of stress to strain.

$$E = \frac{\text{stress}}{\text{strain}} = \frac{\frac{F}{A}}{\frac{\Delta t}{t}} = \frac{F \cdot t}{A \cdot \Delta t}$$

$$F = \frac{A \cdot E}{t} \Delta t \qquad \text{...3}$$

A = area of the crystal, m^2

t = thickness of the crystal, m

From equation 1 and 3

$$Q = \frac{d \cdot A \cdot E \cdot \Delta t}{t} coulombs \quad \text{..4}$$

The charge at the electrodes produces the voltage

$$V = \frac{Q}{C} \quad \text{..5}$$

The capacitance of the piezoelectric material between the two electrodes is

$$C = \frac{\varepsilon A}{t} = \frac{\varepsilon_0 \varepsilon_r A}{t} \qquad \text{………………………………………………………6}$$

ε_r = the dielectric constant (permittivity) of the material

ε_0 = for free space

$$V = \frac{Q}{C} = \frac{d \cdot F}{\varepsilon_r \varepsilon_0 \frac{A}{t}}$$

$$V = \frac{Q}{C} = \frac{d \cdot F}{\varepsilon_r \varepsilon_0 \frac{A}{t}} = \frac{dtF}{\varepsilon_r \varepsilon_0 A}$$

By expressing g as the crystal voltage sensitivity factor

$$g = \frac{d}{\varepsilon_r \varepsilon_0} \quad \text{Vm/N}$$

$$V = \frac{gtF}{A} = g.t.P$$

also

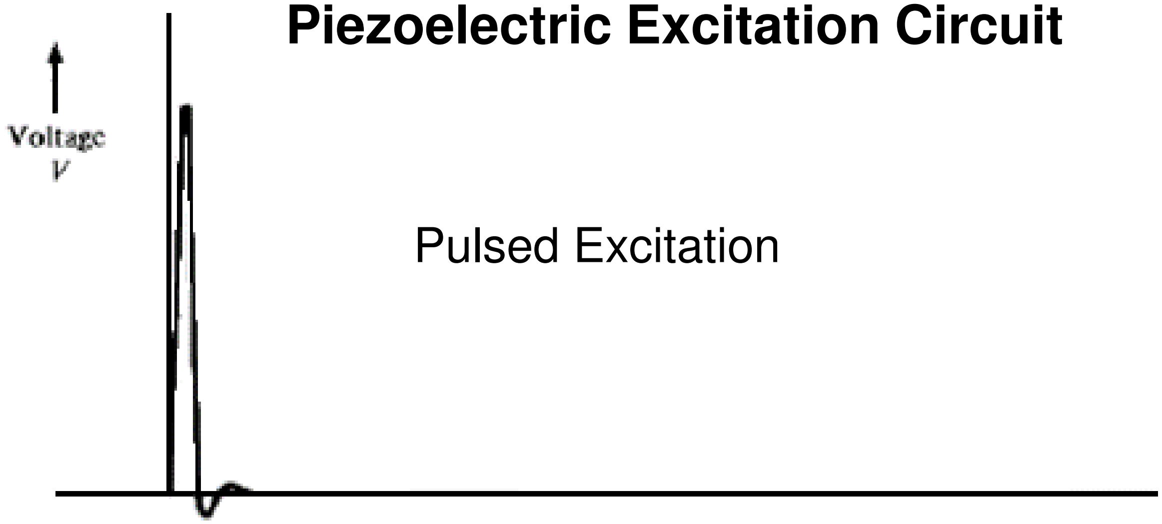
$$g = \frac{V}{tP}$$

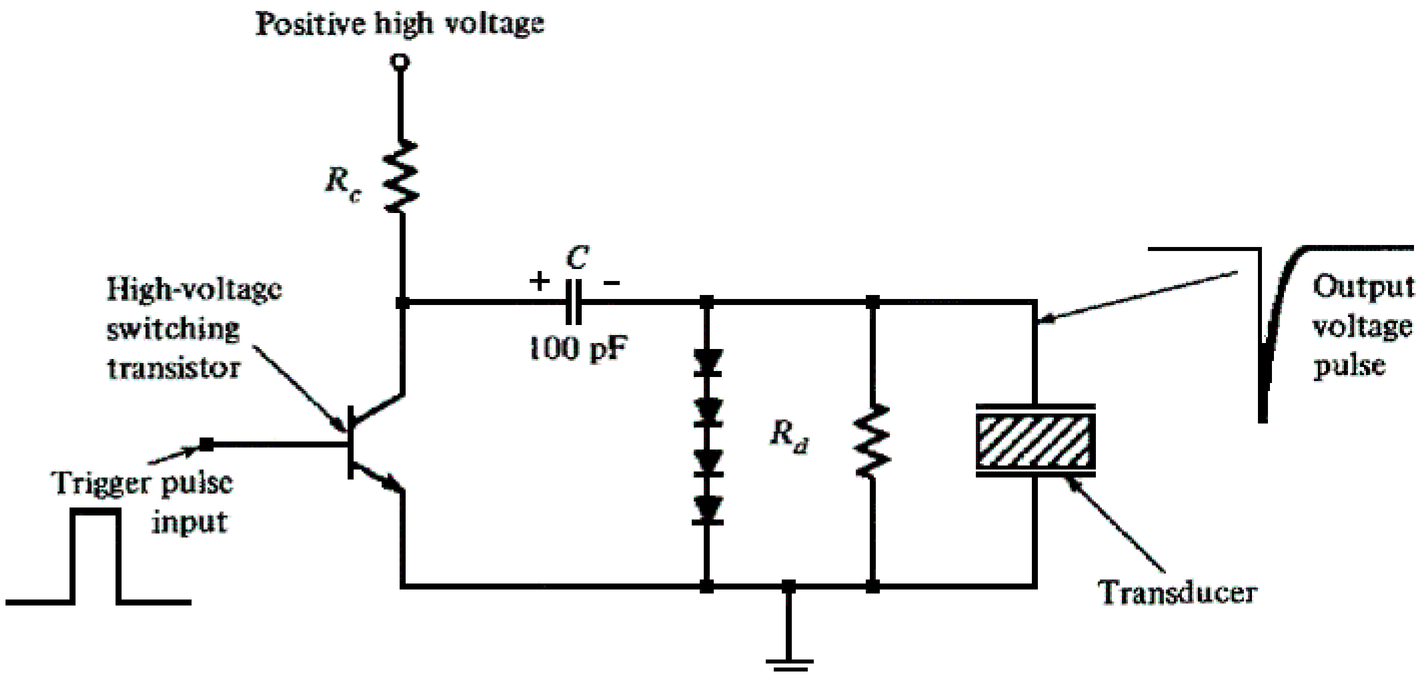
Where

V/t is the electric field strength, ***P*** is the pressure or stress

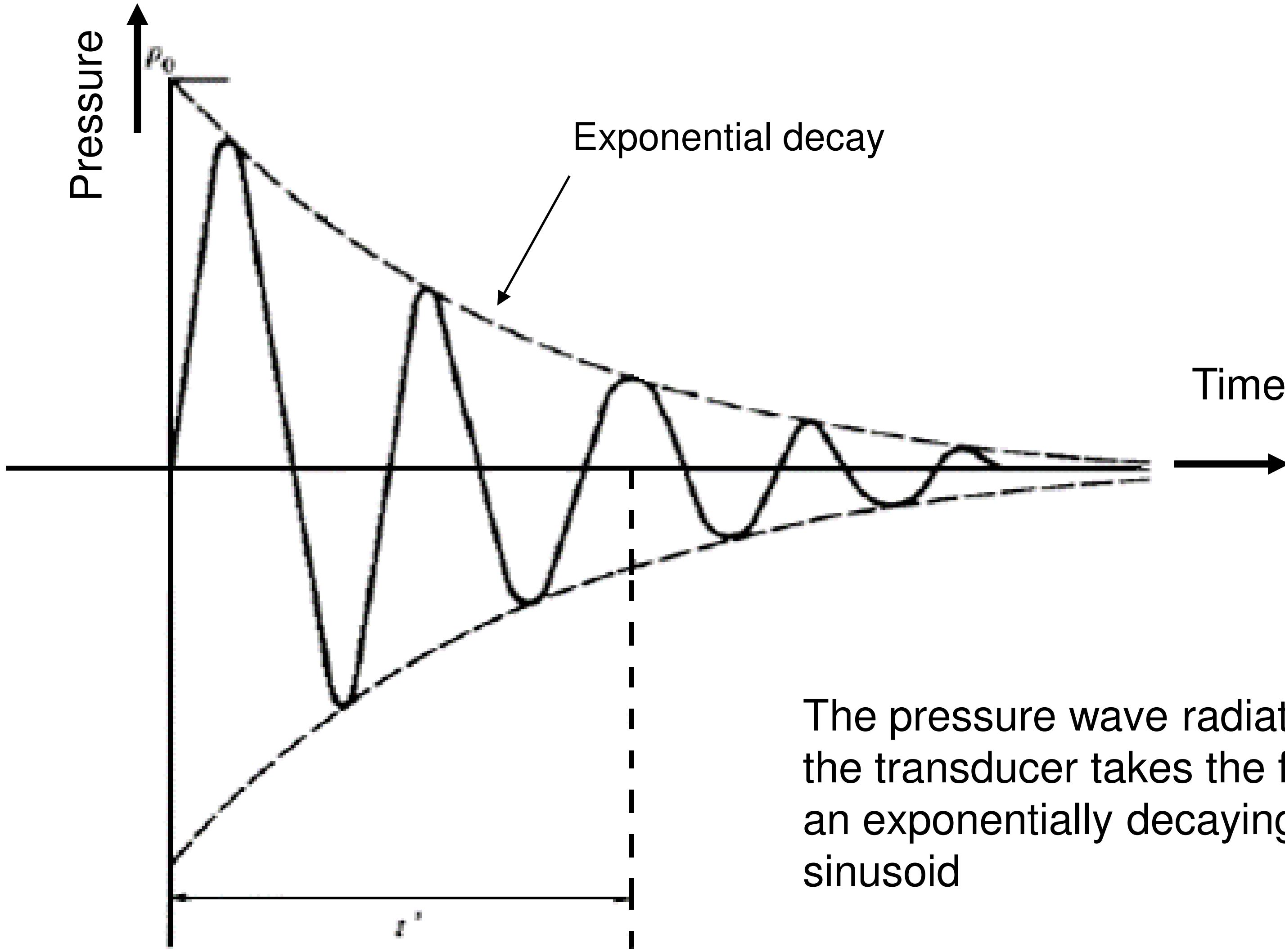
Piezoelectric Excitation Circuit

Pulsed Excitation





- The electrical circuit generates a sharp voltage pulse to a transducer.
- During the off-time of the transistor, the capacitor charges to the high supply voltage.
- When the transistor is turned ON by the trigger pulse, its low on resistance takes the left side of the capacitor to the near ground voltage.
- Thus the left side of the capacitor is applied to the ground voltage, applying a large negative pulse to the upper transducer terminal .



The pressure wave radiated by the transducer takes the form of an exponentially decaying sinusoid

Sensitivity

The sensitivity of a piezoelectric crystal may be represented either by

A -Charge sensitivity

B -Voltage sensitivity

A - Charge sensitivity

$$S_q = \frac{\partial q}{\partial F}$$

q = the generated charge

F = the applied force

For a crystal with surface area A

$$S_q = \frac{1}{A}\frac{\partial q}{\partial p}$$

p = the stress or pressure applied to the crystal surface $P = \frac{F}{A}$

B - Voltage Sensitivity

Voltage sensitivity is given by the change in voltage due to a unit increment in pressure per unit thickness of the crystal.

$$S_v = \frac{1}{d}\frac{\partial v}{\partial p}$$

d = the crystal thickness

Since $$V = \frac{Q}{C}$$

$$\delta q = C\delta v$$

As $$C = \frac{\varepsilon A}{d}$$

$$S_q = \frac{1}{A}\frac{\partial q}{\partial p} \qquad S_v = \frac{1}{d}\frac{\partial v}{\partial p}$$

$$\frac{S_q}{S_v} = \frac{d}{A}\frac{\partial q}{\partial v}$$

$$\frac{S_q}{S_v} = \frac{d}{A}C \qquad \varepsilon = C\frac{d}{A}$$

$$S_q = \varepsilon Sv$$

The relation ship between charge sensitivity and voltage sensitivity

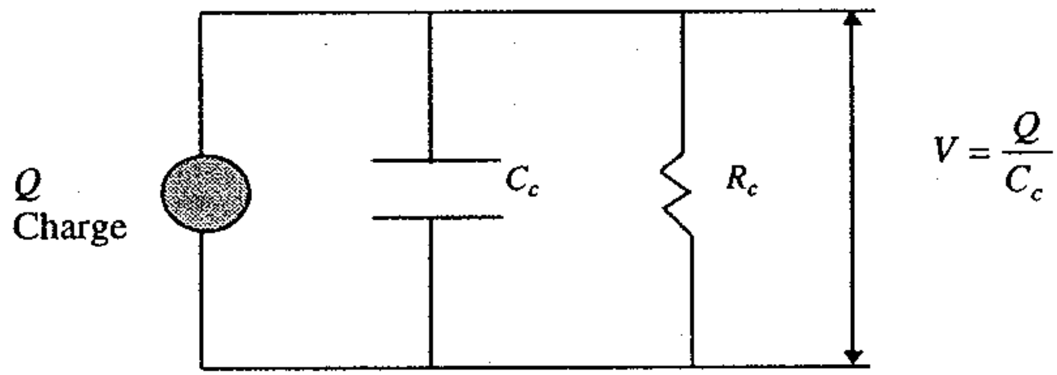
$$S_q = \varepsilon S_v$$

ε Is the dielectric constant (permittivity) of the crystal capacitor

Equivalent Circuit of a piezoelectric Transducer

The equivalent circuit can be derived from the electrical and mechanical parameters of the transducer.

$$V = \frac{Q}{C} = \frac{dF}{C_c}$$



The charge generated Q is across the capacitance C_c and its leakage resistance is R_c

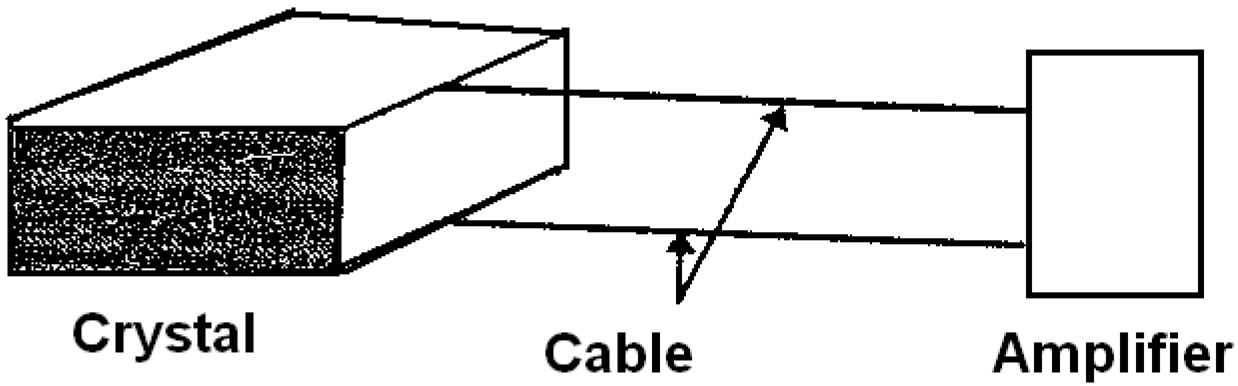
The charge source can be replaced by a voltage source

$$V = \frac{Q}{C} = \frac{d \cdot F}{C_c}$$

When the piezoelectric crystal is coupled with leads and cables as well as a readout device, the voltage depends not only on the element but also on the capacitance of cables, charge amplifier and oscilloscope display.

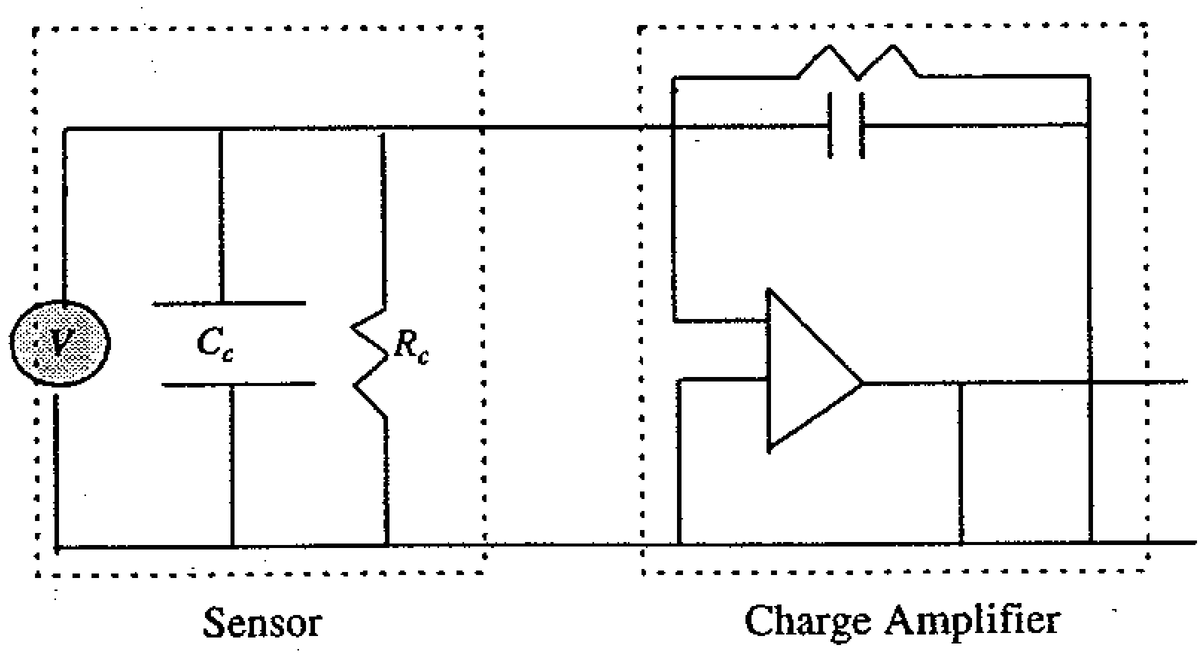
The total capacitance is

$$C_T = C_C + C_{amplifier} + C_{display}$$

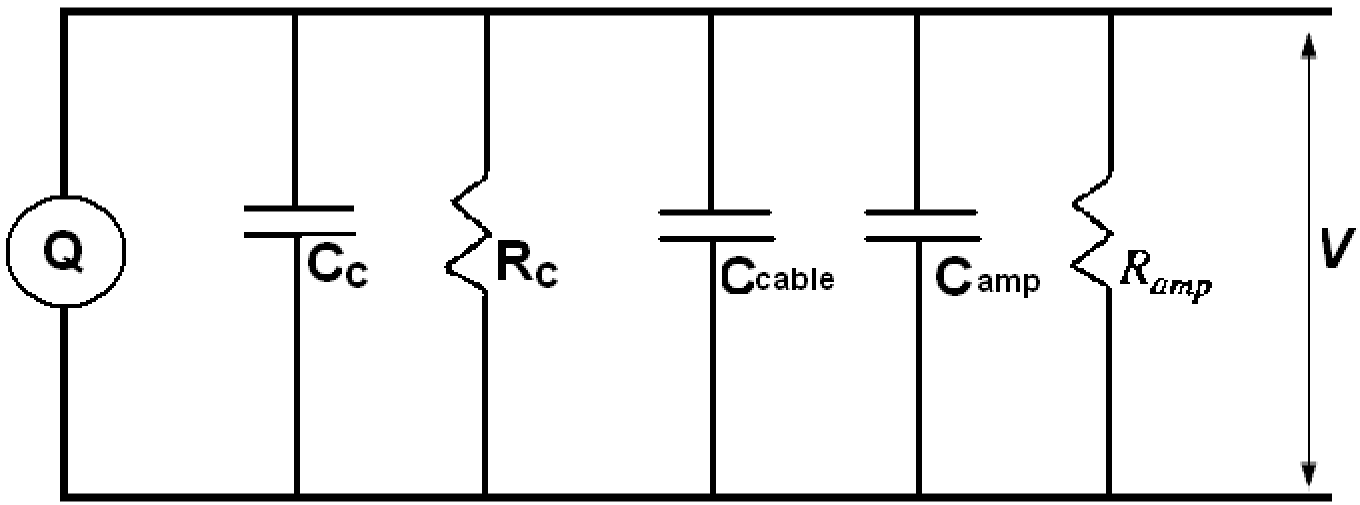


The feedback resistance of the charge amplifier is kept high so that this circuit draws very low current and produces a voltage output that is proportional to the charge

The typical arrangement is shown

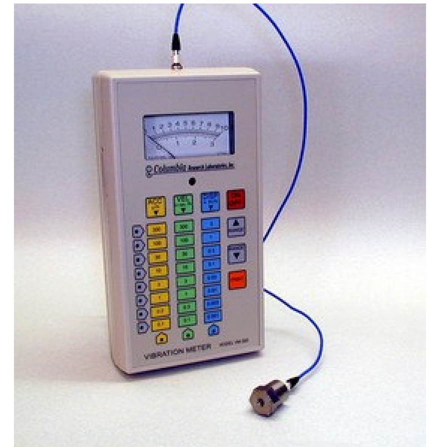


Typical arrangement when sensing element and charge amplifiers are present



Combined equivalent circuit

Piezoelectric Applications



Piezoelectric Accelerometer (Theory of Operation)

The construction is as follows:-

A piezoelectric element in the form of a cylinder is bonded to a central pillar.

A cylinder mass is bonded to the outside piezoelectric element.

Acceleration in the direction of the cylinder axis causes a shear force on the element , which provides its own spring force $Q = d.F$

As the housing of the accelerometer is subjected to vibrations, the force exerted on the piezoelectric element by the mass is altered .

The charge generated on the crystal is sensed using a charge amplifier.

A force F applied to the crystal develops a charge .

When a varying acceleration is applied to the mass crystal assembly, the crystal experiences a varying force described by

$$F = M \cdot a$$

$$Q = d \cdot F = d \cdot M \cdot a$$

$$V = \frac{Q}{C}$$

$$V = \frac{d \cdot F}{C} = \frac{d \cdot M \cdot a}{C}$$

a = acceleration

V = the voltage produced

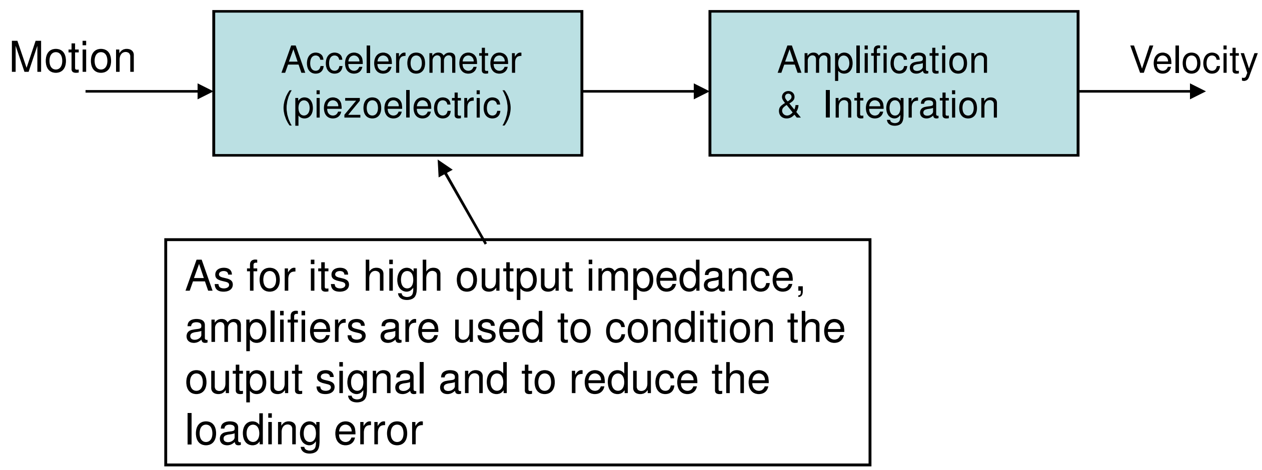
Piezoelectric Accelerometer

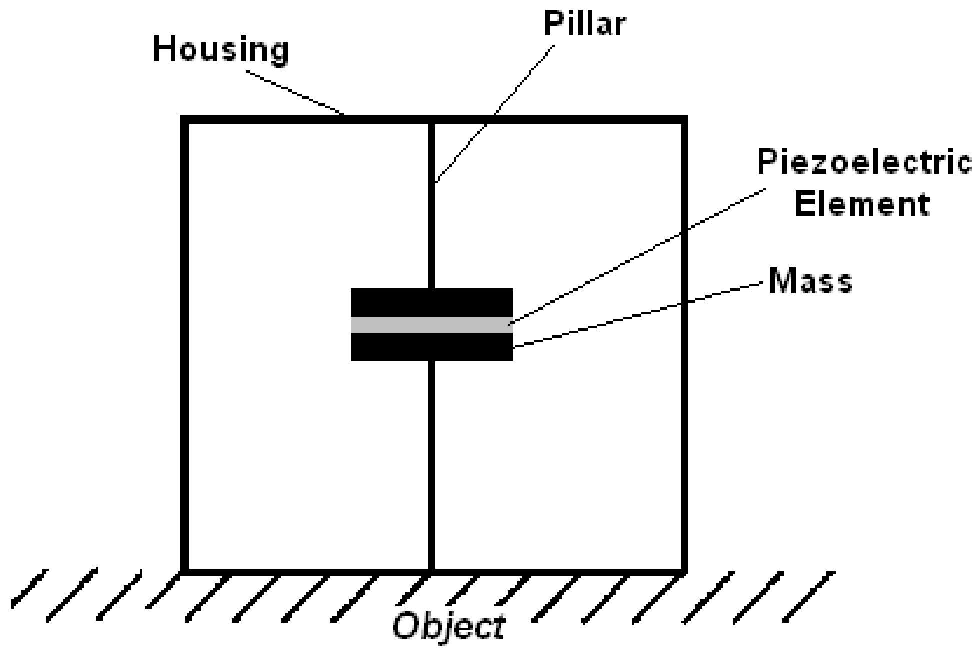
- Accelerometers are sensing transducers that provide an output proportional to acceleration, vibration and shock.

- These sensors have found a wide variety of applications such as package testing, accelerometers, airbag sensors and automotive security alarms.

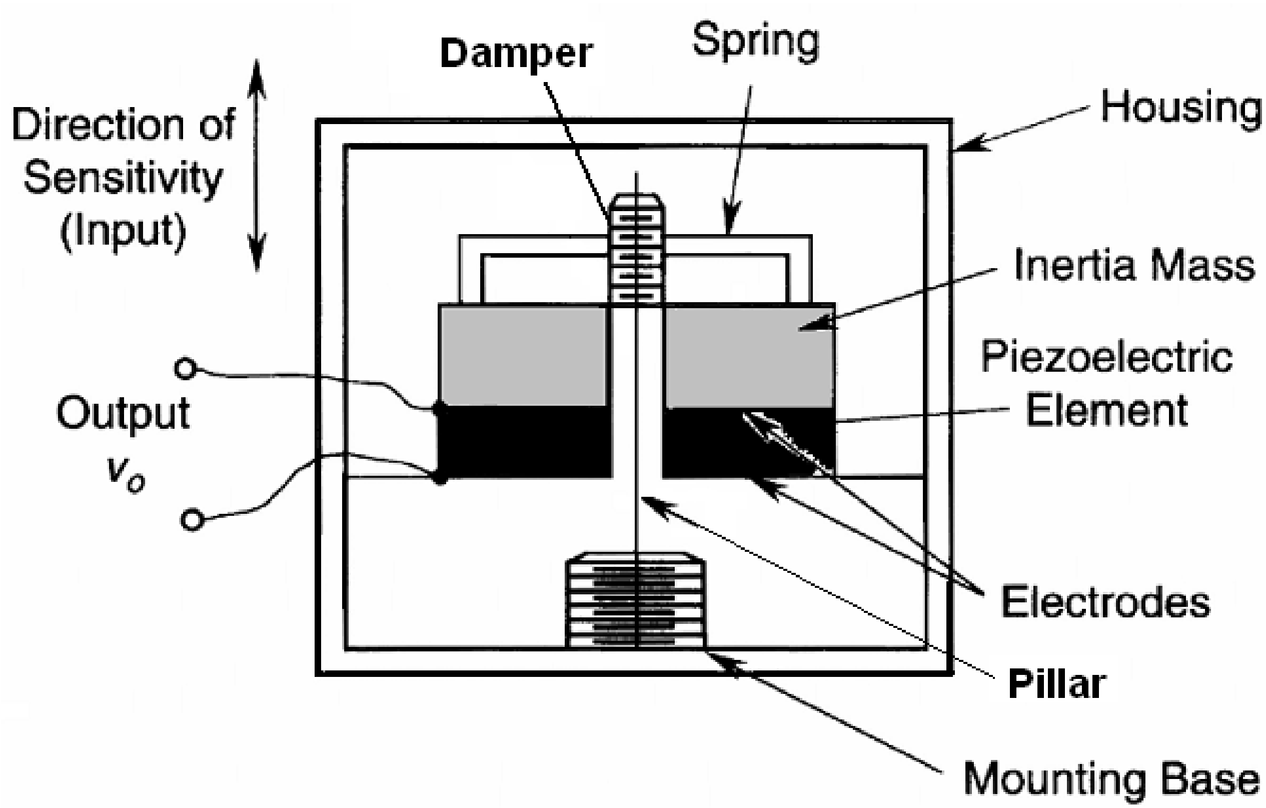
- It is possible to measure velocity by first converting the velocity into force

- By using a viscous damping element and then measuring the resulting force with piezo-electric transducer.





- The piezoelectric accelerometer is an acceleration sensor.
- Used to measure the inertia force caused by acceleration

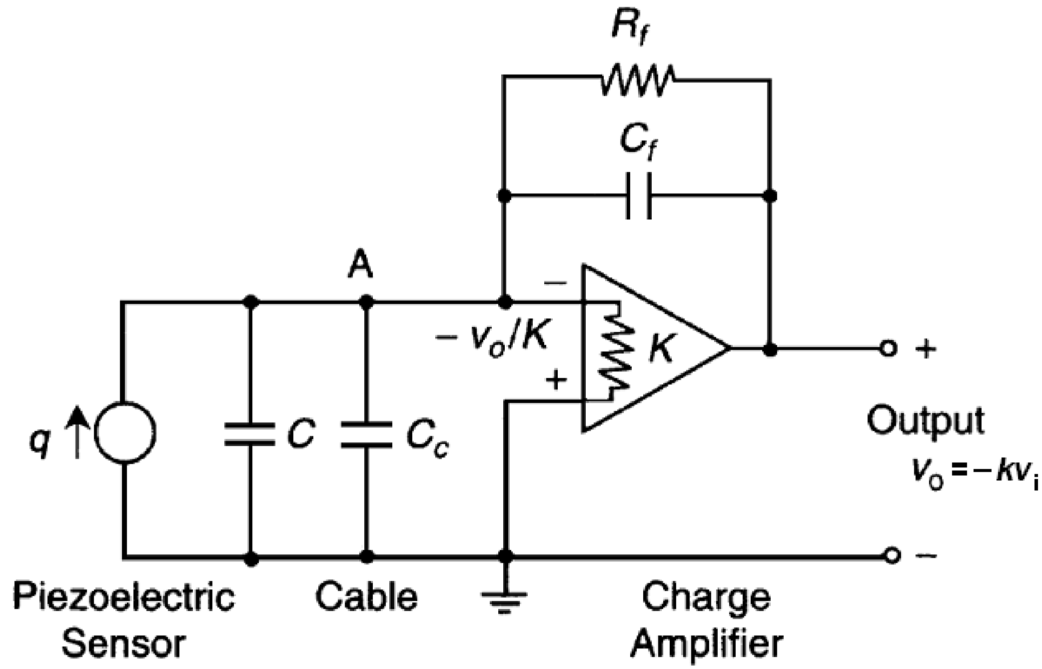


The base of the device is attached to the object whose motion is to be measured.

Inside the piezoelectric acceleration transducer, mass ***m*** is supported on a spring of stiffness ***K*** and a viscous damper with damping coefficient ***c***

X, Y , Z = the three possible axis of motion (generally represented by d)

Charge Amplifier

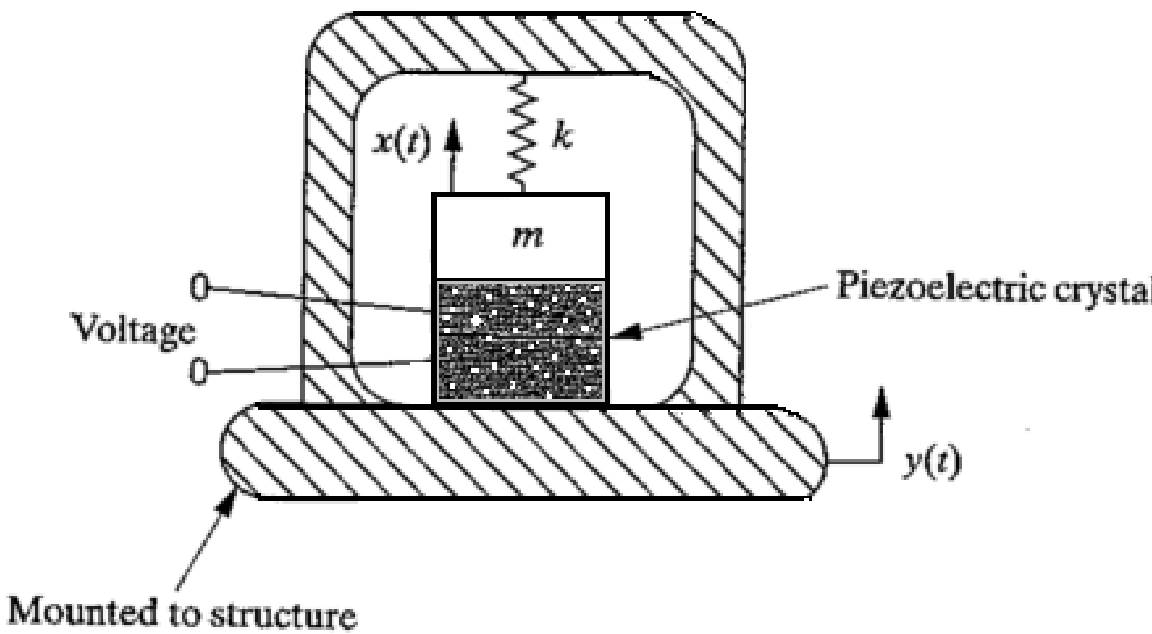


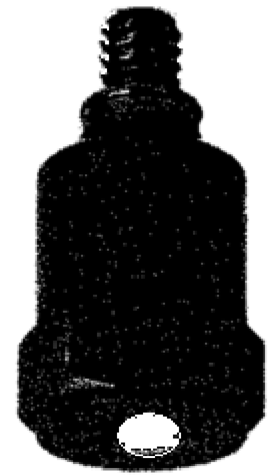
The piezoelectric signals cannot be read using low impedance devices as for

1- High output impedance in the sensor, results in small output signal levels and large loading errors.

2- The charge can quickly leak out through the load.

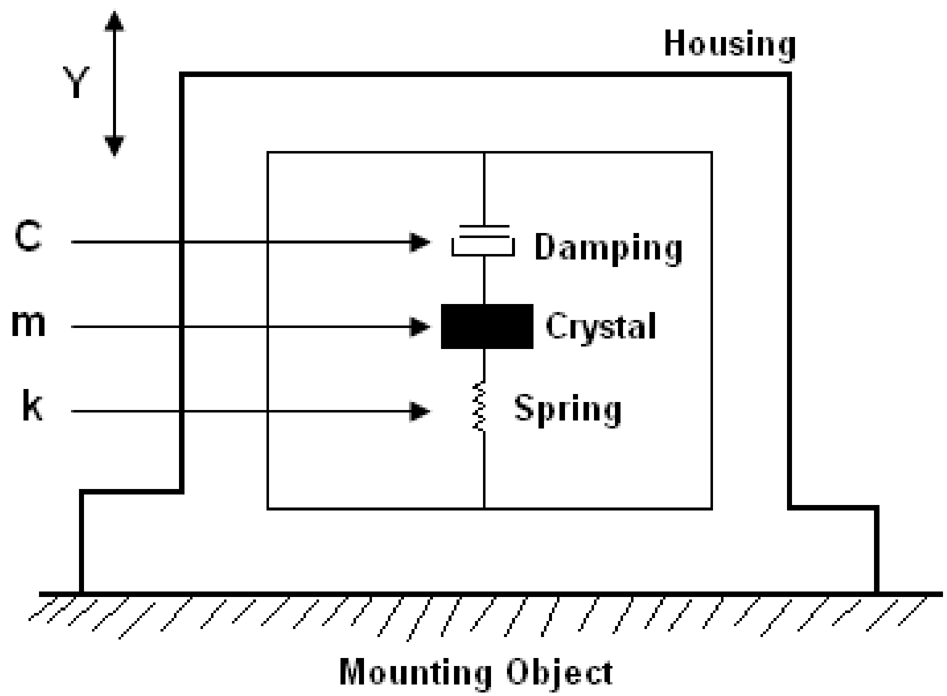
3- by using charge amplifier circuit with relatively large time constant, speed of charge leakage can be decreased





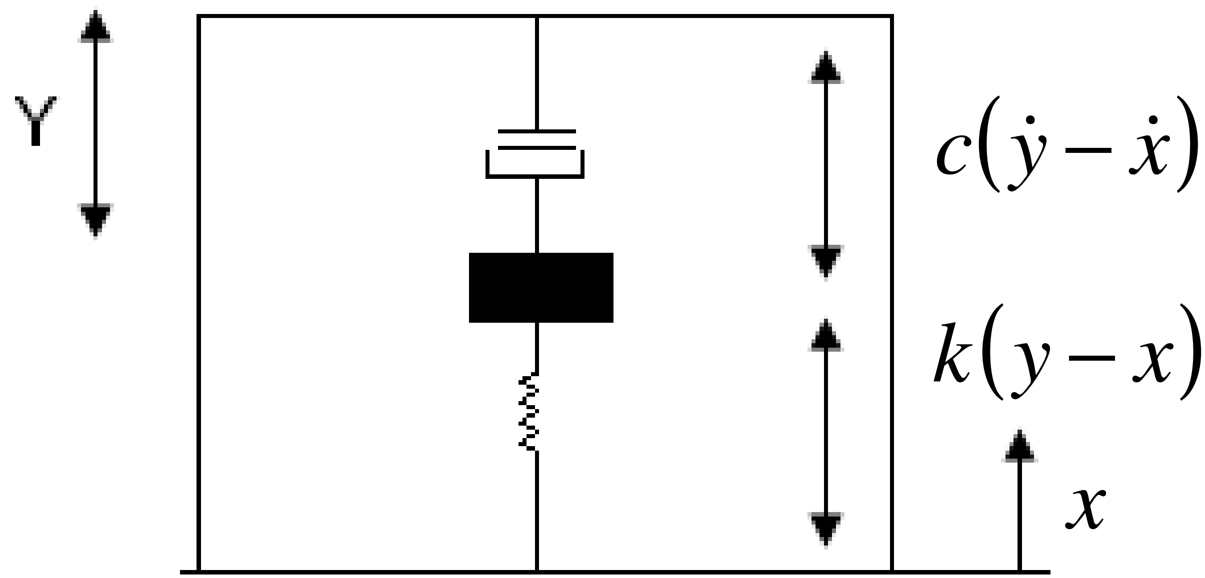
Piezoelectric accelerometer

Analogy Equations



- The base of the device is attached to the object whose motion is to be measured.
- The piezoelectric acceleration transducer, mass ***m*** is supported on a spring of stiffness ***k*** and damper with damping coefficient ***c***.
- The motion of the object results in the motion of the mass relative to the frame.

- The transducer equation is obtained by considering the inertial forces of the mass and the restoring force of the spring and the damper



$$m\frac{d^2y}{dt^2}+c\frac{d(y-x)}{dt}+k(y-x)=0$$

Where y = absolute motion of the mass

The relative motion ***z = y - x*** is expressed as

$$m\frac{d^2(z+x)}{dt^2}+c\frac{dz}{dt}+kz=0$$

$$(mD^2+cD+k)z=-mD^2x$$

where $$D=\frac{d}{dt}$$

The equation is of the second order and relates the input and output of the transducer

We can discuss the analogy approach, by using the mechanical elements (inertial elements , spring and damper.

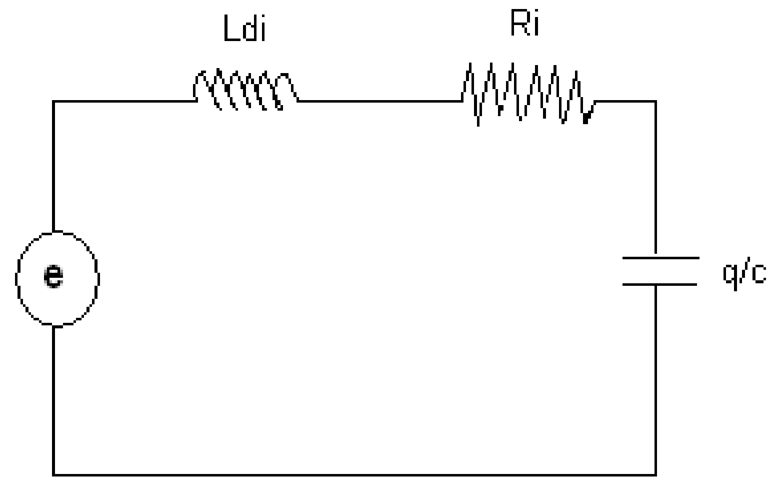
The mechanical system can be analyzed C, L, and R

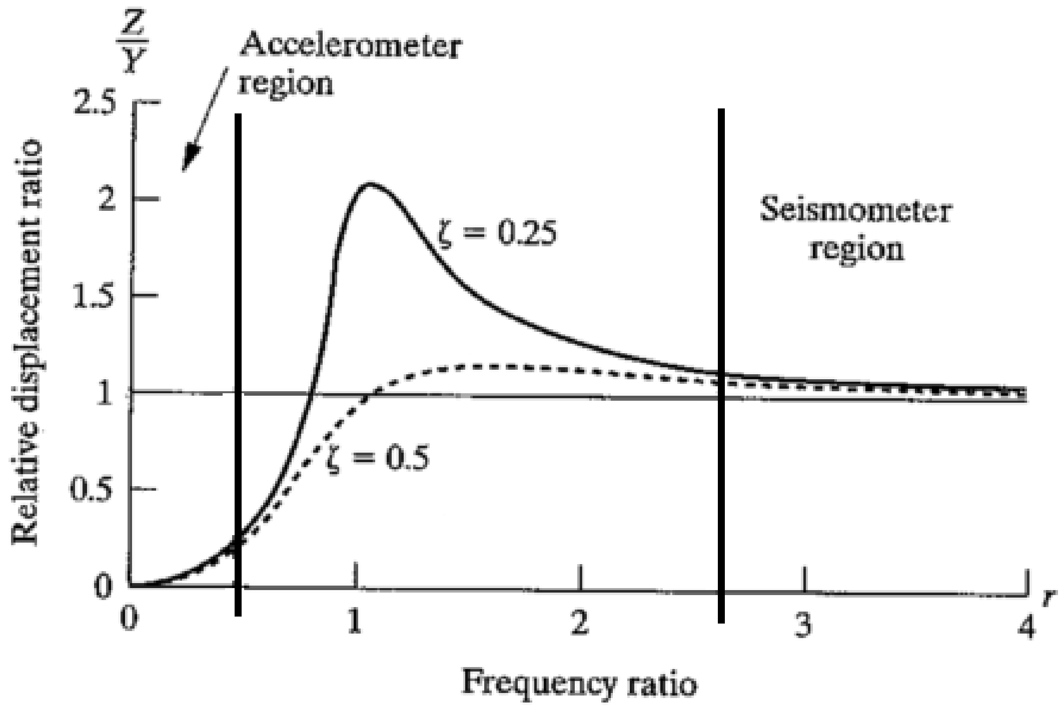
$$F = m\frac{d^2x}{dt^2} + c\frac{dx}{dt} + kx$$

$$v = \frac{dx}{dt}$$

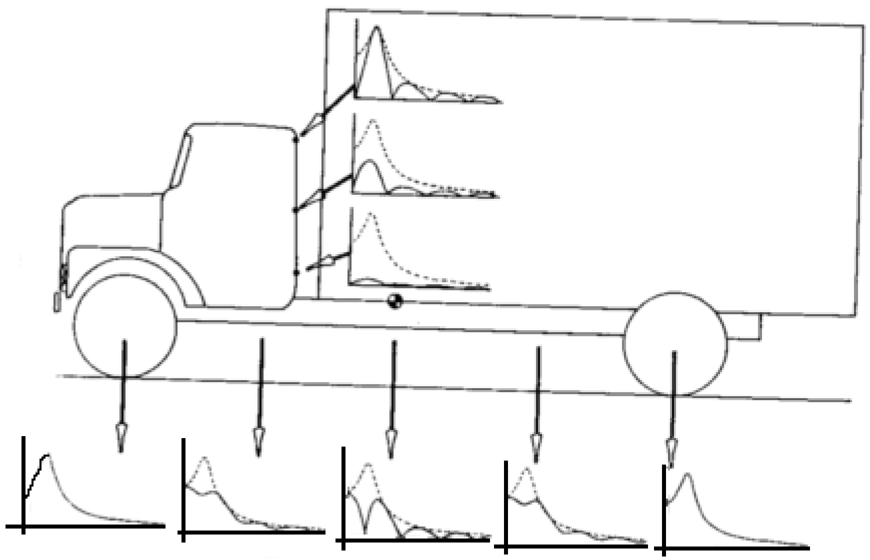
$$F = m\frac{dv}{dt} + cv + k\int vdt$$

$$e = Ri + L\frac{di}{dt} + \frac{1}{c}\int idt$$





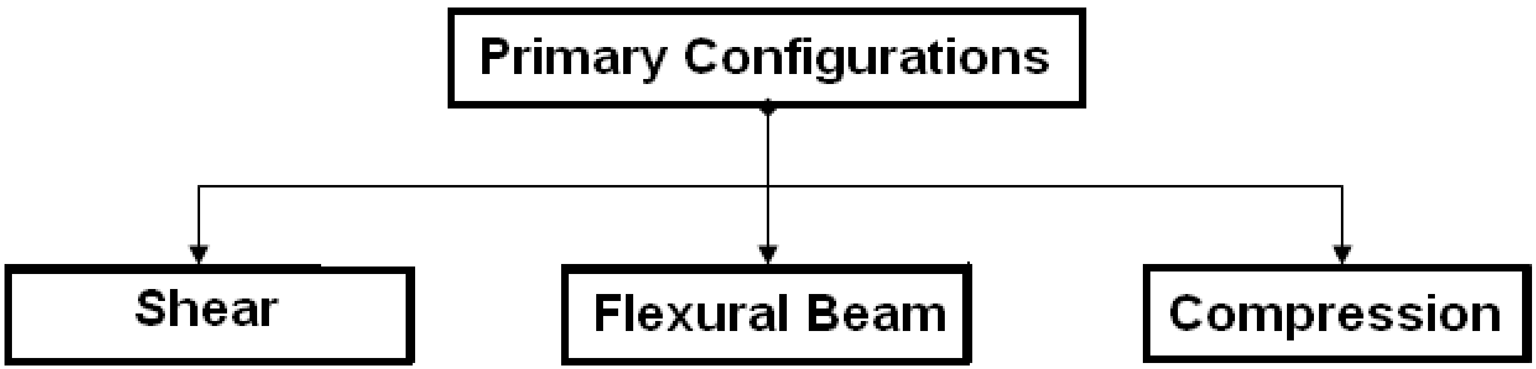
Magnitude frequency of the relative displacement for a transducer used to measure acceleration



Vibration and longitudinal response gain

Structures for Piezoelectric Accelerometers

A variety of mechanical configurations are available to perform the transduction principles of a piezoelectric accelerometer. These configurations are defined by the nature in which the inertial force of an accelerated mass acts upon the piezoelectric material.



Shear Mode

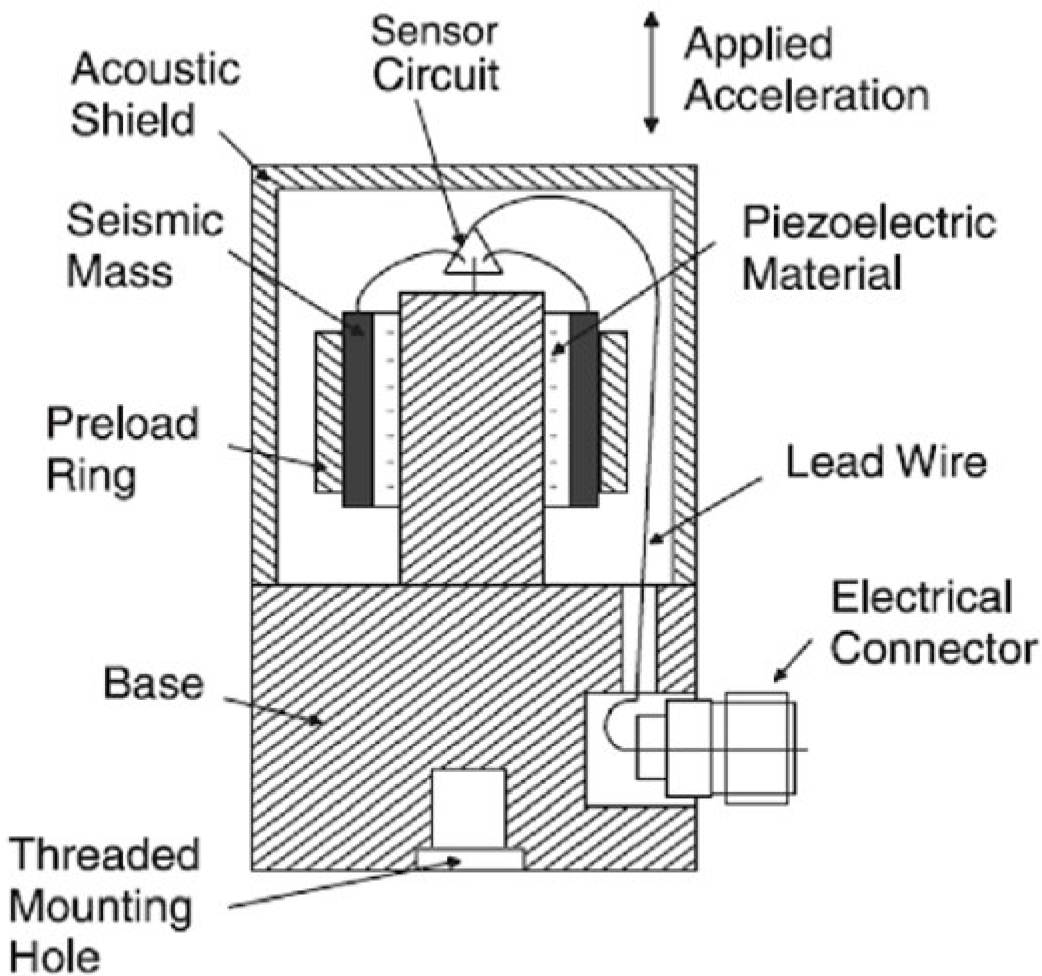
-Shear mode accelerometer designs bond, or “sandwich,” the sensing material between a center post and seismic mass.

-A compression ring or stud applies a preload force required to create a rigid linear structure.

-Under acceleration, the mass causes a shear stress to be applied to the sensing material.

-This stress results in a proportional electrical output by the piezoelectric material.

-The output is then collected by the electrodes and transmitted by lightweight lead wires to either the built-in signal conditioning circuitry, or directly to the electrical connector for a charge mode type.



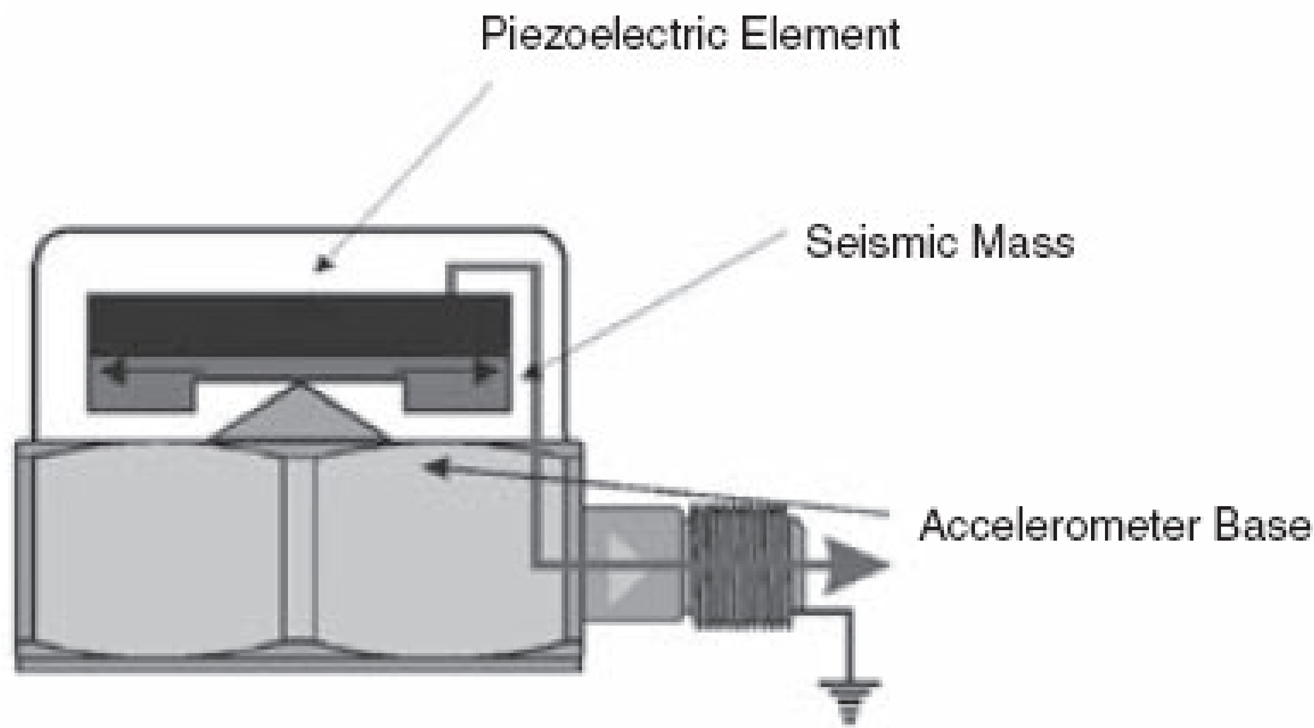
Shear mode accelerometer.

Flexural Mode

-Flexural mode designs utilize beam-shaped sensing crystals, which are supported to create strain on the crystal when accelerated.

-The crystal may be bonded to a carrier beam that increases the amount of strain when accelerated.

-Flexural beam designs are well suited for low frequency, low gravitational (*g*) acceleration applications such as those that may be encountered during structural testing.


Piezoelectric Element
Seismic Mass
Accelerometer Base

Compression Mode

-Compression mode accelerometers are simple structures which provide high rigidity.

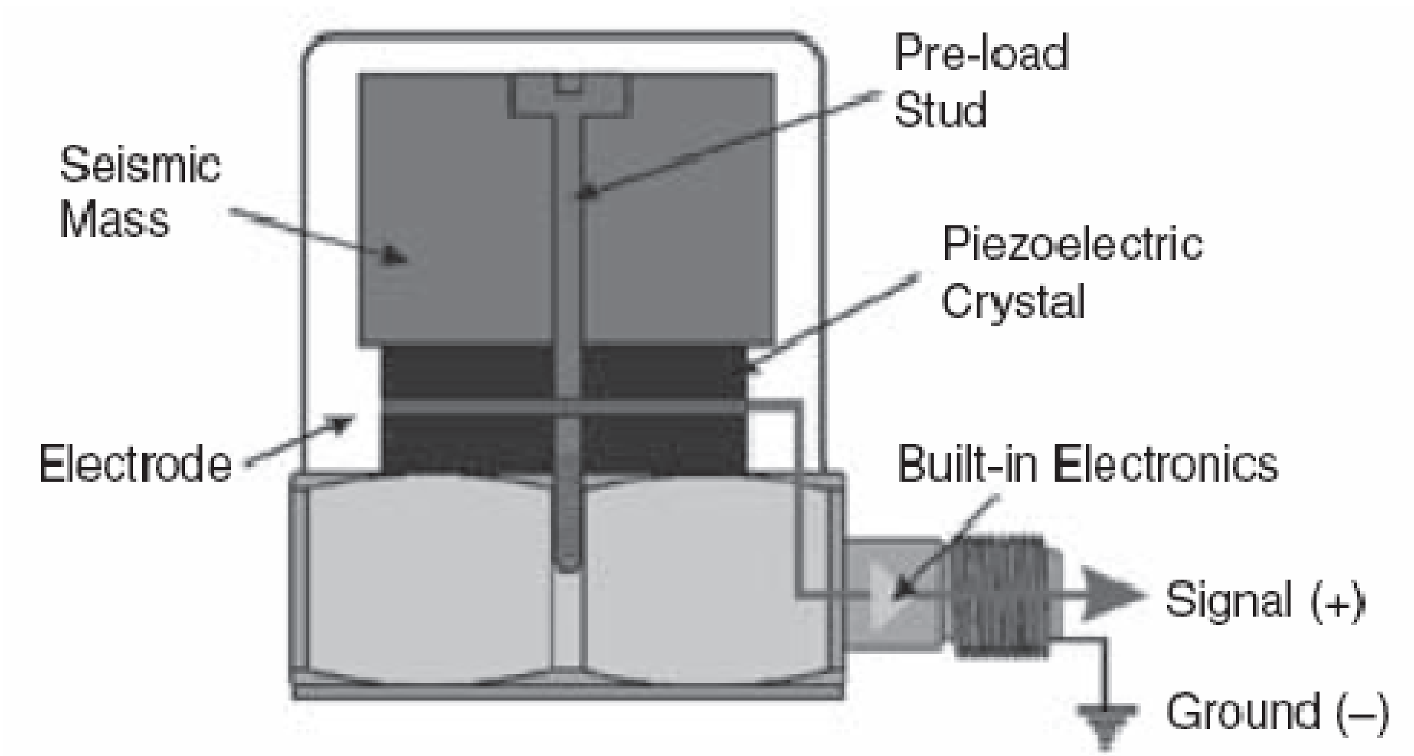
-Upright compression designs sandwich the piezoelectric crystal between a seismic mass and rigid mounting base.

-A pre-load stud or screw secures the sensing element to the mounting base.

-When the sensor is accelerated, the seismic mass increases or decreases the amount of compression force acting upon the crystal, and a proportional electrical output results.

The larger the seismic mass, the greater the stress and, hence, the greater the output.

This design is generally very rugged and can withstand high-*g* shock levels. However, due to the intimate contact of the sensing crystals with the external mounting base, upright compression designs tend to be more sensitive to base bending (strain).



Compression mode accelerometer.