# Lecture #6

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## Basic Intent

This lecture is intended to provide an overview of piezoelectric devices. Some examples are worked using this sensing technique.

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## Piezoelectricity

Piezoelectricity is the name of a phenomenon which sounds as if it might be similar to piezoresistivity, but there is really very little in common between these two. Piezoelectricity refers to a phenomenon in which forces applied to a segment of material lead to the appearance of electrical charge on the surfaces of the segment. The source of this phenomenon is the distribution of electric charges in the unit cell of a crystal. The textbook describes the example of the quartz crystal, in which forces applied along the x axis of the crystal lead to the appearance of positive and negative charges on opposite sides of the crystal along the z axis (Fig 1). The strain which is induced by the force leads to a physical displacement of the charge in the unit cell.

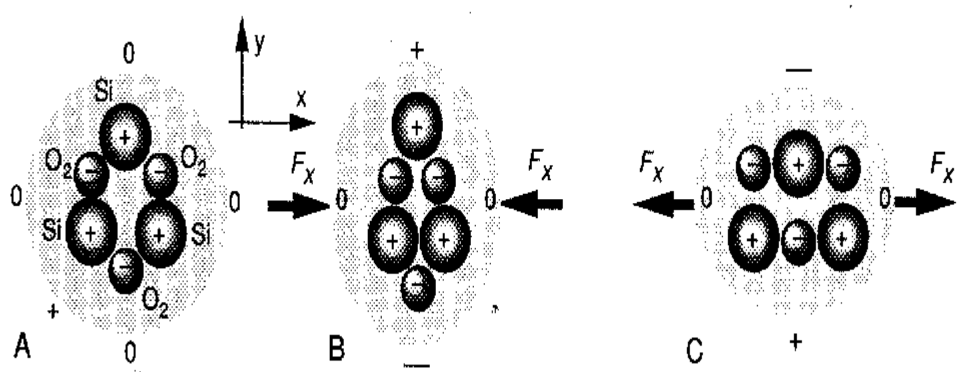


**Fig 1. Piezoelectricity**

This polarization of the crystal leads to an accumulation of charge according to the following expression:

$$Q \text{ (charge)} = \mathbf{d} F$$

In fact, the force is a vector quantity, and the **d** (piezoelectric coefficient) is a 3x3 matrix. Forces along the x axis produce charges along the x, y, and z axes, with the charge along the x axis given by the d11 coefficient of the matrix, the charge along the y axis given by the d21 coefficient, and so on.

Piezoelectric coefficients have been tabulated for several materials (primarily those materials with large coefficients), and a table of coefficients is in the textbook. The detailed properties of this phenomenon and the materials properties which are responsible for it are not of our concern in this course. We will need to perform calculations based on these materials and the piezoelectric effect, since this phenomena has been very useful in the development of sensors.

*(Incidentally, it is important to note that the last part of equation 3.7.10 in the book and the text immediately following it are incorrect.)*

Typical values of the piezoelectric charge coefficients are 1-100 pico-coulombs/N.

As an example, assume we have a 1 cm x 1cm slab of 1 mm thick PZT material. A 1 N force is applied along the z axis, which is the 1mm dimension. What voltage appears across electrodes on the large surfaces?

$$V = \frac{d_{33} L F}{\varepsilon \varepsilon_0 A} = \frac{\left(110 \times 10^{-12}\, C/N\right)\left(1 \times 10^{-3}\, m\right)(1N)}{\left(8.8 \times 10^{-12}\, \frac{C}{Vm}\right)(1200)\left(1 \times 10^{-2}\, m\right)^2} = 1.0 \times 10^{-1}\, V$$

The capacitance of this device is

$$C = \frac{\varepsilon \varepsilon_0 A}{d} = \frac{\left(8.8 \times 10^{-12}\, \frac{C}{Vm}\right)(1200)\left(1 \times 10^{-2}\, m\right)^2}{\left(1 \times 10^{-3}\, m\right)} = 1.1 \times 10^{-9}\, F$$

If we want to produce a larger voltage, we need to reduce the capacitance of this structure. The easiest way to do this is to reduce the area. Out of curiosity, how much has the length of the crystal changed under this load of 1 N?

$$\frac{F}{A} = E \frac{dL}{L}$$

$$dL = \frac{FL}{EA} = \frac{(1N)\left(1 \times 10^{-3}\, m\right)}{\left(8.3 \times 10^{10}\, N/m^2\right)\left(1 \times 10^{-2}\, m\right)} = 1.2 \times 10^{-10}\, m$$

An interesting corollary effect is that this effect is reversible - which is to say that application of voltages results in dimensional changes of the crystal. The effect is exactly the same, and the coefficients are exactly the same. In the above calculation, we found that a 1N force produces a 3 mV signal, and causes a 100Å change in crystal dimension.

The change in length per unit applied voltage is given by:

$$\frac{dL}{V} = \frac{(FL)/(EA)}{(d_{11}FL)/(\varepsilon\varepsilon_0 A)} = \frac{\varepsilon\varepsilon_0}{d_{11}E}$$

$$\text{for PZT.}\ \frac{\left(8.8\times10^{-12}\,C/Vm\right)(1200)}{\left(110\times10^{-12}\,C/N\right)\left(8.3\times10^{10}\,N/m^2\right)} 1.2\times10^{-9}\,m/V$$

Note that the intermediate expression turned out to depend only on the piezoelectric coefficient, the dielectric constant, and Young's modulus. This means that any shaped object of a given piezoelectric material will undergo the same change in length upon the application of a given voltage. It is interesting that the dimensions of the object completely cancel out. One could define another kind of material property for these piezoelectric materials based on this relation.

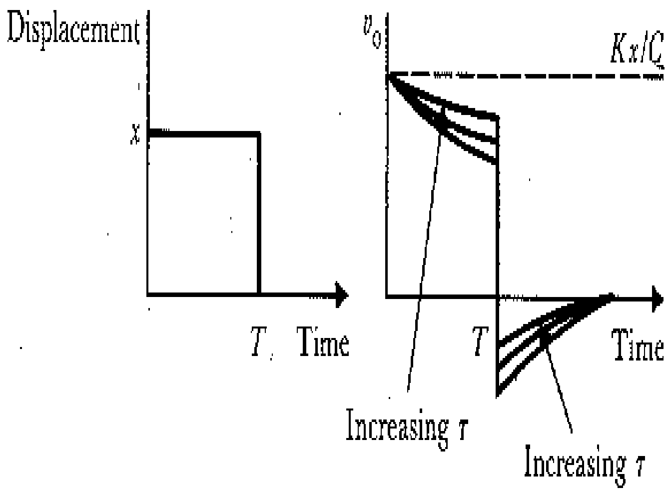


**Fig 2. Piezo leakage**

One interesting effect to take note of is that piezoelectrics are not generally very good dielectrics. In particular, piezoelectric materials are somewhat leaky (Fig 2). This means that a charge placed on a pair of electrodes gradually leaks away. Because of this phenomenon, there is a time constant for the retention of a voltage on the piezoelectric after the application of a force. This time constant depends on the capacitance of the element, and the leakage resistance. Typical time constants are of order 1 sec. Because of this effect, piezoelectrics are not very useful for the detection of static quantities, such as the weight of an object.

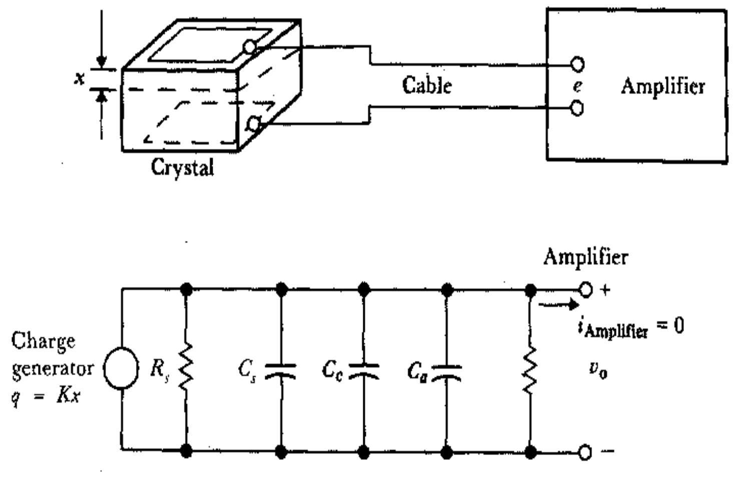


**Fig 3. Equivalent electrical circuit for piezomeasurement circuit.**
**Rx** = Resistance of piezo
**Cx** = Capacitance of piezo
**Cc** = Capacitance of cable
**Ca** = Capacitance of amplifier circuit
**Ra** = Resistance of amplifier circuit

Another important aspect to the use of piezoelectrics is the fact that they are fabricated using a process which relies on the crystallization of the lattice in a particular arrangement. This is accomplished by heating the crystal to above the Curie temperature while applying voltages to the electrodes. If the crystal is ever heated to near the Curie temperature, it can become `de-poled' which can result in a loss of piezoelectric sensitivity. For various materials, this Curie temperature can be as high as 600C or as low as 50C. The need to stay below this temperature can impose serious constraints on the applicability of these sensors.

Overall, piezoelectric elements have several important advantages over other sensing mechanisms. First and foremost is the fact that the device generates its own voltage. Because of this, the sensor element does not need to have power applied to it in order to function. For applications where power consumption is a significant constraint, piezoelectric devices can be very valuable. In addition to this, the piezoelectric effect has some interesting scaling laws which suggest it is useful in small devices. The primary disadvantage of piezoelectric sensing is that it is inherently sensitive only to time varying signals. Many application require sensitivity to static quantities, and piezoelectric sensing simply does not work for such applications.

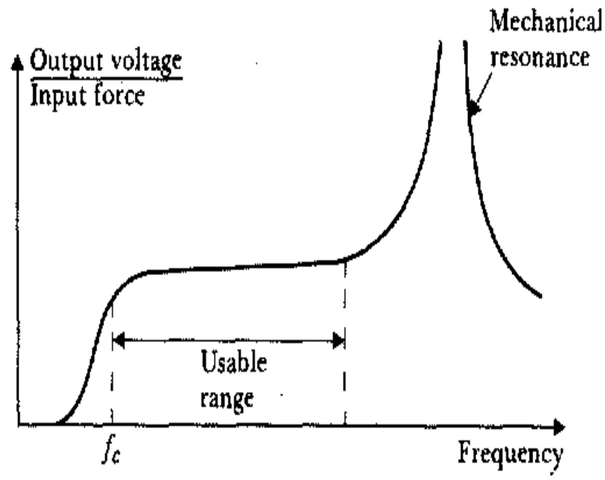


**Fig 3. Useful frequency range**

Nevertheless, if you have a time-varying signal, you should give serious thought to the use of piezoelectric sensing elements.

One recently-developed technology for piezoelectric materials involves the use of poly-vinyl di-fluoride films which are treated during manufacture to have a piezoelectric coefficient. The primary advantage of this process is that the films can be made at extremely low cost, and they are becoming very popular for low-cost sensing applications. One company in particular has pioneered the development of this material **AMP Inc.**. In addition to the successful commercialization of a number of products based on these piezo films, they offer unmounted film elements which are suitable for use in the construction of simple test devices. These film elements will be the basis for Laboratory assignment #2 of this course - Build your own Accelerometer.

Before we look at the lab in detail, lets review the properties for the film. Throughout this review, I'll follow the descriptions given in the handout entitled : **Piezo Films Technical Manual from AMP**.

*(Note: The lecture continues on to a more detailed discussion of piezoelectric sensors using the handout "Piezo Films Technical Manual from AMP". The copy of the handout is provided for all students and therefore is not duplicated in the Web notes. Please refer to the copy for the lecture relating to the piezo film sensors.)*

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# Piezoelectric Accelerometer

A final example is that of a piezoelectric accelerometer. In this case, we consider an accelerometer which consists of a 10 gm mass resting on a slab of piezoelectric material. Assume the piezo slab has dimensions of 1 square cm in area, and 1mm thick. It is made of PZT material with its z axis perpendicular to the large faces, which are coated with metal contacts. What voltage is expected? where is the resonance?

The voltage is given by :

$$V(F) = \frac{d_{33}L}{\varepsilon\varepsilon_0 A}F = \frac{\left(110\times10^{-12}\,C/N\right)\left(1\times10^{-3}\,m\right)}{\left(8.8\times10^{-12}\,C/Vm\right)(1200)\left(1\times10^{-2}\,m\right)^2}F = 1.0\times10^{-1}\frac{V}{N}\cdot F$$

an acceleration of 1 milli-g exerts a force given by Newton's law :

$$F = ma = \left(1\times10^{-2}\,kg\right)\left(1\times10^{-3}\,g\right)\left(9.8\,m/s^2\right) = 9.8\times10^{-5}\,N$$

which would produce a voltage of ~10^-4 V. This is measurable. As we discussed in the piezoelectric sensor lecture, this situation can be improved in several ways. For instance, the piezoelectric element can have a smaller area and a larger thickness.

The resonant frequency can be calculated (an exercise for the reader) and is of order 200 kHz for the above geometry. So this device can be good for applications which require sensitivity to very high frequency vibration signals. It has the added feature that it does not require excitation voltages. On the other hand it does require a good preamplifier.

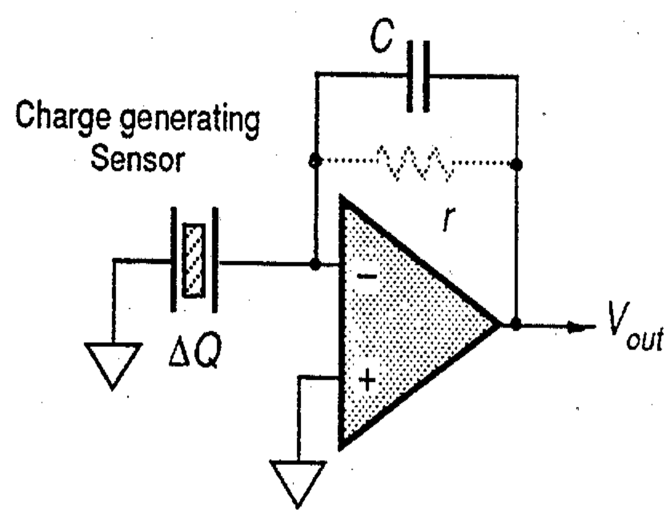


**Fig 4. Charge amplifying circuit**

In any case, piezoelectric accelerometers are on the market, and are primarily offered for vibration measurement. For moderate signals (milli-gs), fairly small devices with simple circuits are quite sufficient, so these devices can be in the 10-100 dollar range.

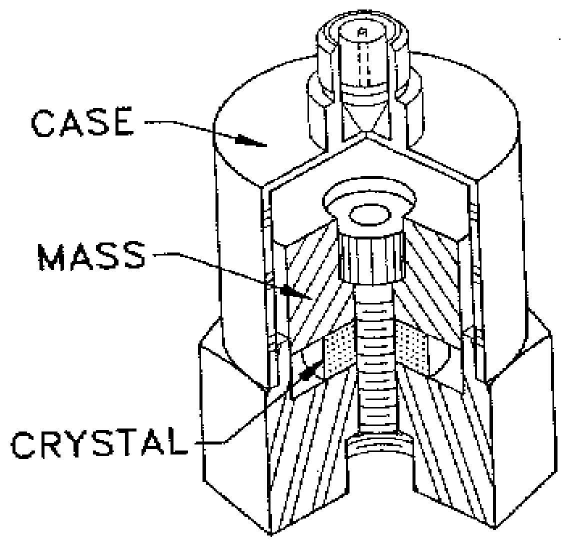


**Fig 5. Commercial accelerometer**