Energy harvesting using Piezo-Electric Effect

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Abstract: Piezoelectric materials can be used as mechanisms to transfer mechanical energy, usually ambient vibration, into electrical energy that can be stored and used to power other devices. With the recent advances in wireless and MEMS technology (micro-electro-mechanical system), sensors can be placed in exotic and remote locations. Since these devices are wireless it becomes necessary that they have their own power supply. The power supply in most cases is the conventional battery; however, problems can occur when using batteries because of their finite life span. Because most sensors are being developed so that they can be placed in remote locations such as structural sensors on a bridge or GPS tracking devices on animals in the wild, obtaining the sensor simply to replace the battery can become a very expensive task.

These issues can be potentially alleviated through the use of power harvesting devices. The goal of a power harvesting device is to capture the normally lost energy surrounding a system and convert it into usable energy for the electrical device to consume. By utilizing these untapped energy sources electronics that do not depend on finite power supplies, such as the battery, can be developed. This source of energy is ideal for the use of piezoelectric materials, which have the ability to convert mechanical strain energy into electrical energy and vice versa.

Keywords: piezoelectric, energy, batteries, power, harvesting.

1. Introduction

Piezoelectric Effect is the ability of certain materials to generate an electric charge in response to applied mechanical stress. The word Piezoelectric is derived from the Greek piezein, which means to squeeze or press, and piezo, which is Greek for “push”. Many materials, both natural and synthetic, exhibit piezoelectricity.

The direct piezoelectric effect was first seen in 1880, and was initiated by the brothers Pierre and Jacques Curie. By combining their knowledge of pyro-electricity with their understanding of crystal structures and behavior, the Curie brothers demonstrated the first piezoelectric effect by using crystals of tourmaline, quartz, topaz, cane sugar, and Rochelle salt. Their initial demonstration showed that quartz and Rochelle salt exhibited the most piezoelectricity ability at the time. Over the next few decades, piezoelectricity remained in the laboratory, something to be experimented on as more work was undertaken to explore the great potential of the piezoelectric effect. The breakout of World War I marked the introduction of the first practical application for piezoelectric devices, which was the sonar device. This initial use of piezoelectricity in sonar created intense international developmental interest in piezoelectric devices. Over the next few decades, new piezoelectric materials and new applications for those materials were explored and developed. During World War II, research groups in the US, Russia and Japan discovered a new class of man-made materials, called ferroelectrics, which exhibited piezoelectric constants many times higher than natural piezoelectric materials. Although quartz crystals were the first commercially exploited piezoelectric material and still used in sonar detection applications, scientists kept searching for higher performance materials. This intense research resulted in the development of barium titanate and lead zirconate titanate, two materials that had very specific properties suitable for particular applications.

2. Main Work

DETAILED DISCUSSION

When the crystal is mechanically strained, or when the crystal is deformed by the application of an external stress, electric charges appear on certain of the crystal surfaces; and when the direction of the strain reverses, the polarity of the electric charge is reversed. This is called the direct piezoelectric effect, and the crystals that exhibit it are classed as piezoelectric crystals.

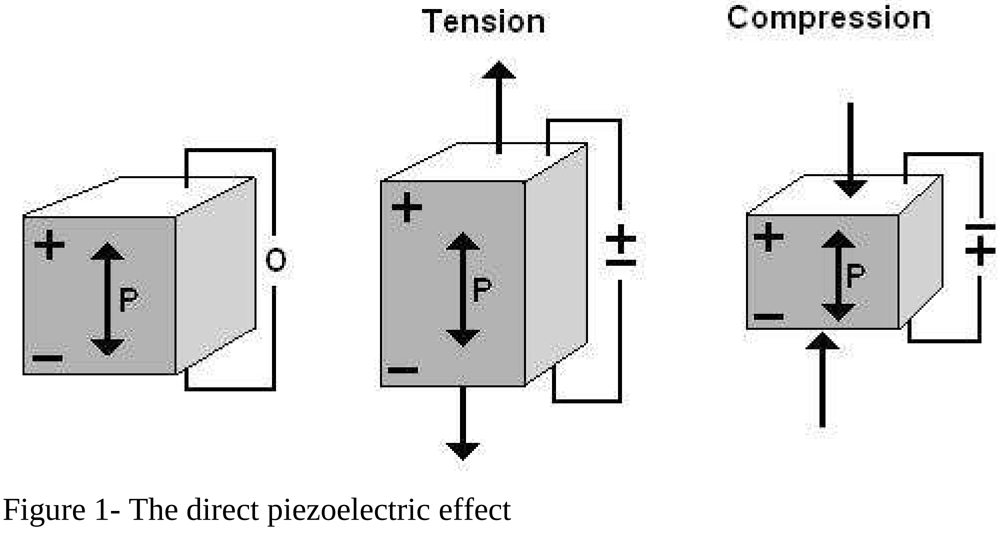


Figure 1- The direct piezoelectric effect

Conversely, when a piezoelectric crystal is placed in an electric field, or when charges are applied by external means to its faces, the crystal exhibits strain, i.e. the dimensions of the crystal
change. When the direction of the applied electric field is reversed, the direction of the resulting
strain is reversed. This is called the converse piezoelectric effect.

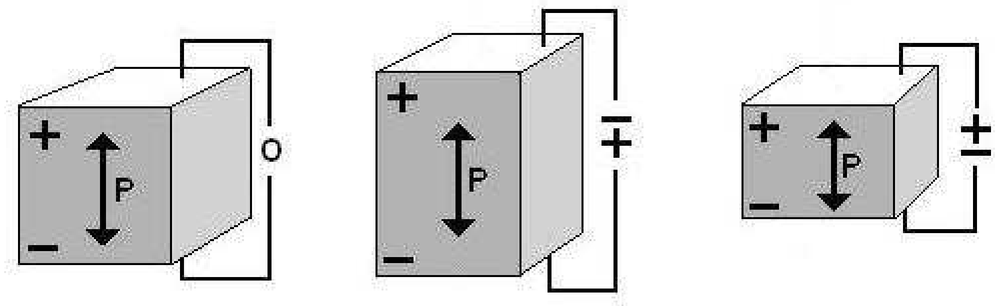
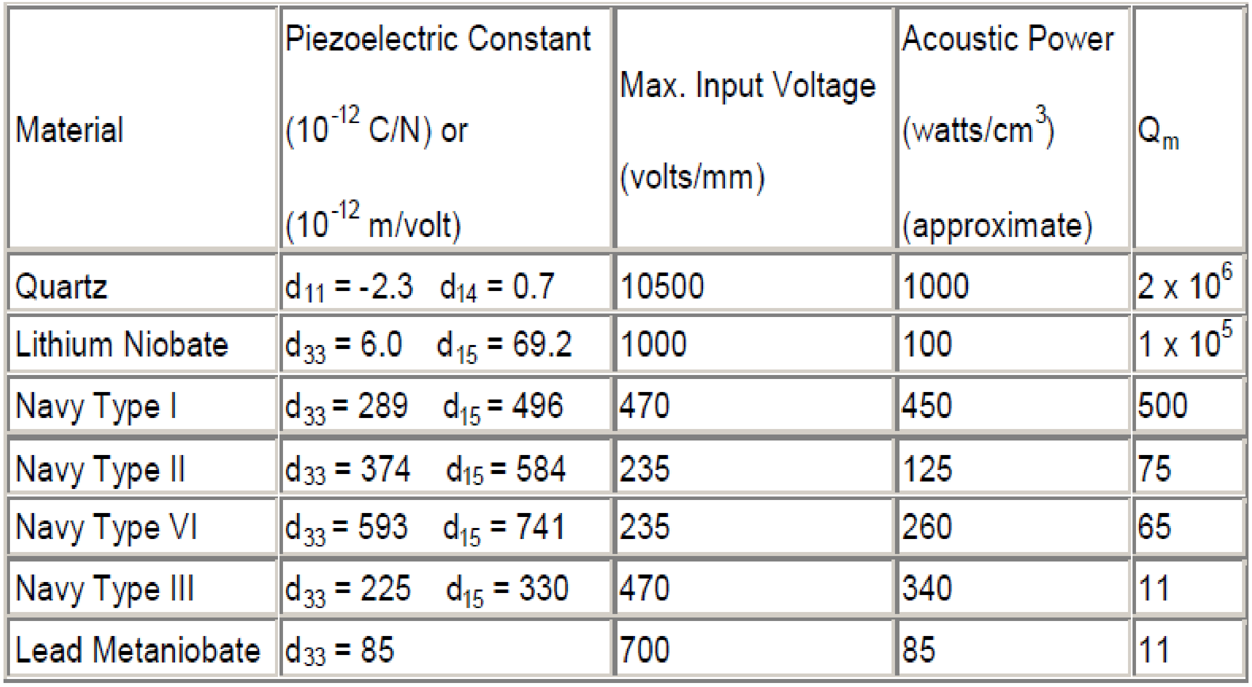


Figure 2- The converse piezoelectric effect

2.1. *Piezoelectric Constants*

Piezoelectricity has been demonstrated qualitatively in approximately 1000 crystal materials.
These include materials where piezoelectricity occurs naturally, and other single crystal and polycrystalline materials in which piezoelectricity can be induced by the application of high voltage or poling. Typical piezoelectric materials available from Boston Piezo-Optics Inc. are listed in Table 1. In both the direct and converse piezoelectric effects, the strain and stress are related to the electrical parameters by the piezoelectric constants, d_{ij}, g_{ij}, h_{ij} and e_{ij}. These piezoelectric constants have different values for different directions in the material. Furthermore,
the stresses and strains are related to each other by the elastic constants of the material in different directions.

Table 1- Material Characteristics



Material	Piezoelectric Constant (10^{-12} C/N) or (10^{-12} m/volt)	Max. Input Voltage (volts/mm)	Acoustic Power (watts/cm^3) (approximate)	Q_m
Quartz	$d_{11} = -2.3$ $d_{14} = 0.7$	10500	1000	2×10^6
Lithium Niobate	$d_{33} = 6.0$ $d_{15} = 69.2$	1000	100	1×10^5
Navy Type I	$d_{33} = 289$ $d_{15} = 496$	470	450	500
Navy Type II	$d_{33} = 374$ $d_{15} = 584$	235	125	75
Navy Type VI	$d_{33} = 593$ $d_{15} = 741$	235	260	65
Navy Type III	$d_{33} = 225$ $d_{15} = 330$	470	340	11
Lead Metaniobate	$d_{33} = 85$	700	85	11

2.2. *Crystal Orientation*

The direction in which tension or compression develops polarization parallel to the strain is called the piezoelectric axis. In quartz, this axis is known as the "X-axis", and in poled ceramic materials such as PZT the piezoelectric axis is referred to as the "Z-axis". From different combinations of the direction of the applied field and orientation of the crystal it is possible to produce various stresses and strains in the crystal. For example, an electric field applied perpendicular to the piezoelectric axis will produce elongation along the axis as shown in Figure 2. If, however, the electric field is applied parallel to the piezoelectric axis, a shear motion is induced.

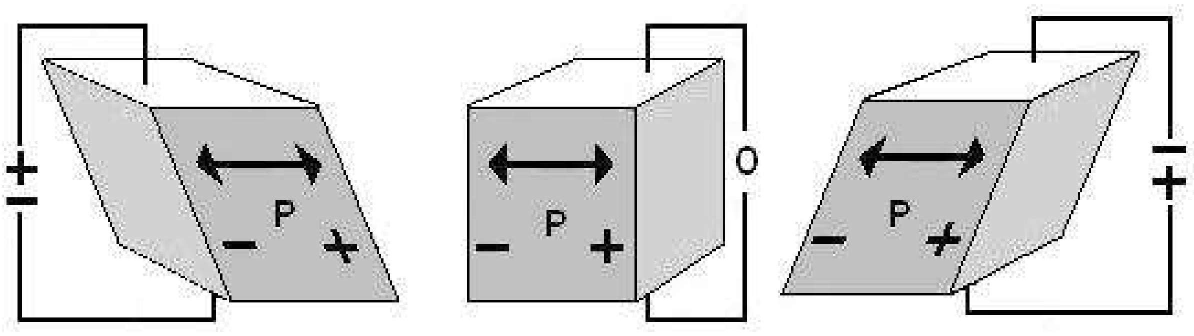


Figure 3- Shear motion

2.3. *Resonance Frequencies*

If, instead of the DC field shown in Figures 2 and 3, an alternating field is applied, the crystal will vibrate at the frequency of the AC field. If the frequency of the AC field corresponds with the frequency where the thickness of the crystal represents half a wavelength, the amplitude of the crystal vibration will be much greater. This is called the crystal's fundamental resonance frequency. The crystal will also have frequencies of large amplitude whenever the thickness of the crystal is equal to an odd multiple of half a wavelength. These are termed harmonic, or overtone resonance, frequencies (such as 3rd overtone, 5th overtone, etc.). The largest amplitude, however, occurs at the fundamental frequency and as the harmonic number increases the vibration amplitude decreases. A large percentage of energy loss occurs at the two faces of a crystal. For this reason, Boston Piezo-Optics provides overtone polished crystals for use at the higher harmonic frequencies. This specially developed process limits the energy loss, and thereby facilitates the use of higher harmonics (9th overtone, 11th overtone, etc.) and increases the amplitude of all the resonance frequencies.

2.4. The Piezoelectric Constants Defined

It is instructive to take a close look at the meanings of several piezoelectric constants. The most commonly measured of these constants is the piezoelectric strain constant d_{ij}. In the longitudinal mode of X-cut quartz, the applicable value is d11. For an applied voltage, Vin, d11 will determine the resultant thickness change Δtout or

$\Delta tout = d_{11} V_{in}$ (Equation 1.)

Equation 1 is only used to interpret the converse piezoelectric effect. To determine the resultant voltage for the direct piezoelectric effect two different piezoelectric constants are used. The piezoelectric deformation constant h_{ij} is used to relate the resultant voltage to a given deformation. In this case the thickness change, Δtin, produces an output voltage according to

$Vout = h_{11}\Delta tin$. (Equation 2)

A second constant, the piezoelectric pressure constant, g_{ij} is used to relate the resultant voltage to a given applied pressure, P, the resultant voltage Vout is given by

$Vout = g11P$. (Equation 3)

Electro-mechanical Coupling Constant

For many applications the material constant of interest is the electro-mechanical coupling factor,
k_{ij}. This constant is a measure of the piezoelectric material's ratio of output energy to input energy or efficiency. It is related to the piezoelectric constants according to Equation 4

$k_{ij} \approx h_{ij} d_{ij}$ (Equation 4)

The coupling factor is electrically determined using the resonance frequency data. In Equation 5
the resonance frequency f_r and the antiresonance frequency f_a are used to determine the widely
used thickness mode coupling factor k_t. The locations of these two frequencies are depicted for a
hypothetical transducer in Figure 4.

$k_t = \pi/2\ (f_r/f_a)\ \mathrm{Cot}\ \pi/2\ (f_r/f_a)$ (Equation 5)

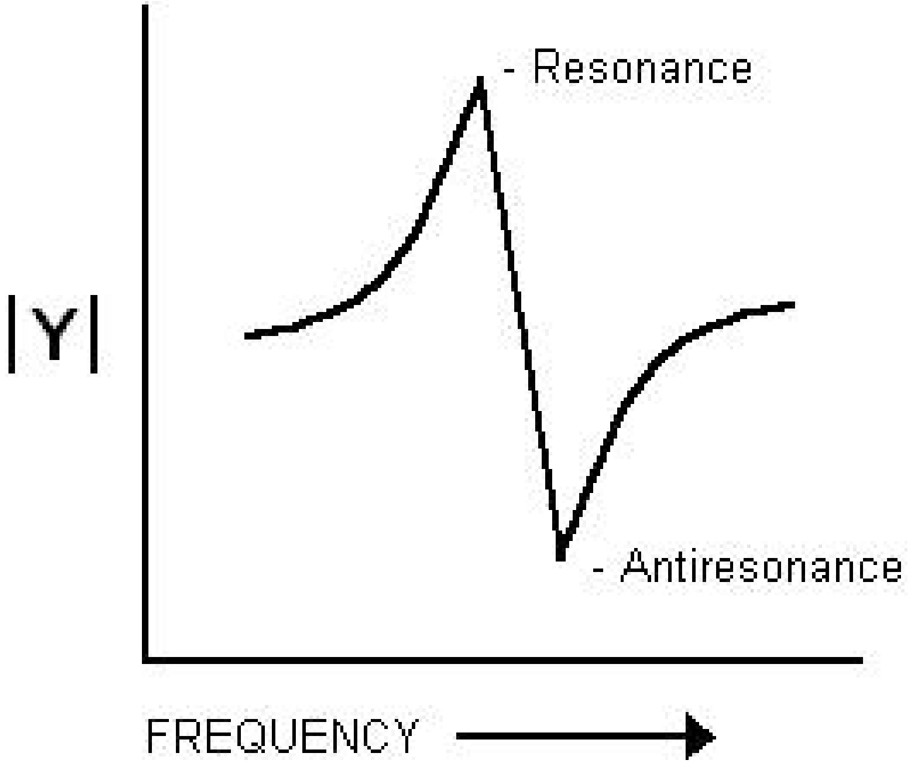


Figure 4- Theoretical frequency response

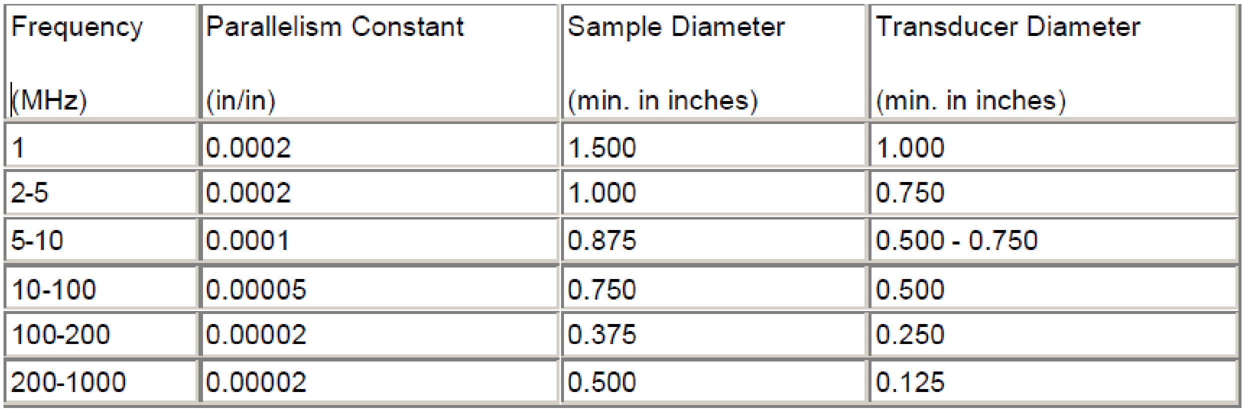
2.5. Displacement Amplitude and Output Power

In many instances, it is desirable to know the displacement amplitude and power output of a transducer. Theoretical expressions can be derived for these quantities but they are usually complicated functions involving a number of parameters. Theoretically, piezoelectric plates can be excited to any amplitude of vibration at any frequency, however far from resonance, if the applied voltage is sufficiently high. In practice, however, the maximum power output which can be achieved without damaging the crystal depends on several variables including the type of mounting, frequency, medium, inertia, elastic compliance and internal damping losses of the vibrating crystal itself. These internal losses are a function of the driving frequency. When the operating frequency approaches a resonance, the internal losses sharply decrease and accordingly the amplitude of deformation increases. For high fields, the crystal can suffer dielectric breakdown and mechanical fracture. A resonant voltage which is safe when the transducer is in a liquid or backed by a solid medium may not be safe if the transducer is operated in air. In Table 1, the maximum input voltage for several materials is given. Also given is the approximate maximum acoustic power which is dependent on the input voltage, frequency, electro-mechanical coupling and dielectric properties of the material.

2.6. Using Overtone Resonance

The particular size and frequency of the transducer element to be used depends on the conditions at which one plans to work. For example, a compression mode PZT-5A transducer, 0.500" in diameter with a 5 MHz fundamental frequency, is approximately 0.0168" thick and can be driven at its odd harmonics to cover a frequency range of 5 to 105 MHz For higher frequencies up to 1000 MHz, a transducer crystal made from X-cut quartz with a fundamental frequency of 20 MHz (thickness 0.00564") will experience smaller internal losses and is easier to drive at its higher harmonics. Transducers can also be fabricated in the KHz range for low frequency work.

Table 2- Size Selection Guide



Frequency (MHz)	Parallelism Constant (in/in)	Sample Diameter (min. in inches)	Transducer Diameter (min. in inches)
1	0.0002	1.500	1.000
2-5	0.0002	1.000	0.750
5-10	0.0001	0.875	0.500 - 0.750
10-100	0.00005	0.750	0.500
100-200	0.00002	0.375	0.250
200-1000	0.00002	0.500	0.125

3. Conclusion

The concept of utilizing piezoelectric material for energy generation has been studied by many researchers over the past few decades. Much of the research into power harvesting has dealt with optimizing the power harvesting configuration or developing circuitry to store the energy, however, some researchers have looked into the ability to use circuitry for extracting more energy from the piezoelectric material. One such study, used the concept of energy transfer from the piezoelectric to the load and maximized when the impedance of the two are matched, to develop a circuit whose impedance could be modified. An adaptive step down DC-DC converter was used to maximize the power output from a piezoelectric device. It was found that at very high levels of excitation the power output could be increased by as much as 400%. However, this study did have a drawback, the additional electronic components required to optimize the power output dissipated energy. This additional circuitry needed an open circuit voltage greater than ten volts for an increase in the generated power. To overcome this problem, Circuit was modified by removing the adaptive circuitry and replacing it with a fixed switching frequency. However, the improvements made to the circuit now required more than 25 volts open circuit for increased power to be supplied to the load. Furthermore, the level of excitation necessary to produce greater than 25 volts open circuit is far greater than present in any typical vibrating machinery, making the circuitry unrealistic. While significant headway has been made in the field of power harvesting, the amount of energy produced in most cases is still not sufficient to power the desired electronic systems.

Another study showed that a watch battery could be recharged from a completely discharged state, in less than one hour by vibrations consistent in amplitude with those found on a typical vibrating machine. Furthermore, comparing this new concept to the more traditional method of storing the energy in a capacitor it was found that the use of a battery provided more flexibility in the electronics to be powered, due to the capacitor's quick discharge time.

The key to replacing the finite power supplies used for these applications is the ability to capture the ambient energy surrounding the electronics. Piezoelectric materials form a convenient method of capturing the vibration energy that is typically lost and converting it into usable electrical energy. This material has been used in the power harvesting field for some time; however, the energy generated by these materials is far too small for directly powering most electronic systems. This problem has been found by most all researchers that have investigated this field, thus showing the need for methods to accumulate the generated energy until a sufficient amount is present.

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