An Overview of the Properties of Different Piezoceramic Materials

Material Families

Four of the more important types of piezoceramic materials are introduced below.

Lead Zirconate-Titanate - Because of their high coupling factors and wide range of possible variations, most of the piezoceramics used in the world are a variation of lead zirconate-titanate (PZT). PZTs are often broken into two groups, hard and soft. Hard PZT materials are typically used for applications where low energy loss is critical. Soft PZT materials are used where large response or bandwidth is needed.

Lead Metaniobate - Lead metaniobate ceramics have unusual properties that can make them an ideal choice for requiring high bandwidth.

Lead Titanate - Lead titanate (PT) is often used for high intensity focused ultrasound (HIFU) applications.

Bismuth Titanate - Bismuth titanates have high Curie temperatures and are used in applications where most other materials will not survive.

Coupling Coefficients

Let us consider a piezoceramic formed into a disk with one electrode covering the entire top surface and a second electrode covering the entire bottom surface (see Figure 1). The axes of this structure are defined in Figure 2. The polarization direction is parallel to the central axis 3 of the disc. The relative movement motion of the top and bottom surfaces of the disk when it is driven by a voltage across the 3 axis is characterized by thickness coupling coefficient d_{33}. The change in the diameter of the disc is characterized by the radial coupling coefficient d_{31}.

The same coefficient describes the reverse response. That is, d33 is also proportional to the voltage generated by squeezing the ceramic along the central axis 3. d31 is proportional to the voltage generated by radially compressing the part.

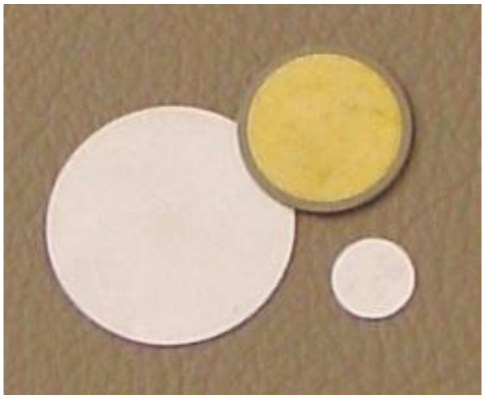

Figure 1: Piezoelectric Disks. *A metal electrode covers the top and a second metal electrode covers the bottom of the disks.*

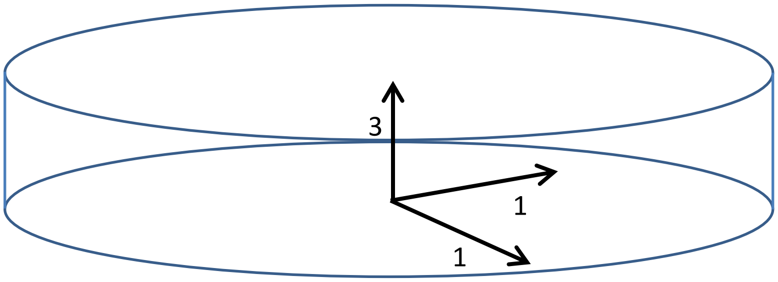

Figure 2: *Axes in a piezoceramic disk. For piezoceramic disks as shown in Figure 1, the two axes 1, which are in the plane of the disk, are equivalent. The axis 3 is perpendicular to the plane of the disk.*

Dielectric Constant

In general, a pair of electrodes separated by a dielectric material is a capacitor, and piezoceramic devices behave much like an ordinary capacitor. The coefficient K_3 compares the capacitance of the piezoceramic to a capacitance of a pair of plates of the same area and gap, but with only air between the plates. Typical values of K_3 are in the range of hundreds or thousands. The capacitance of a piezoceramic is sensitive to the stress on the part.

The capacitance of piezoceramics increases with temperature and decreases with stress on the ceramic. The capacitance is also prone to significant hysteresis. After a large thermal excursion or hard driving, the capacitance of the part may take tens of hours to return to its prior value.

Resonance Frequencies

If an ac voltage is applied to a piezoceramic disc with a diameter several times its thickness, two series of resonances may be observed. These resonance values are associated with reflections of ultrasound within the body of the ceramic. The resonance at the lowest frequency corresponds to motion in the largest dimension of the ceramic, which in this case is in the radial direction of the ceramic (see Figure 3). Often, several harmonics will also be seen at higher frequencies (see Figure 4).

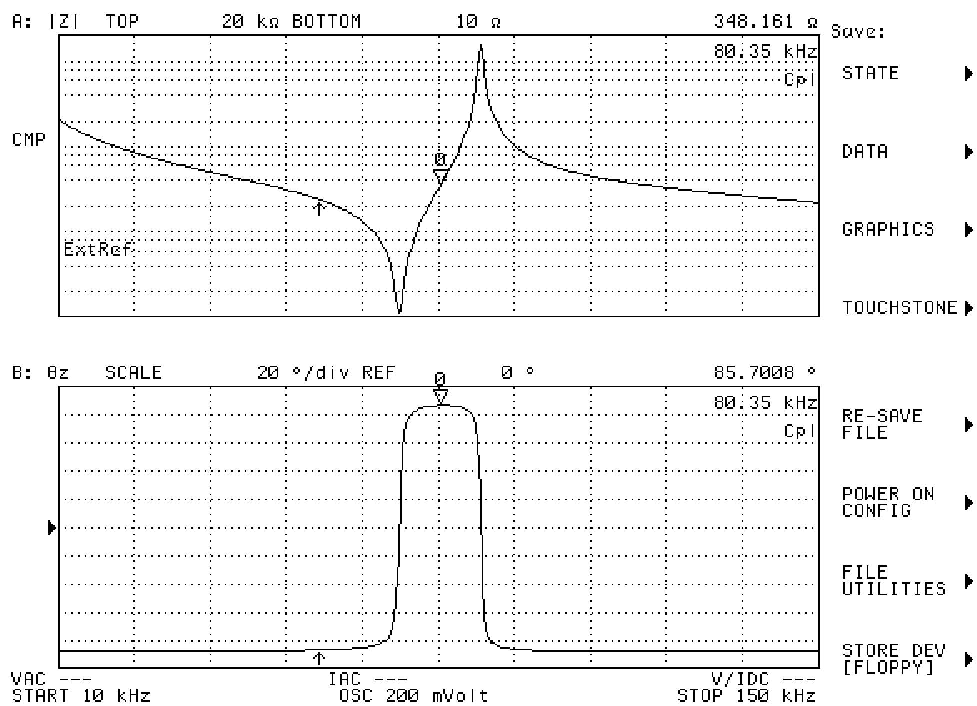

Figure 3: Fundamental Radial Resonance. *The fundamental resonance consists of a resonant and antiresonant frequency. The impedance (top curve) drops to a minimum at the resonant frequency and rises to a maximum at the antiresonant frequency. The phase angle (bottom curve) rises to a maximum value roughly at the center of the resonance.*

The first thickness resonance appears quite different from the radial harmonics that are found just below it (see Figure 5). The impedance drops to a much lower value and the span in frequency is far wider. The thickness mode frequency often appears much “rougher” than the radial mode. This is because the harmonics of the radial mode are excited by the strong thickness mode.

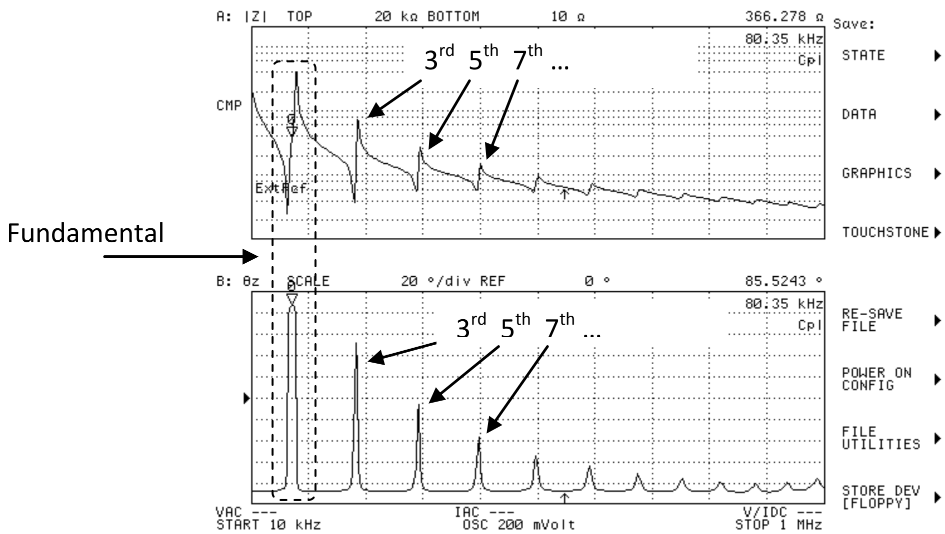

Figure 4: Radial Frequency Harmonics. *The fundamental resonance is followed by a series of odd harmonics at progressively higher frequencies. The strength of the harmonic and the spacing between the resonances decreases as the order increases.*

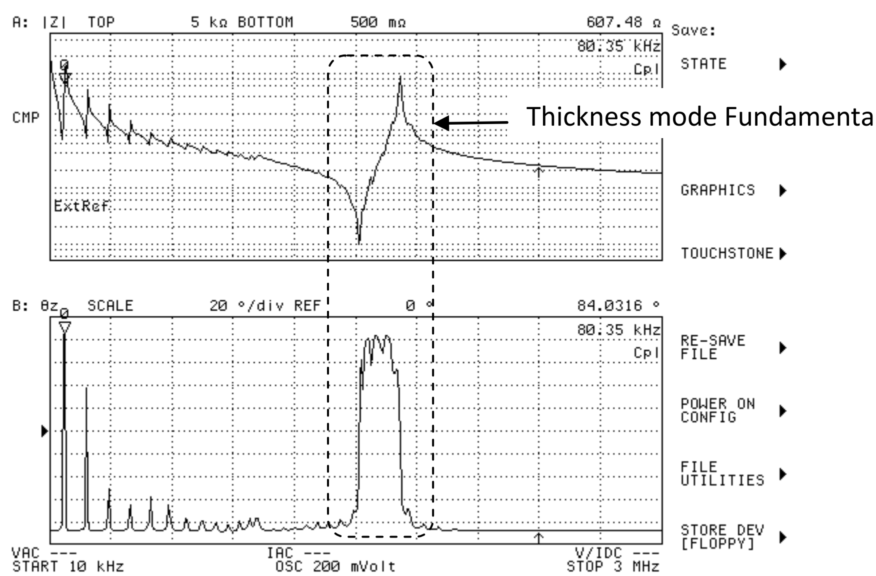

Figure 5: Fundamental Thickness Mode Resonance. *The thickness mode resonance is much wider and stronger than the radial mode harmonics.*

Figure 6 shows that the frequency spans of the increases and decreases in impedance and phase angle, which give it the ragged appearance, match the step size of the harmonic modes at frequencies just below the thickness mode. Just like the radial mode, the thickness mode has a series of odd harmonics which occur at higher frequencies (see Figure 7).

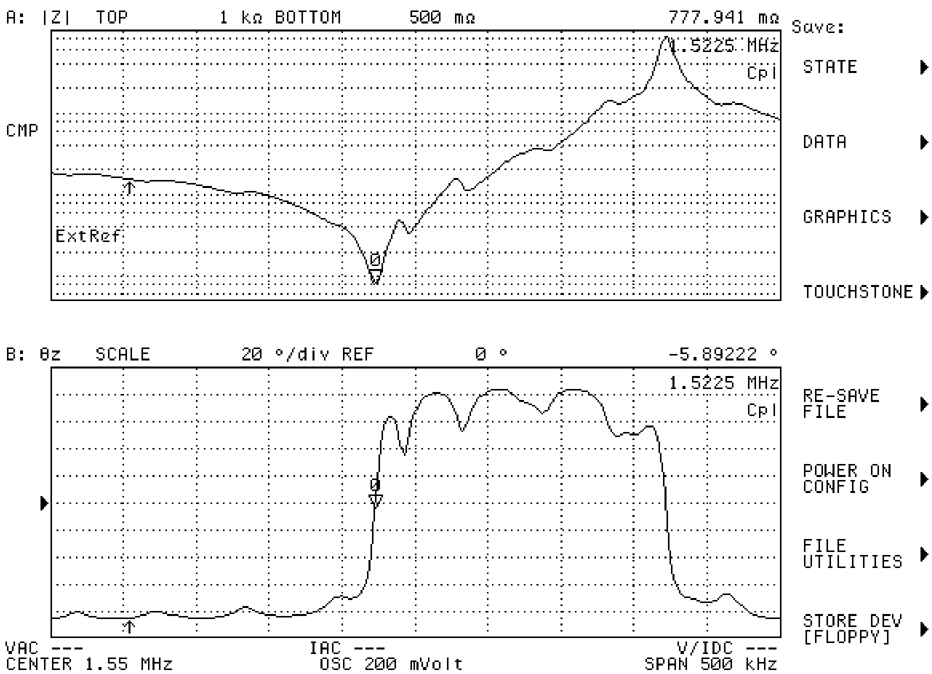

Figure 6: Fundamental Thickness Mode and Nearby Radial Mode Harmonics. *Note the spacing of the "serrations" in the impedance (upper curve) and phase angle (lower curve) in the radial mode matches that of the radial mode harmonics seen to the left (lower frequency).*

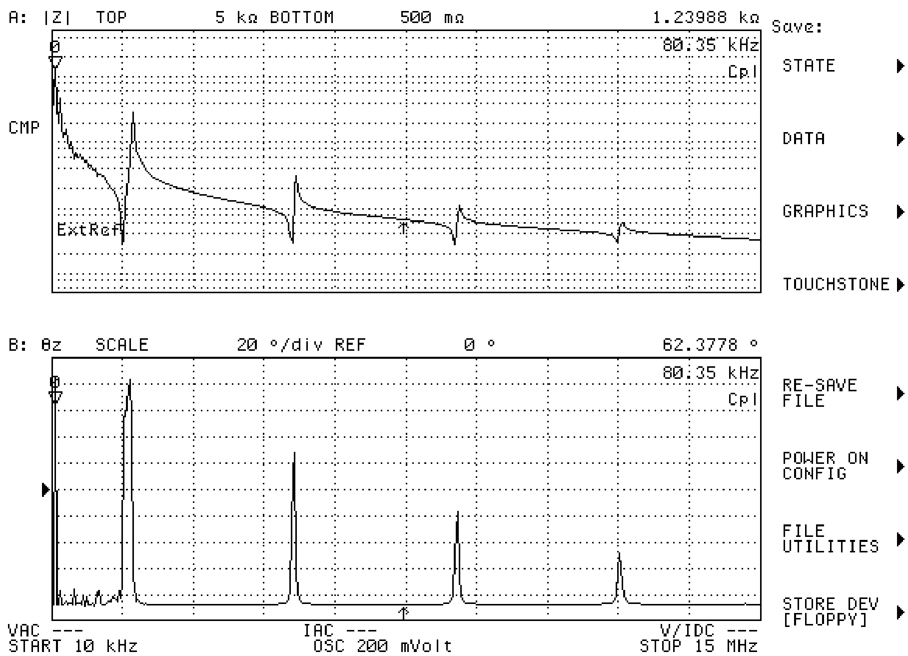

Figure 7: Thickness Mode Harmonics. *The 3rd, 5th, and 7th harmonics are progressively weaker than the fundamental thickness mode.*

Frequency Constants

If one were to halve the thickness of a piece of piezoceramic, they would find that the frequency of the thickness resonance would double. However the product of the thickness multiplied by the thickness resonance frequency would remain constant. This value, denoted $F_{c\text{-}th}$ or N_{th}, is the thickness frequency constant and allows one to readily calculate the resonant frequency given the thickness (or vice versa, to calculate the thickness given a resonant frequency). There is a similar relationship for the radial modes (i.e. halving the diameter doubles the radial resonance frequency). In general, the thickness mode frequency constant is different from the radial mode frequency constant. This is because the lattice structure of the ceramic is distorted by the poling process. In other words, before poling a piece of ceramic the speed of sound would be the same in all directions, but after poling it, the speed of sound in the radial direction is often 20% to 30% higher than the speed in the axial direction. This effect is weakest in soft PZTs and is more important in many other types of piezoceramic.

Quality Factor Q

The quality factor Q of a resonant system may be defined based on two seemingly unrelated descriptions. The first is defined in terms of how much energy is dissipated in the system with every oscillation. In this case, Q is defined by…

$$Q = 2\pi E/\Delta E$$

In this formula, E is the stored energy in the oscillating system and ΔE is the energy lost in one cycle. Thus, a high Q system is one which loses very little of the energy that can be stored in it.

Another definition of Q is related to the bandwidth of a resonant system. If a system with some amount of dissipation is driven with a oscillating force and the response is measured as a function of frequency, then a maximum response will be found at the resonant frequency and the amplitude will drop as a driving frequency is changed from the resonant frequency (see Figure 8). A common example of this effect is a car with a wheel that has lost a balance weight. As the car speeds up, the frequency at which the wheel oscillates increases. For a range of speeds, the oscillation will not be bothersome, but when the frequency at which the wheel turns matches some vibratory mode within the car, large vibrations (say, a creak somewhere in the dashboard) may suddenly arise which then abate as the speed further increases. When the frequency of wheel corresponds to some vibration mode of the suspension, the vibration can become dangerous as the wheel starts bouncing up and down. Again, this violent motion may abate with increasing speed, even though the force which the wheels is vibrating the car is increasing.

The quality factor of a resonant system can be defined by the width of its resonance…

$$Q = Fr/BW$$

In this formula, Fr is the resonant frequency and the bandwidth, BW, is the range of frequency values where the response is at least one half of the maximum response. Thus a high Q system is one which has a very narrow bandwidth. These two definitions get to one of the major trade-offs which must be made in the design of piezoelectric transducers: bandwidth versus dissipation. High bandwidth devices are very dissipative, while systems with low dissipation have a narrow bandwidth.

Material data sheets often list the Q of a ceramic type. This Q can be thought of as a material property, but the Q of a piece of piezoceramic is a property of not only its material properties, but also the uniformity of its material properties across the sample, the uniformity of its dimensions, and the sample geometry. While perfect machining and sample preparation will not increase the Q of a soft ceramic, imperfections and mode-mixing can greatly lower the measured Q of a hard ceramic. Most imperfections will cause relatively small changes in the resonant frequency of the ceramic. These small changes are not easily distinguished from a "perfect" sample, which is more dissipative and which therefore also has a broader bandwidth.

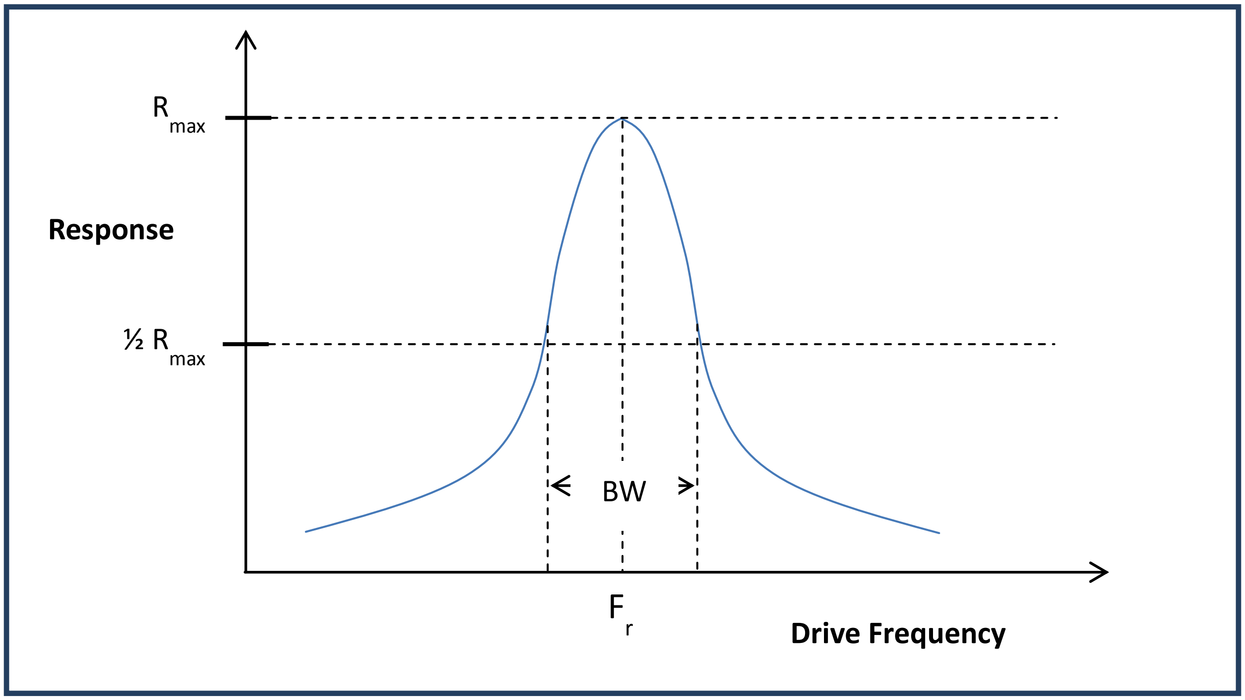

Figure 8: Response Curve for a Damped and Driven System. *The response rises to a maximum at the resonant frequency F. The difference in frequency between the maximum and the point where the response drops to one half of the maximum response defines the bandwidth, BW. The system's quality factor Q = Fr/BW.*

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