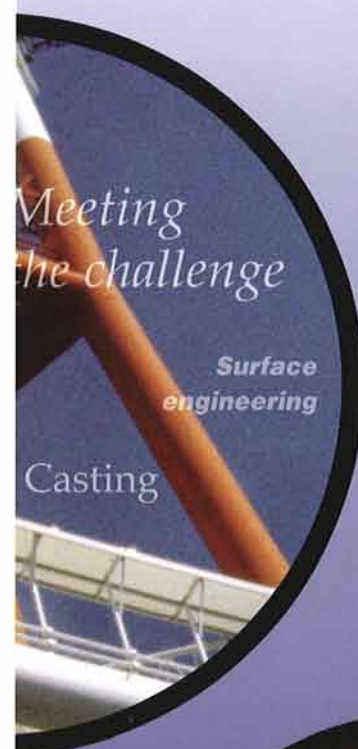


*Measurement
Good Practice Guide*

**Piezoelectric
Resonance**

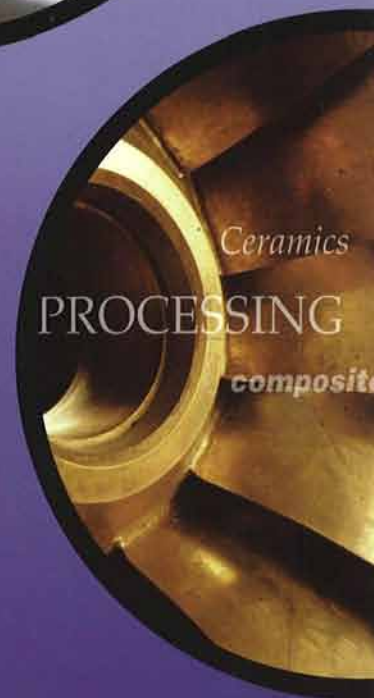
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Measurement Good Practice Guide No. 33

Piezoelectric Resonance

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Abstract:

This Measurement Good Practice Guide is intended to help a user to perform resonance spectra measurements on piezoelectric ceramics. The phenomenon of resonance is introduced and linked to the evaluation of the piezoelectric matrix by appropriate choice of sample geometry, and data analysis method. The IEEE method and complex coefficient method is explained and compared with a worked example helping the user to understand the stages of measurement and analysis.

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Piezoelectric Resonance

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1 Introduction

1.1 Vibrations

Virtually every system, whether mechanical or electrical, possesses the capability for vibration, and most systems may vibrate freely in a large number of ways. Generally, most systems may freely vibrate at a frequency determined by its size – the smaller the size the faster the periodic motion such as the beating of the wings of a bee, conversely the larger the system the slower the periodic motion such as the ground tremors experienced after an earthquake. If the vibrations are approximated as sine waves (which is physically reasonable and mathematically agreeable) then these oscillations are often described to perform simple harmonic motion. Simple harmonic motion (SHM) may be characterised by an amplitude of motion (displacement for example) and a period (the time between successive maxima). SHM has meaning only when the true steady state of oscillation has been reached – that is long after any transient phenomena have passed. Apart from the system's size, its frequency of free vibrations is determined by other properties such as its stiffness or elastic modulus. Compared to a compliant material, a very stiff material means that sound can travel much faster from one of its boundaries to another and this means that its free vibrational frequency is correspondingly higher. The resonant frequency is equal to the speed of sound in the material, C , divided by the acoustic length of the device, L . This is the definition of acoustic resonance frequency: $f = \frac{C}{2\pi L}$. At resonance the standing wave set up in a sample is thus

related to the speed of sound within that material. Since the speed of sound is related to the stiffness of the material it is possible to determine the material stiffness using this behaviour as a basis for a measurement technique. For example, by suitably holding a simple bar shaped sample a resonance can be excited by the application of a mechanical impulse (much like striking a xylophone), and the acoustic response can be measured to determine some of the materials elastic properties.

1.2 Resonance

When an external force drives a freely oscillating system, then at a certain driving frequency, the system displays a similar – but not identical - maximum in oscillatory amplitude. Resonance in any system can thus be defined as a state of ongoing oscillations that persists for a time much longer than the period for internal motion in that state. Additionally, a resonant system may be excited efficiently by a relatively weak driving force in a narrow band of frequencies close to its resonant frequency.

For piezoelectric materials, since the material can be excited electrically, applying an AC voltage across the device can induce resonance without the need for external mechanical stimulation. Electrically induced resonance occurs in a piezoelectric material because of the

electromechanical coupling that exists between applied field and induced strain, and that is defined by the complete set of piezoelectric equations [IEEE Standard on Piezoelectricity]. This strain oscillates at the same frequency as the imposed field that act to set up sound waves in the material. In a similar manner to that described above, a resonance is set up in the specimen when dimensions of the specimen match some integral number of sound wavelengths – depending on the mode of vibration. It is clear then that the electrical impedance of a piezoelectric material measured as a function of frequency exhibits peaks that correspond to electromechanical resonance in the specimen. The form of the response is described by 2 quantities – frequency, f , and its frequency width at half amplitude, δ , ($=f/Q$) with Q called the Quality factor – that characterise the distinctive properties of a driven system.

The sample response can be measured externally using acoustic or displacement measurements. However, since the current flowing through the device is proportional to the functional response, it is simpler to measure the electrical current. Therefore, the electromechanical resonance of a piezoelectric sample can be readily measured by frequency sweeping a fixed voltage across the sample and measuring the current, i.e. measuring the *impedance*. One disadvantage of this method is that it can take time to perform a frequency sweep, whereas impulse techniques naturally favour the fundamental and take little time to complete. However, there are a number of high speed impedance analysers on the market that can perform a frequency sweep in a matter of seconds or less, so, although it is possible to use less sophisticated instrumentation, it is more convenient to use impedance analysers.

1.3 Modes of Vibration

Any real body will have a very large number of modes of vibration. It is important at this stage to understand the meaning of *modes of vibration* in real piezoelectric solids and the meaning of *harmonics*. A vibrational mode in piezoelectric materials depends on the sample geometry *and* the equations of motion governing the piezo-mechanical properties.

Some of these modes are harmonics of other modes, however, the lowest frequency mode will, by definition, be a fundamental mode of some sort. The next maxima may or may not be the first harmonic of this fundamental mode. It may actually be a fundamental mode of a different harmonic series. This is graphically depicted in Figure 1. Consider a cuboid of length a , b , c .

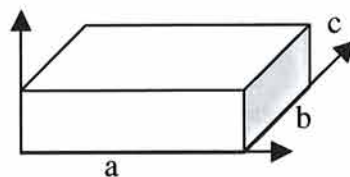


Figure 1: Cuboid of length a , b , c .

The harmonic series defined by the lengths a , b , c will be:

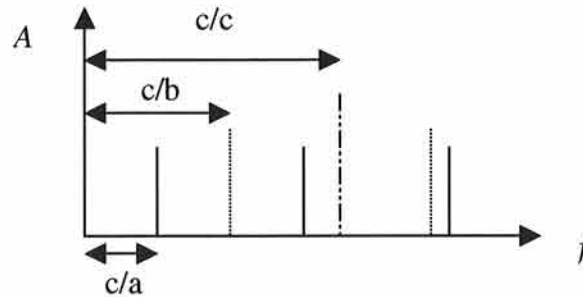


Figure 2: Progression of higher harmonics from three modes of vibration in cuboid.

Here, the length b is such that the second mode is not the 1st harmonic of the fundamental. The modes of vibration are clearly related to the physical boundary conditions of the cuboid and the harmonic series associated with each mode simply fits the vibrational forms into the lengths a , b , c .

For example, for a long thin rod the fundamental mode is longitudinal, which is characterised by a fundamental frequency, f_0 . The rod will also vibrate at harmonics of this fundamental frequency - $2f_0$, $4f_0$ etc, albeit at reduced intensity. The frequency f_0 is dependent on material parameters and the length of the rod. Of course the rod is free to vibrate in many other modes, although because its length dominates its dimensions their frequencies will be above the fundamental longitudinal mode. If the length of the rod is reduced then other modes of vibration with their own harmonic series - f_1 , $2f_1$, $4f_1$, ... - will be superimposed upon the first series, f_0 , $2f_0$, $4f_0$... where f_1 is dependent upon other geometric and material parameters.

Of course the frequency of vibration depends on the velocity of sound waves through the material, which in itself depends on material properties such as the stiffness tensor. The factors that affect the shape of the resonance spectra for piezoelectric materials include sample: dimensions, geometry, density, and its elastic, dielectric and piezoelectric constants. The power of this non-destructive technique now becomes clear. It is possible to calculate the various piezoelectric, dielectric and mechanical 'constants' of piezoelectric materials by performing resonance measurements on a range of sample geometries. The reason why a range of geometries is necessary is because of the complex coupling that exists between the electrical and mechanical response of piezoelectric materials. When an arbitrary piezoelectric sample is made to resonate a complicated superposition of different resonant vibrations exists within the material. These resonance's are made up from the various piezo-electro-

mechanical couplings that occur between applied electrical field and boundary conditions arising from the samples fixed surfaces. If samples can be manufactured such that only one resonant vibration exists that can be directly linked to just one of the piezoelectric constants (remember this 'constant' is a 3rd rank tensor) then all the components of the piezoelectric tensor may be extracted from measurement data taken from resonance experiments, on a set of sample geometries. This forms the basis of the IEEE standard method. Here, the wave equations for vibration within resonating piezoelectric materials have been formulated based on well-defined boundary conditions of sample geometry. This allows the piezoelectric equations to be uncoupled to give an equation for the impedance of the specimen as a function of frequency – resonance analysis. These equations have then been solved to yield some of the components of the piezoelectric matrix. Some of the geometries needed to determine the piezoelectric matrix are given in Figure 3.

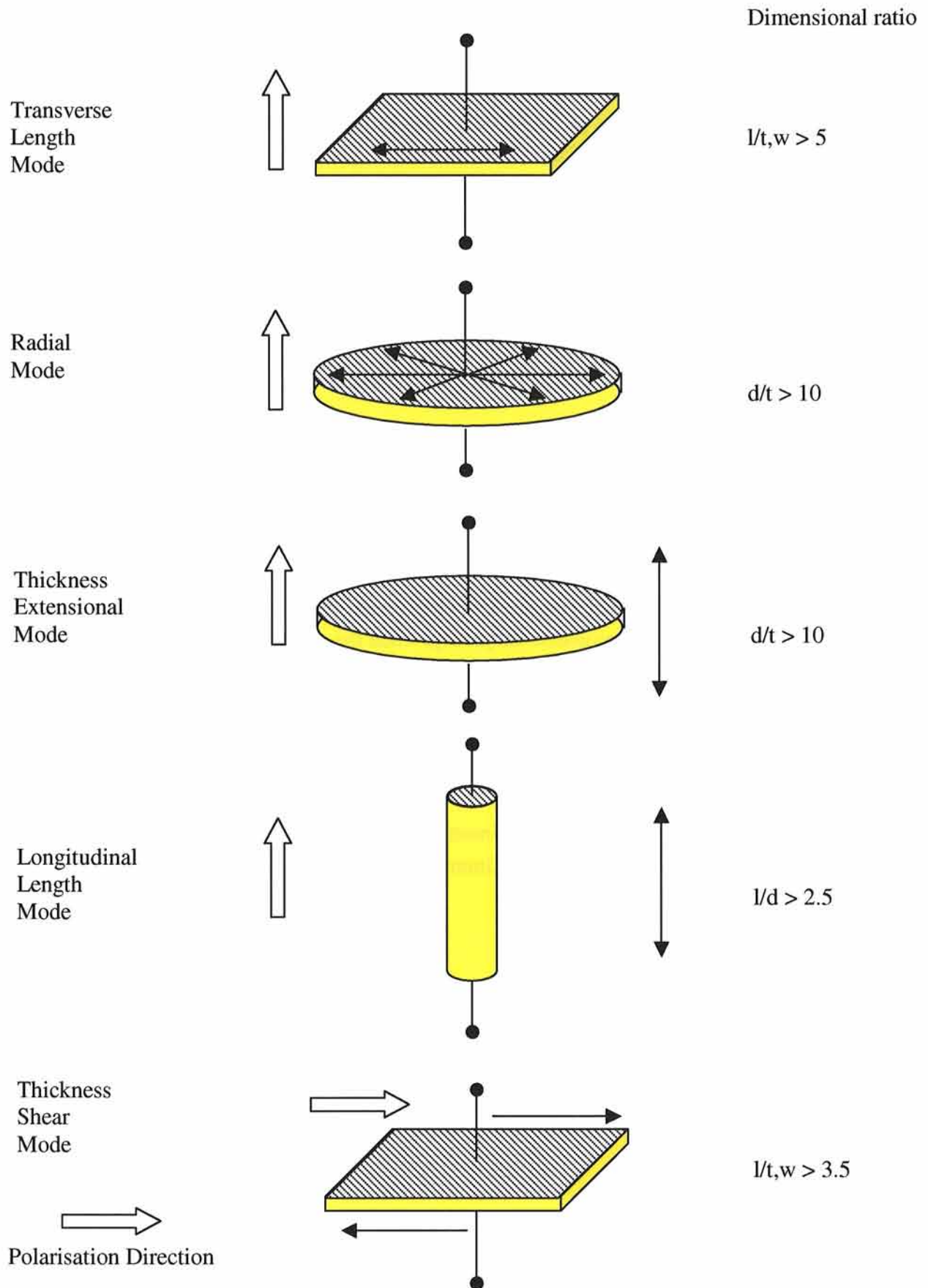


Figure 3: The Cenelec pre-standard gives recommended sample geometries for exciting the various modes and these are shown. l , w are length and width, t thickness, and d diameter.

So far we have introduced the concept of resonance, mainly as a mechanical phenomenon, but the concept is also familiar in electrical circuits. If the impedance of a piezoelectric device is measured and the results plotted on the complex impedance plane they will describe a characteristic circle, Figure 4. The three lines OA, OB, OC describe three pairs of frequencies that can be used to denote the resonance behaviour. OA is where the behaviour is purely resistive. OB the frequency of maximum resistance, and maximum conductance, and OC is the maximum and minimum impedance (Z_n and Z_m). Although the three lines have been drawn separately it can be seen that if the circle were symmetrical about the X-axis all three pairs would coincide. This is the case for a material with zero loss, and although strictly speaking most piezoelectric materials exhibit some loss it is assumed that the frequencies coincide for materials with a figure of merit, M greater than 20:

$$M = Q_m k_{\text{eff}}^2 / (1 - k_{\text{eff}}^2) > 20$$

k_{eff} – effective electromechanical coupling factor

Q_m – mechanical quality factor

f_r – resonance frequency, when the susceptance is zero

f_a – anti resonance frequency, when the reactance is zero

f_s – series resonance frequency, frequency of maximum conductance
(Series arm has zero reactance $X=0$)

f_p – parallel resonant frequency, frequency of maximum resistance

f_m – frequency of minimum impedance

f_n – frequency of maximum impedance

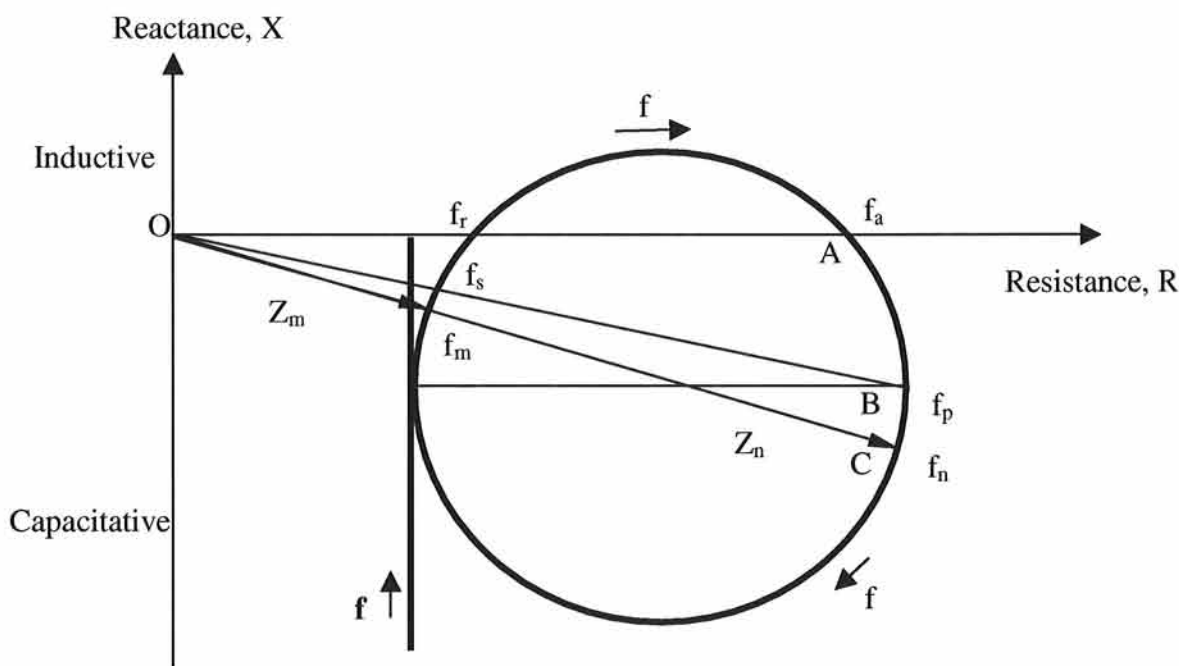


Figure 4: Representation of the results on the complex impedance plane.

1.4 Equivalent Circuits

As discussed previously purely electrical circuits also exhibit resonant behaviour. This concept can help in understanding some of the behaviour in piezoelectric resonators. An equivalent circuit that displays resonant behaviour similar to a piezoelectric is shown in Figure 5. Here the left hand branch of the circuit represents the behaviour at resonance, and is sometimes termed the motional arm, the resistor determines the resistance at resonance and the capacitor and inductor control the resonant frequency. C_0 is the capacitance of the system without mechanical resonance, and the low frequency capacitance of the device is the sum of C_0 and C_1 . In mechanical terms L represents the vibrating mass, C_1 the elastic compliance, and R the mechanical damping, whilst the right hand arm C_0 is the pure electrical capacitance and has no mechanical significance. The use of equivalent circuits in describing the electrical properties of piezoelectrics or ferroelectrics is commonplace and is a useful tool for property prediction assuming the materials response is linear. Of course this is not the case when fields and stresses are increased beyond quite modest values. Methods have been developed to tackle this problem and the work of Holland, Smits and Sherit have utilised complex quantities for the circuit elements and compared these with the complex descriptions of the piezoelectric, dielectric and mechanical (stiffness) tensors. The complex notation for these tensor quantities has been implemented in order to include the magnitude *and* phase or loss associated with the driving field/force and response.

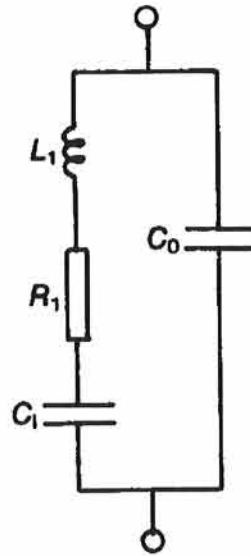


Figure 5: Equivalent circuit of resonator.

1.5 Resonance and Anti-resonance

On first inspection it seems a little odd that a piezoelectric resonating system can be described by two frequencies – resonance and anti-resonance. The differences may be easily explained by noting that at resonance the magnitude of the impedance passes through a minimum value and at anti-resonance the magnitude of the impedance passes through a maximum value. However, this does not explain why these changes occur at all. Remember, the electrical impedance is an indication of current flow or charge generation (since current is the flow of charge). In a piezoelectric material, charge is generated when the piezoelectric effect generates a strain in response to an applied stimulus (voltage). At resonance the matching of sample dimensions to wavelength of strain amplitude occurs and there is a net charge transfer into and out of the sample during one complete cycle. This is due to the large strains occurring at resonance leading to a maximum change in capacitance of sample and hence charge flow. This amounts to an average current flow and an impedance minimum. At anti-resonance, when the impedance is maximum and hence minimal current is able to flow, the response to the driven field is such that during one complete cycle there is no or little net charge developed because of the symmetry of the field induced vibrations. The symmetry of the strains within the material may be seen as a mix of tensile and compressive regions within the sample. On average there is no net change in capacitance and hence minimal current flow.

1.6 Tensor Terminology

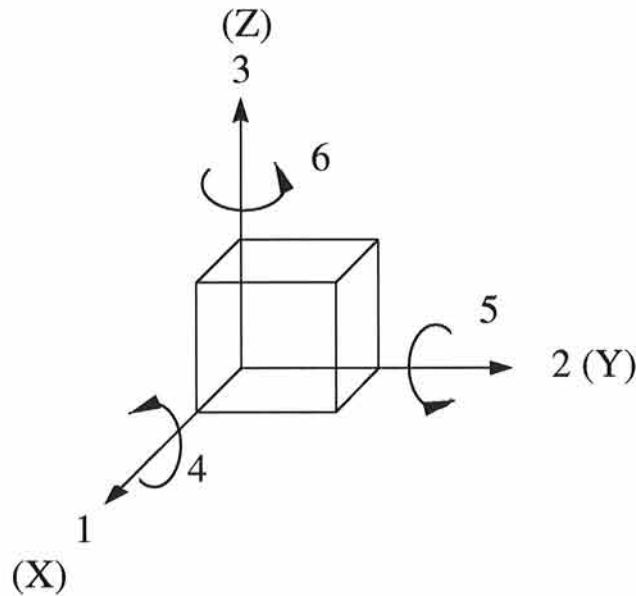


Figure 6: Axis Notation for piezoelectric crystals.

In order to describe the anisotropy of piezoelectric ceramics the axis notation in Figure 6 is commonly used. For poled ceramics the material symmetry is ∞mm and the poling axis is taken to be in the Z or 3 direction. All the piezoelectric coefficients have two subscripts, the first identifies the direction of excitation, and the second the direction of the response. So for example the coefficient d_{31} in relation to Figure 6 would refer to an excitation in the 3 (poled) direction, giving rise to a response in the 1 direction. A shear deformation around one of the three orthogonal axes would be represented by a subscript 4, 5 and 6. So the piezoelectric coefficient d_{15} represents a shear deformation around the 2 (Y) axis brought about by an excitation in the 1 direction (perpendicular to the poling direction). Since the 1 and 2 direction are equivalent all occurrences of the 2 axis can be replaced by the 1 axis, and due to the material symmetry conditions many of the coefficients for the ∞m case are zero, leading to the following: -

The dielectric matrix

$$\begin{bmatrix} \epsilon_{11} & 0 & 0 \\ 0 & \epsilon_{11} & 0 \\ 0 & 0 & \epsilon_{33} \end{bmatrix}$$

The piezoelectric matrix

$$\begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{31} \\ 0 & 0 & d_{33} \\ 0 & d_{15} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

The stiffness matrix

$$\begin{bmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{11} & c_{13} & 0 & 0 & 0 \\ c_{13} & c_{13} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{c_{11}-c_{12}}{2} \end{bmatrix}$$

2 Resonance Measurements

2.1 Impedance Measurement Systems

In making impedance measurements there are several possible terminal configurations but usually the choice comes down to either two or four terminal connections. Although four terminal is usually considered better there are a number of reasons why it is preferable to use two terminal connections when making impedance measurements on piezoelectric resonators. The main reason is the difficulty in making suitable contacts at the nodal point with more than two electrodes. However, having settled on two terminal measurements it is a mistake to carry this reduction in cabling back to the analyser itself, and the two terminal wire pair should be kept to a minimum, and should be shielded as far as possible. It is good practice to use four-wire connection from as close to the sample contacts as possible. Another common error is to assume that the shielding used in the four terminal cabling is actually at ground potential and to ground the shield at several points. Some impedance analysers use a “driven shield” so that an equal current flows in the opposite direction to the measurement signal, in order to reduce inductive coupling. In this case the shields of the four terminals should only be connected together near the sample, and should not be connected to ground. It is also advisable to have a shield surrounding the sample that is also connected to the driven shield, although the necessity of its use depends greatly on the environment and the measurement frequency. However it is possible to see measurable changes in spectra when merely moving a finger close to the sample, Figure 7, when the sample is unshielded.

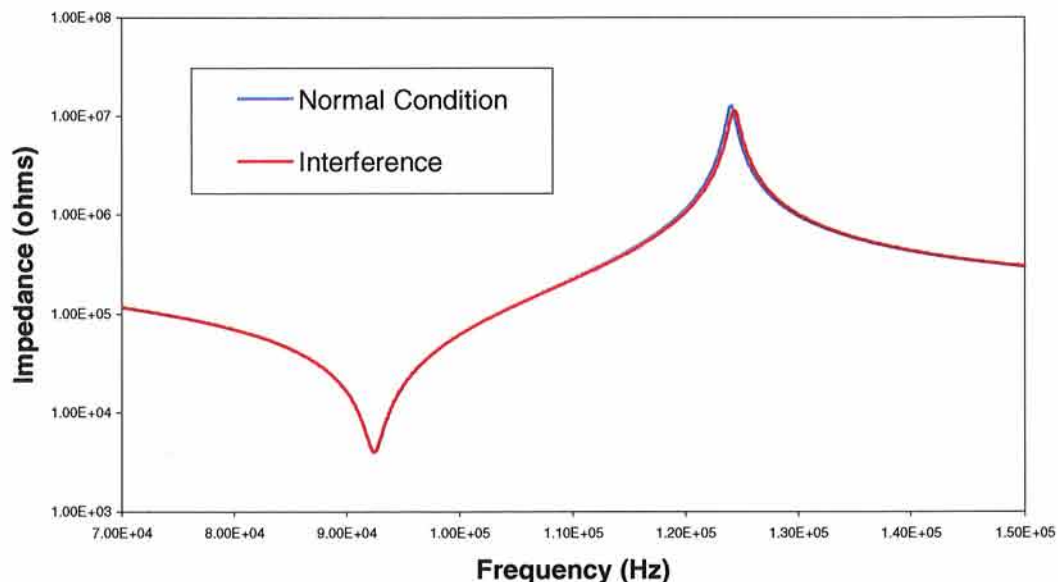


Figure 7: Changes in spectra when moving a finger in close proximity to the sample, when the sample is unshielded.

2.2 Compensation

There is a danger in using sophisticated analyser systems to trust the output implicitly, and perhaps neglect some of the subtleties of these systems. One of these forgotten areas is the compensation for fixtures and cabling. Most analysers come equipped with standard fixtures and fittings that are designed for use with standard electronic components, however these must often be modified for use with piezoelectric shapes or perhaps if used in conjunction with an environmental chamber. These modifications will often have an effect on the impedance measurements since the measured result is a combination of the impedance of the sample and the impedance of the cabling and fixtures. The analysers will often be compensated to account for the impedance of the 'as supplied' fixtures and modifications may invalidate this compensation.

The solution is simple; the impedance of the fixture must be measured separately and subtracted from the measurement. Some systems can do this automatically or alternatively there is a relatively simple calculation. To determine the impedance of the fixture and its cabling there are three measurements needed; open, short and load. The short measurement is simply the fixture shorted with a very low resistance artefact, typically gold plated brass. Care must be taken that this is clean and the contact to the fixture is also clean. The open measurement is simply the fixture in the open circuit condition, i.e. no sample in position. For all the compensation measurements it is preferable to have the set up as it is to be used. This means for the open circuit measurements that the contacts are as far apart as they are when the intended sample is in place. The final form of compensation is load compensation, and this involves testing a load of known impedance, preferably similar to the DUT (device under test), but often a simple 100-ohm resistor is used.

$$Z_{DUT} = (Z_{meas} - Z_s) / (1 - (Z_{meas} - Z_s)Y_o)$$

Z_s = impedance of short circuit

Y_o = admittance of open circuit

Z_{meas} = measured impedance

Z_{DUT} = DUT impedance

The importance of the compensation in the measurement results obviously depends on the impedance of the DUT. For a typical piezoelectric sample the lowest impedance (at resonance) is large enough so that inadequate short corrections do not introduce a large error. However, at anti-resonance the impedance can approach that of the open circuit and thus it is possible to introduce significant errors.

The analyser is an instrument for performing frequency sweeps and so the compensation must also be carried out at or near the measurement frequency. The more advanced systems measure the compensation artefacts over the entire range and use this to correct the

measurements, whereas some of the older systems only measure at a fixed frequency and use this value in the corrections.

2.3 Sample Holding and Contacts

Since we are using the resonance of a sample to determine material parameters, not of a device, an ideal sample holder should have no effect on resonance of the sample. Obviously electrical connections need to be made, but these should be constructed so that there is a minimal influence on the resonance of interest.

It is difficult to define exact rules for how a sample should be held in terms of clamping load, position etc. since this can depend on the sample and the desired resonance. A simpler approach is to see the effect of changing these parameters on the resonance spectra. For a simple geometry sample with no defects the optimum holding conditions should produce the highest resonance, maximum admittance at resonance and no spurious peaks, and any excessive clamping will produce the converse.

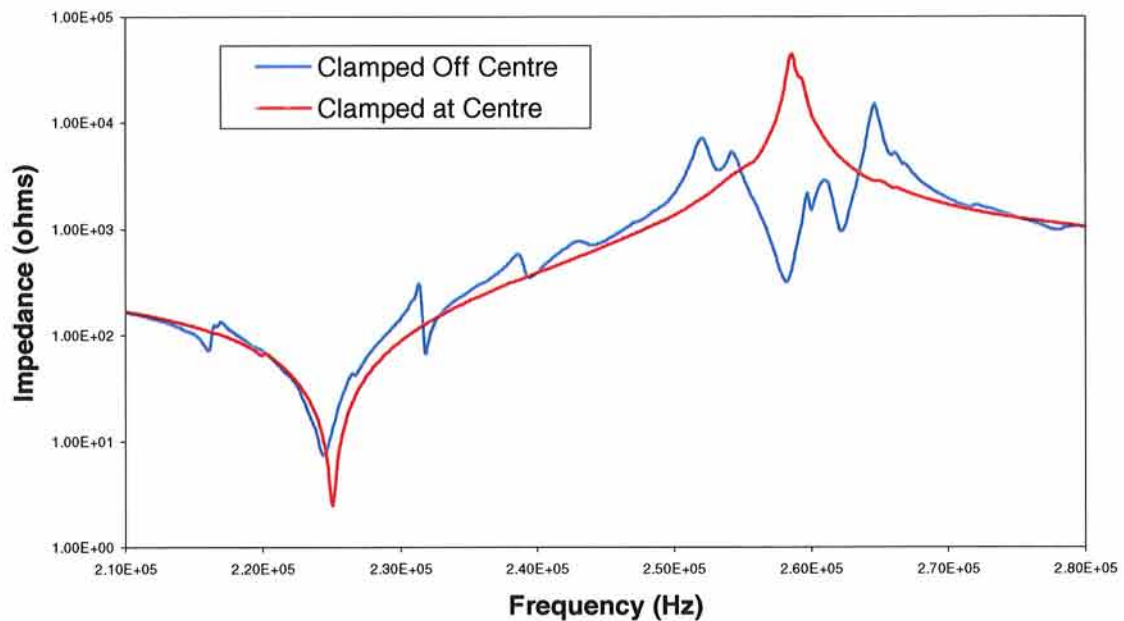


Figure 8: The effect of holding the sample away from the nodal positions for a thin disc resonator.

The sample should be held at the nodal points, so for a thin disc resonating in the radial mode it should be held with a point contact at the centre of each face. Any offset from the centre will result in increased impedance at resonance, reduced resonance frequency and spurious peaks around between the resonance and anti-resonance, (Figure 8).

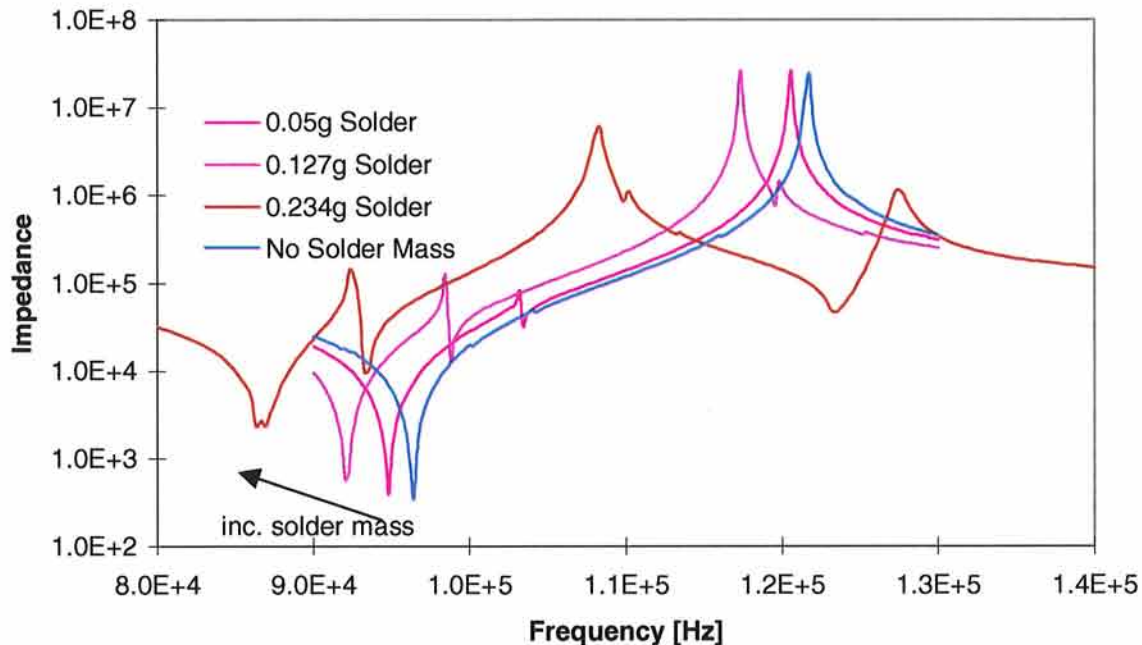


Figure 9: The effect of increasing the solder mass on a 15mm long 6.35mm diameter length resonator.

In order to make simple, repeatable contacts to a sample there is a choice of either soldering wires to the sample, or using some sort of clamping arrangement to force electrodes onto the sample. Some workers have suggested using a mixture of both whereby a low melting point indium/gallium eutectic is used in conjunction with a very low clamping force. Soldering is somewhat invasive in that a heating cycle is needed and the solder presents added mass, however it can provide the lowest contact resistance. Also, for higher field experiments where a much higher displacement is produced, it may be the only method since any spring loaded contact will either not be able to hold the sample or dampen the vibration. Figure 9 shows the effect of increasing the solder mass on a 15mm long 6.35mm diameter length resonator. Obviously the amount of solder in this case has been increased to highlight the effect, but it does illustrate the need to keep the solder mass to a minimum.

A method less invasive than soldering is to use spring-loaded contacts. These can either be simple wires bent to provide a small retaining force, or the spring loaded probes that are commonly used in the electronics industry for making test points on printed circuit boards. These come in a variety of end shapes to cope with differing conditions, but the pointed types are better than the inverted cone or crown shape for this type of application. Also, as these probes are designed for contact they usually come gold plated to reduce contact resistance.

The spring in these probes also have defined spring constants, although the tolerances on these tend to be quite high because of their small size. However, the spring constant can be measured for the individual spring used and a defined clamping load can then be set by the stroke of the spring. These spring probes are designed to apply around 2N, which is sufficient to punch through dirty contact on circuit boards, however this load may be somewhat high for the clamping of resonant piezoelectric devices. Applying a shorter stroke can reduce the load.

2.4 Samples

The problems associated with adding mass to samples by soldering wires to them has been discussed in the previous section. Of course the sample will not be purely piezoelectric ceramic since in order to make any kind of electrical connection, and to initially pole the material the ceramic will have some form of electrode. These will introduce deleterious

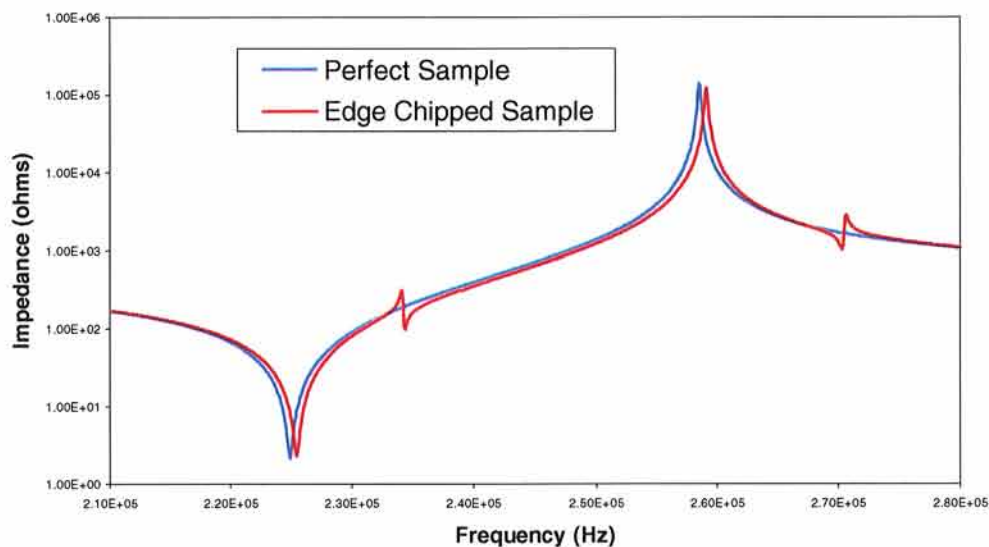


Figure 10: The effect of edge chips on the radial resonance of a 10 mm diameter disc

effects on the sample resonance, through the additional mass, the electrode stiffness, and if there is a substantial difference in the electrodes on either side there will be bending stresses introduced. The magnitude of this effect is obviously not as great as for soldering, but could be a problem for very thin discs, where a fired on silver frit electrode could be a substantial fraction of the sample thickness.

In order to produce a clean resonance the sample should be geometrically perfect. Any imperfections in the sample will cause spurious peaks; in effect the sample dimensions have been changed in the area of the imperfection. Figure 10 shows the effect of edge chips on the radial resonance of a 10 mm diameter disc, with the magnitude of the chip shown in Figure 11. Although the presence of these defects can be detected in the resonance spectra, it does not greatly affect the calculated material parameters since this mainly depends on the

resonance and anti-resonance frequencies. However, less noticeable geometric irregularities could affect the results, for instance if the ends of a length resonator are not plane parallel, then this will give rise to a broadening in the resonance peaks.



Figure 11: The chipped disc tested in Figure 10.

2.5 Excitation Voltage

In most of the calculations to determine material parameters from resonance it is assumed that the behaviour is linear with respect to applied field. In most cases this assumption is true since it is difficult to apply large enough fields at resonance because of the increased current requirements. For most of the commercial impedance analysers the maximum applied field is 1 volt and so maximum field levels for typical ceramic samples are restricted to around

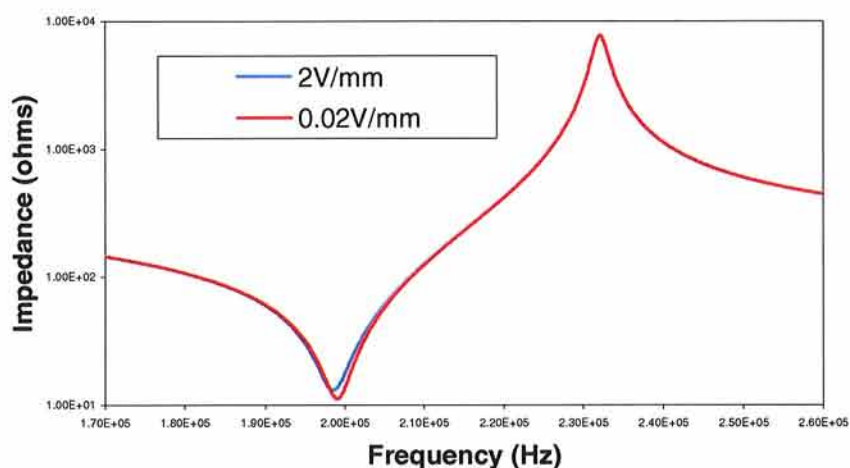


Figure 12: Small change in radial resonance peak in going from 0.02V/mm to 2V/mm for a 0.5mm thick soft PZT.

1V/mm. The US Navy standard (MIL-STD-13767) recommends a field level of less than 0.1V/mm, and a forthcoming CENELEC standard recommends an upper limit of 0.01V/mm. In practice it is usually better to use larger signals because of the increased signal to noise, and it is only when fields go above 1V/mm that it is possible to detect non-linear behaviour in soft PZT. Figure 12 shows the small change in radial resonance peak in going from 0.02V/mm to 2V/mm for a 0.5mm thick soft PZT. The reduction in the magnitude and

position of the resonance frequency while the anti-resonance remains unchanged is characteristic of high field non-linearity.

2.6 Modes of Resonance: Sample Geometry

In order to use the resonance behaviour as a technique for measuring material parameters it is important that the sample resonates in a well defined mode with minimal coupling from other unwanted modes. The IEEE standard gives recommended sample geometries for exciting the various modes and these are shown in Figure 3. Figure 13 shows the consequence of using non-ideal geometry. Here the frequency range covers the first and second series radial resonance of a 10mm diameter disc of a PC 4D material. The 0.5mm thick sample, which is the IEEE recommended maximum thickness for this diameter, shows only the two expected resonance peaks, whereas the 5mm thick sample has many more peaks in this range. More importantly these other modes have depressed the frequency of the first radial resonance. Obviously the 5mm thick sample is much thicker than the recommended size, and for thinner samples of say 1mm the multiple resonance peaks are not present, however it is possible to detect the effect of other modes in the higher order harmonics, and in the second series radial

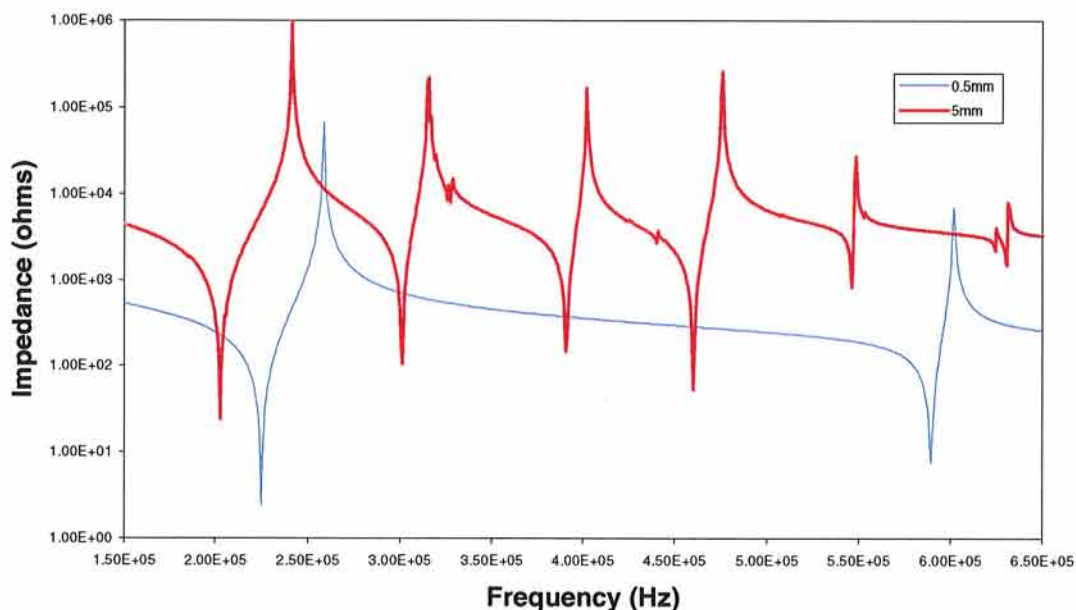


Figure 13: Comparison of the recommended shape with a non-ideal resonator geometry.

resonance peak for these disc samples. Figure 14 shows the first and second series radial resonance for 0.5mm and 1mm thick 10mm diameter samples of a hard and a soft composition. Examining the first radial resonance peak shows little difference between the different thickness samples, as any variation is within the variability from sample to sample. However, for the second series radial resonance there is a definite reduction in frequency for the thicker sample, in particular for the soft material. The difference between the first and second resonance peaks is controlled by the stiffness and the Poisson's ratio of the material, however the difference in the shift of the second radial resonance with increasing thickness is

due to the increased coupling coefficient of the soft PC 5H. This illustrates that the single mode resonance sample geometry restrictions are not only sample dimension but also material dependant, i.e. that some of the geometry restrictions can be relaxed for some material compositions.

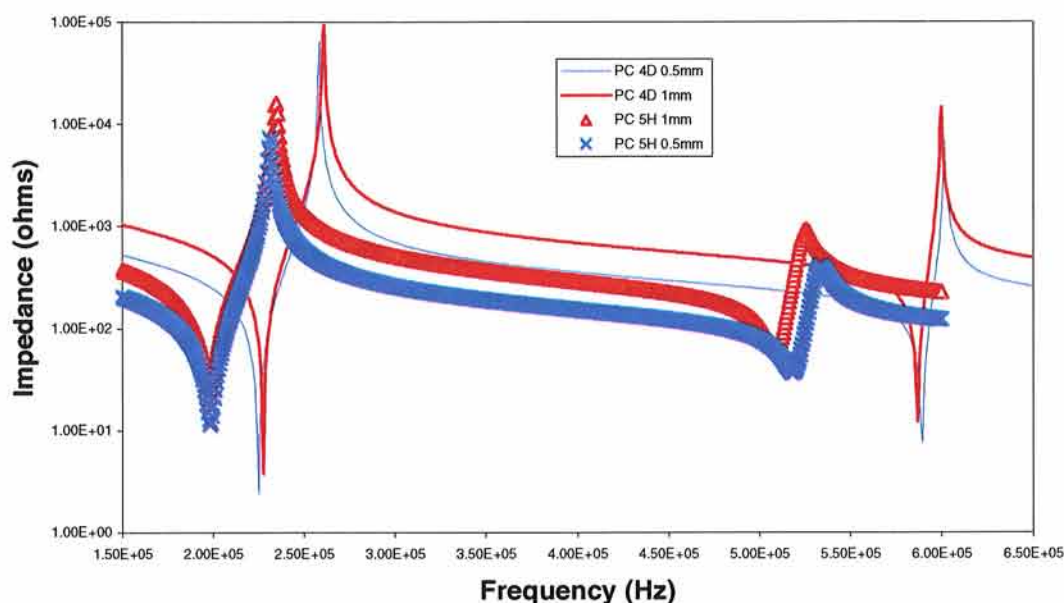


Figure 14: The first and second series radial resonance for 0.5mm and 1mm thick 10mm diameter samples of a hard and a soft composition.

2.7 Repeatability

Table 1 gives some idea of the expected repeatability of resonance measurements. The first two rows are the results of 10 measurements on the same sample, where the sample was removed from the measurement fixture, turned through 180 degrees and replaced. The next two rows are for measurements on 10 different samples from the same batch. Clearly if the measurement fixture is correctly set up and the samples are placed roughly centrally in the fixture the measurements are extremely repeatable. No special precautions were taken to ensure that the sample sat in the same position each time. In comparison the sample variability of is over 100 times greater than the measurement variability.

		First resonance (Hz)	First Antiresonance (Hz)	Second Resonance (Hz)
10 Measurements	Mean	224854	258514	588975
	Standard deviation	7	7	33
10 Different samples	Mean	227207	258519	594025
	Standard deviation	1510	1321	3692

Table 1: Repeatability of radial resonance measurements of a 10mm diameter 0.5mm thick PC 4D disc.

3 Methods of Resonance Analysis and Losses in Piezoelectrics

Historically, the method defined by IEEE has been used extensively to analyse the resonance spectra of piezoelectric materials. Here, the resonance frequencies from a set of samples of different geometries are measured and along with their dimensions and sample density the piezoelectric coefficients determined. This method is simple to carry out in principle, and the calculations are relatively straightforward (although the wave equations for some of the geometries must be solved empirically through the use of Bessel functions).

In our original analysis of resonance in Section 1 losses were only briefly described. It is now relevant to discuss losses prevalent in piezoelectric ceramic compositions since these values are often as important as the functional, dielectric and elastic constants that resonance analysis yields. In reality, a piezoelectric material comprises losses originating from its dielectric response to an electrical field, mechanical response to applied stress or following piezoelectric motion and its piezoelectric (strain) response to an electric field. The impact of these losses on a resonance sweep is a reactive and resistive part to the measured impedance. A material with zero losses would exhibit zero impedance at resonance. The significance of loss results in sample heating or noise production and this is why for many applications an understanding of loss mechanisms and absolute values becomes important. Normally, the mechanical loss at resonance is calculated from the width of the resonant peak and is labelled the mechanical Q or Quality factor. The narrower the resonant peak, the higher its Q . Dielectric losses are normally calculated from the phase angle between observed capacitance and applied field, labelled $\tan \delta$. Piezoelectric loss may not normally be calculated from resonance data but may be assessed through strain – electric field response whereby any hysteresis present may be ascribed to this loss alone - of course, if strain is produced then mechanical loss may also have an additive effect.

A method adapted by Sherit and co-workers from earlier work by Holland [Holland, 1967], Smitts [Smitts, 1976] and ultimately commercialised by TASI Technical Software (© PRAP), was to treat the entire piezoelectric matrix as complex. Again, assuming ideal linear piezoelectric behaviour and small field level perturbations, then the same formulation used for ideal loss-less resonators could be utilised, yielding similar equations but of complex form. Here, the impedance, resonant frequencies, piezoelectric, stiffness and dielectric coefficients are all complex quantities now and the forms of the equations may be iteratively fitted to the various shapes of resonance curves for each of the different geometries. PRAP makes extensive use of complex elastic, dielectric, and piezoelectric properties in fitting the resonance curves. Since the method fits to the data around resonance peaks an improved estimate of the resonant and anti-resonant frequencies is obtained through interpolation.

Additionally, this method automatically takes into account the losses by virtue of its complex notation.

The use of complex coefficients to represent the three types of loss in piezoelectric materials has its merits, and it is important to be able to verify the values given by this analysis by independent experimental means. This section of the Measurement Good Practice Guide has attempted to explore these complicated issues. The losses may be identified and measured as follows:

1. Dielectric loss – or $\tan \delta$. This may be calculated by measuring the phase angle between applied electric field and current, for example with a capacitance bridge.
2. Mechanical loss – or Q . This may be determined by drawing graphs of stress against strain and measuring the hysteresis between increasing and decreasing stress. This area is related to the energy absorbed during the cycle wherein mechanical loss may be calculated according to the following equation [Uchino, 2000]:

$$W_m = \pi S^E X_0^2 \tan \phi$$

with W_m = work done per half cycle, S^E = compliance at constant E , X_0 = strain, ϕ = loss angle.

Alternatively, measuring the phase angle between stress and strain using gain phase analysers would also yield this loss. Another method would be ultrasonic attenuation techniques or DMTA methods.

3. Piezoelectric loss. This is the most difficult to measure independently because when the material deforms under the action of the piezoelectric effect it also must endure mechanical losses. However, a method to investigate the piezoelectric loss would be to measure the piezoelectric strain as a function of applied field. The hysteresis is indicative of the loss. Alternatively, the use of a gain phase analyser in the measurement of the phase angle between strain and field can also be used perhaps to an advantage since over many cycles an average may be calculated and signal to noise thus increased.

The material coefficients can be described in either complex format, with real and imaginary parts or in the form of an amplitude and a phase lag or loss. The concept of a phase lag is easier to understand and so the term loss is more prevalent. However, for the description of impedance behaviour that includes lossy behaviour the complex notation is simpler, so that any coefficient can be represented as

$$\text{real part} - j \cdot \text{imaginary part}$$

These can be simply converted to a loss or a Q by the ratio of the real and imaginary component:

$$\text{Mechanical } Q = \frac{\text{real part (elastic coefficient)}}{\text{Imaginary part (elastic coefficient)}}$$

$$\text{Tan delta } \delta = \frac{\text{imaginary part (permittivity)}}{\text{Real part (permittivity)}}$$

The symmetry of the ∞mm structure also leads to several restrictions on the possible values of the imaginary parts of the coefficients. The diagonal elements of all the imaginary coefficients are positive, [Holland, 1969]

$$\text{coefficient}_{ii} \geq 0$$

Also

$$(s_{11}^E)'' \geq |(s_{12}^E)|''$$

$$(s_{11}^E)''(\epsilon_{33}^T)'' \geq (d_{31}'')^2$$

3.1 Comparison of Methods

The losses associated with dielectric constant, piezoelectric constant and elastic constant have been measured independently of one another (but see notes earlier) and most importantly using methods that do not include resonance. This is to try and explore the validity for the use of complex notation – vis. Real and Imaginary components of the parameters with loss given by the ratio real part / imaginary part.

Three losses associated with piezoelectric material have been classified:

1. Dielectric loss
2. Piezoelectric loss
3. Mechanical loss

Each has been determined using the resonance analysis performed by PRAP. In this software, the piezoelectric equations have been uncoupled through the measurement of well-defined sample geometries and the resultant spectra have been fitted to the equations describing the electro-mechanical piezoelectric equations. The result is a value for the real and imaginary parts of dielectric permittivity, piezoelectric strain coefficient, and mechanical stiffness coefficient. In PRAP the real and imaginary parts of the fitted coefficients are refined independently and these results used to calculate the real and imaginary parts of some of the other coefficients. For example, in length extensional analysis, the fitted parameters are k_{33} , f_p , e_{33}^S . The derived real and imaginary coefficients are s_{33}^E , d_{33} , e_{33}^T and s_{33}^D .

3.1.1 Dielectric Loss

The first set of alternative experiments to determine the materials dielectric loss was performed on a hard (PZT 4D) and a soft (PZT 5A) composition PZT ceramic rod. Here, the data from a dielectric analyser (Solartron 1296/1260) were compared to the PRAP data, in Figure 15, Figure 16, Figure 17, and Figure 18.

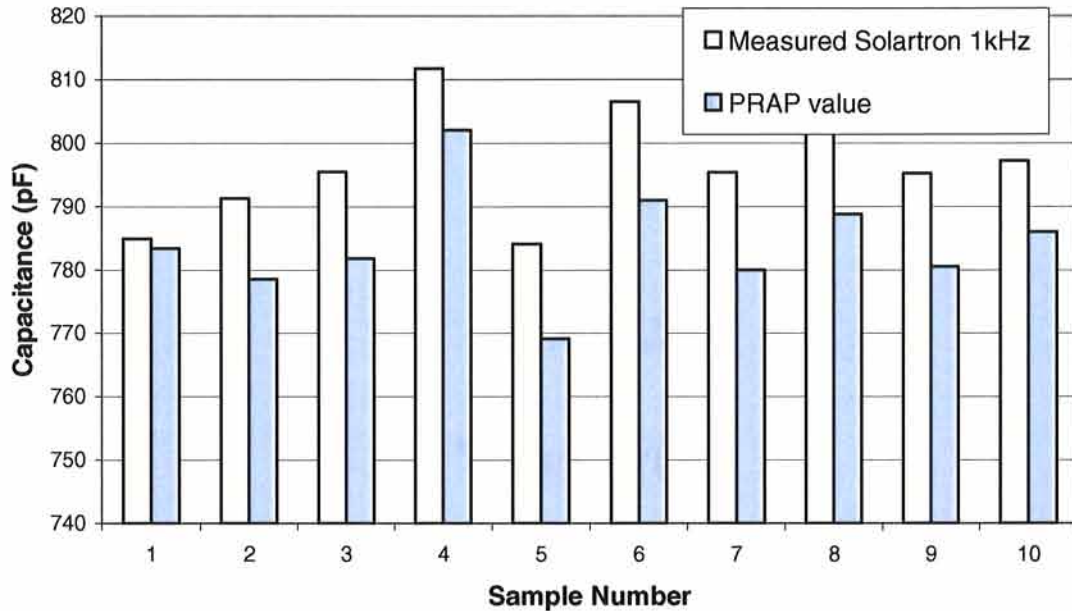


Figure 15: Capacitance values are approximately 3% lower when measured at resonance for PZT 4D hard materials.

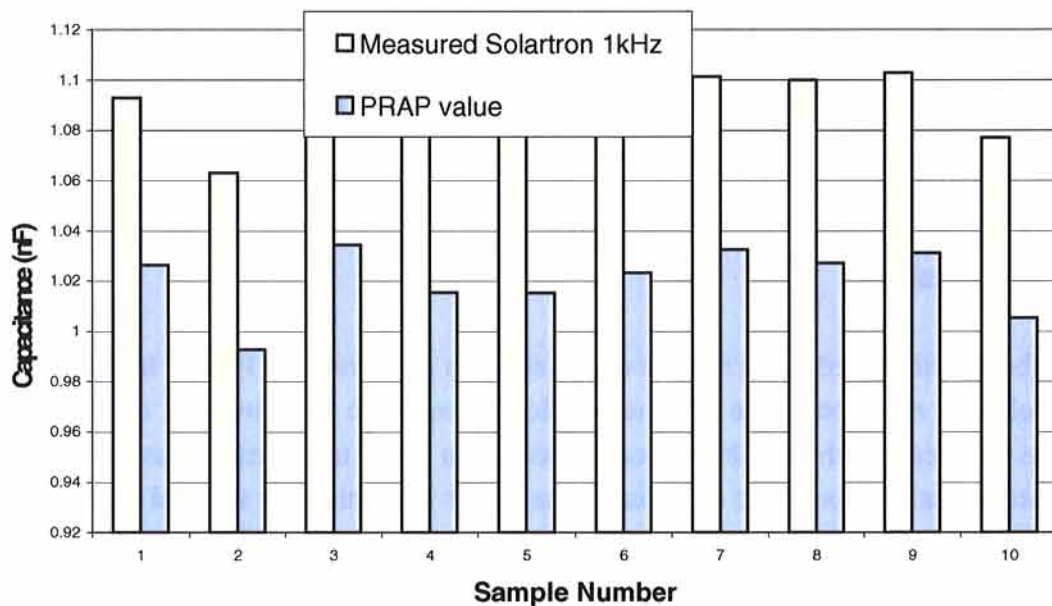


Figure 16: Capacitance values are approximately 5% lower when measured at resonance for soft PZT 5A materials.

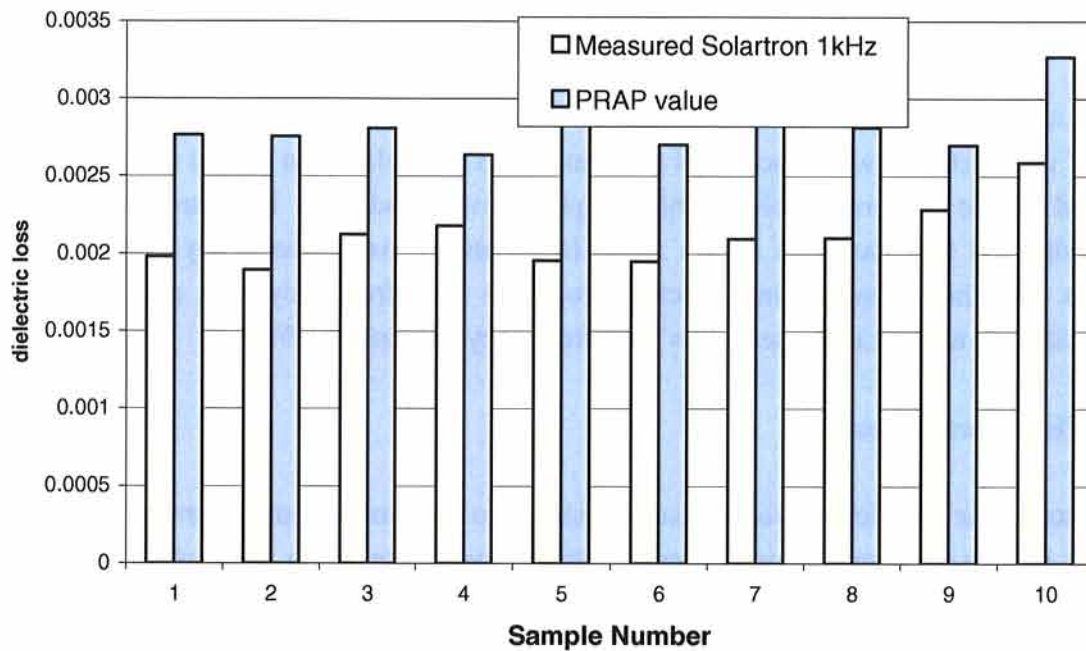


Figure 17: PZT 4D: Loss values are approximately 25% higher when measured using PRAP compared to the Solartron values.

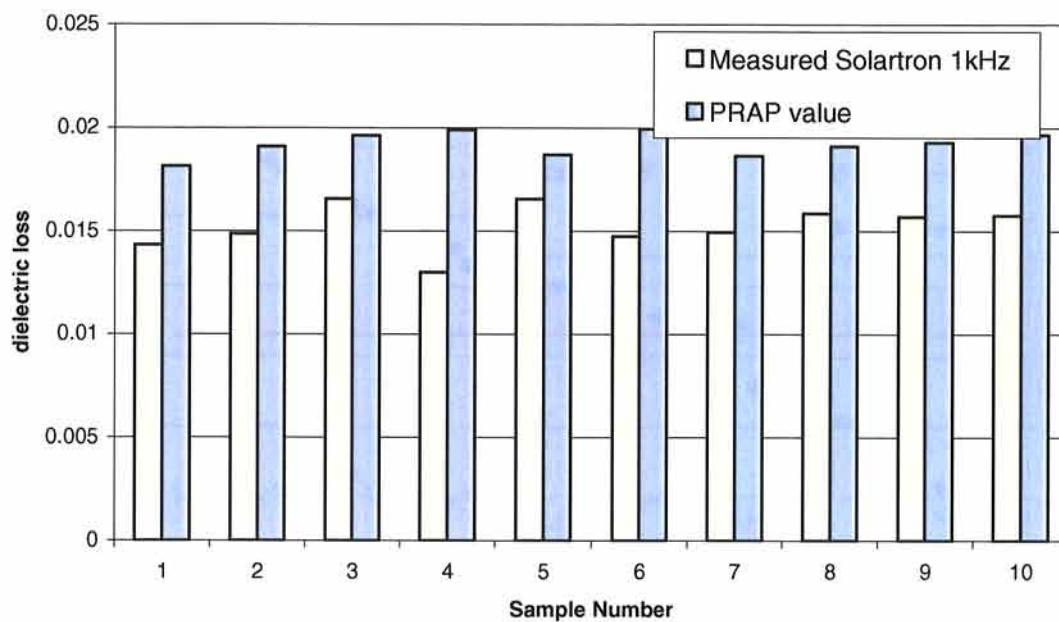


Figure 18: PZT 5A: Loss values are approximately 25% higher when measured at resonance using PRAP than measured with the Solartron.

It is important to note a few differences in the measurement parameters for these tests:

1. the resonance tests were carried out at high frequency – about 180kHz.

- the Solartron tests were carried out at 1kHz and low field but the loss was determined from a direct measure of the phase angle difference between applied field and resultant current. This phase angle leads directly to the loss tangent.

Features of note include the below average levels of recorded capacitance and above average recorded values of loss when measured at resonance. The explanation for the differences may be linked to the dispersive relationship of permittivity and loss. For hard materials the permittivity and loss has been shown to be fairly insensitive to frequency. However, soft materials do exhibit changes in dielectric properties with frequency with a slight drop in permittivity and a slight increase in loss with frequency [Gonzalez, 1996].

3.1.2 Piezoelectric Loss

The piezoelectric coefficient was measured using two additional complimentary techniques. The first was to measure, in one complete driven cycle, the strain response to an applied electrical field. The strain was measured using a fibre optic probe and field with an oscilloscope. The strain and field were acquired and analysed using software specially written for hysteresis loop measurements [NPL Report A152 1999]. The area enclosed by the loop is representative of the piezoelectric loss; these are represented by the Pehyst data points on the graph. Additionally the strain field data was measured using a Solartron Gain Phase analyser, providing a direct measure of the phase angle between strain and electric field. This data was also compared to the resonance PRAP data, in Figure 19.

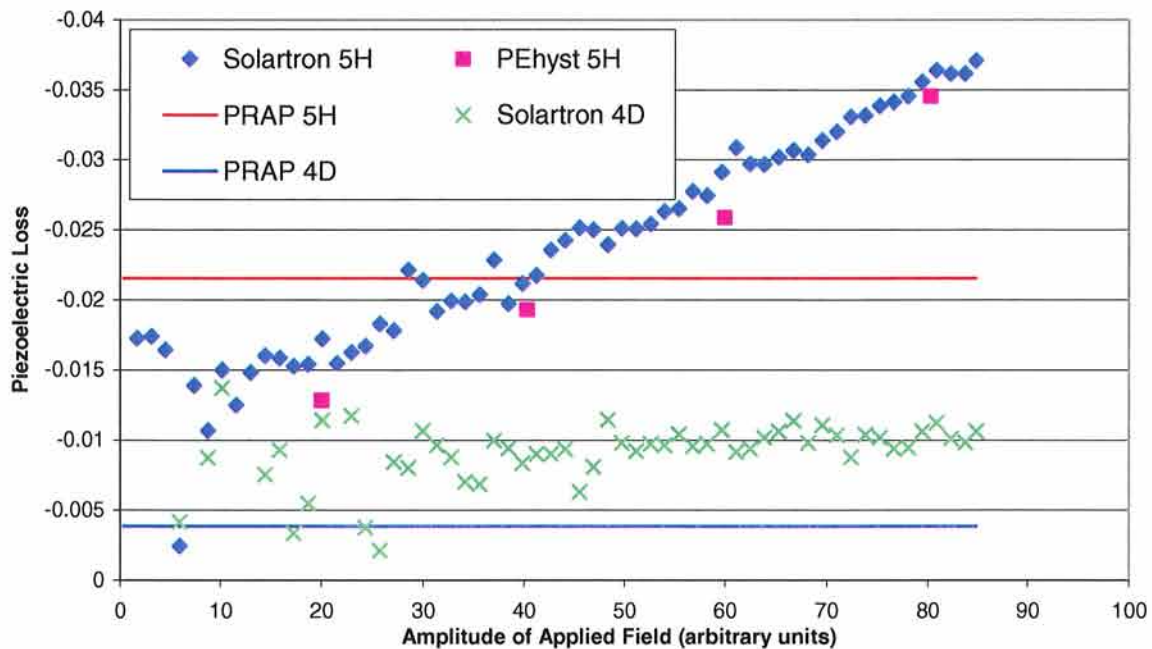


Figure 19: Piezoelectric loss with electric field measured using PRAP (horizontal line), P-E hysteresis loop area, and gain phase analyser.

Direct piezoelectric coefficient and loss was also measured using the Berlincourt method. In this technique, the sample was placed between two ball bearings under a small static preload

and a small alternating mechanical force was applied. The sample electrodes were connected to the input of a charge amplifier (virtual earth and hence short circuit conditions prevailed). A Solartron 1260 gain phase analyser captured the amplitude and phase difference between applied mechanical load (ac) and resultant charge developed. The data is reproduced in Figure 20, which clearly indicates the increase in loss for soft materials with alternating mechanical load and an insensitivity with load for hard materials. This experiment provides some confidence in the indirect displacement measurements in Figure 19.

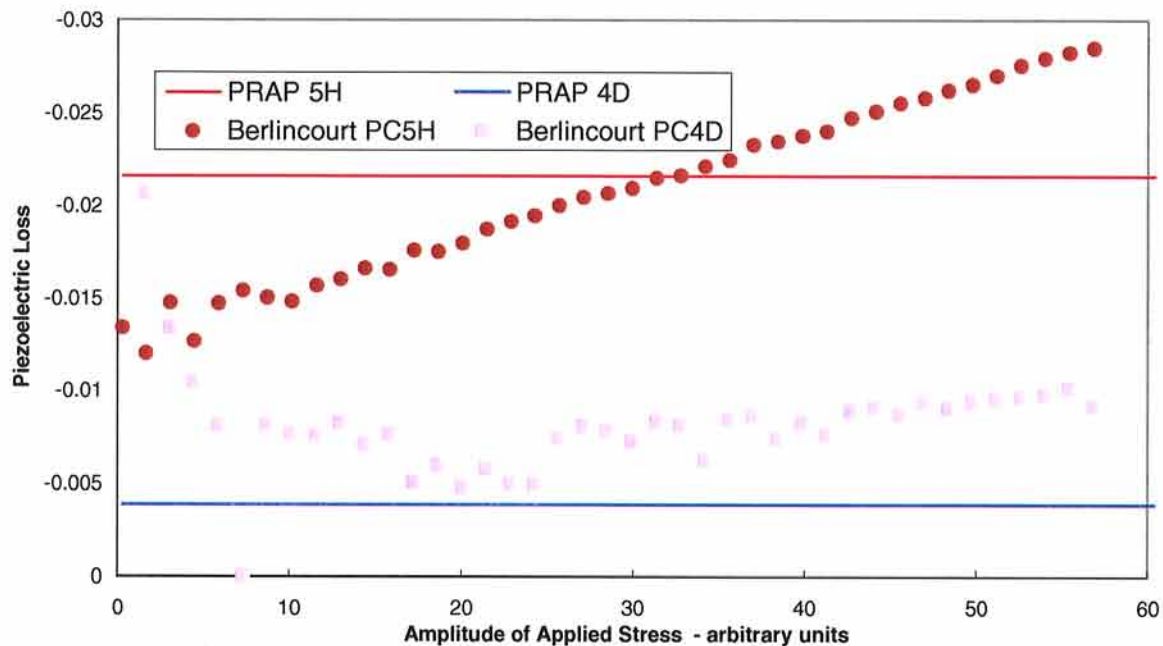


Figure 20: Piezoelectric loss with electric field measured using PRAP (horizontal line) and impedance gain phase analyser for direct (charge) effect.

The piezoelectric loss value for hard materials determined from measurement of displacement is seen to be approximately two times that calculated by PRAP. A potential explanation might involve phenomena that are only active at lower frequencies such as domain wall motion that becomes diminished at resonant frequencies (but this is improbable for hard materials). For soft materials the values of loss are in agreement with the resonance value only at a certain applied field (and hence strain) with loss exhibiting a linear increase with amplitude, as expected. Again the non-resonant measurements are performed at much lower frequencies, kHz rather than hundreds of kHz. Also the non-resonant methods involve measurements conditions well into the non-linear behaviour regime.

3.1.3 Mechanical Loss

The mechanical loss of a series of length mode resonators was measured using conventional strain gauge techniques to measure the stress-strain behaviour up to around 10MPa, and these were then compared with data derived from resonance measurements with subsequent complex analysis using PRAP software. The real part of the compliance was determined from

the slope of the stress strain curve and measuring the enclosed area in the stress-strain hysteresis yielded the imaginary part.

The stress strain measurement technique is difficult to carry out as the displacements involved are very small and can easily be 'lost' in small misalignments. Strain gauge experiments do not suffer from this 'lost' strain, however care must be taken to apply a uniform stress field across the sample. Three strain gauges were placed around the circumference of the samples, length 15mm, and diameter 6.35mm. Care was taken to achieve good alignment, but often there was over 100% difference in the outputs from the three gauges. However considering that the total displacement in any experiment is only 1µm, it is not surprising that there is such a large scatter.

Material	Method	Electrical Conditions	Compliance		Mechanical loss
			Compliance real part (m ² /N)	imaginary part (m ² /N)	
PZT 5A	Stress-strain	open	1.30E-11	-5.87E-13	-4.51E-02
	Stress-strain	short	2.82E-11	-1.46E-12	-5.19E-02
	Resonance	open	1.13E-11	-5.17E-14	-4.57E-03
	Resonance	short	2.09E-11	-2.04E-13	-9.75E-03
PZT4D	Stress-strain	open	1.22E-11	-1.20E-12	-9.82E-02
	Stress-strain	short	1.78E-11	-4.30E-13	-2.42E-02
	Resonance	open	8.77E-12	-7.95E-15	-9.07E-04
	Resonance	short	1.52E-11	-1.84E-14	-1.21E-03

Table 2: Summary of mechanical loss measured using stress strain experiments and PRAP comparisons.

A summary of the results determined by the independent methods on the same samples is given in Table 2. In order to get some idea of the validity of the results since neither method is definitive, the results can be tested against some empirical generalisations. The mechanical behaviour of soft and hard PZT piezoelectric materials can be generalised by the following statements

- Soft materials are more compliant than hard materials.
- Mechanical loss of soft materials is greater than in hard materials (often by an order of magnitude).
- Compliance and mechanical loss are greater for short circuit conditions than in open circuit.

For the resonance method all the results comply with these simple tests, as do the stress strain results except for the anomalously high loss value for the hard material in open circuit conditions. Intercomparison of the two methods show the compliance values for the stress strain technique are between 15 and 40% lower than those determined by resonance. However the mechanical loss values determined by stress strain are between one and two orders of magnitude greater than calculated from the resonance technique.

There are many possible explanations for these anomalies; the frequency for the stress-strain measurements is much less than 1Hz; the stress strain loss measurements are close to the noise level limits for the technique; the stress levels are very different for the two measurement methods; the stress-strain measurement is compression only, whilst the resonance is compression and tension. However, considering the limitations of the stress strain measurement technique the general agreement is remarkable.

The usual way of measuring mechanical losses in transducers is to measure the mechanical Q_m , i.e. the full width at 3dB of the resonance peak. If this is done and compared with the values obtained from the PRAP fit there is excellent agreement. However, this is not surprising since PRAP produces an almost perfect fit to the experimental data, although it does verify that the mechanical loss terms in the PRAP fit produce the expected behaviour.

4 Conclusions

The phenomenon of resonance in piezoelectric crystals has been described. The various modes of vibration depend on sample and electrode geometry, drive frequency and other electro-mechanical constraints.

Materials properties such as elastic, dielectric and piezoelectric coefficients may be calculated from resonance measurements. The method by which the resonance scan is taken can affect the values obtained quite dramatically. If measurements are to be taken in the materials linear regime then excitation fields must not exceed 1V/mm. Resonance is typically measured using Impedance Analysers. It is important to use quality sample fixings and jigs and cable and jig compensation is required if accurate property values are required. Effects such as sample off axis location, excess solder mass contacts and sample imperfections have been investigated. All deviations from perfection degrade the signal quality and hence resultant property accuracy. An important issue is that of non-ideal sample geometry and the mixed mode coupling that results. Differences in resonance spectrum peak positions and shapes were more evident for soft materials than hard for small deviations from the IEEE recommendations. Finally, the variation in properties calculated for different samples was consistently higher than the experimental error in single measurements, when adequate precautions were taken in accordance with the recommendations set out in this Guide.

Conditions for materials characterisation using resonance

In order to make meaningful measurements using resonance analysis the following assumptions must be true for your material:

- samples are of geometry defined in IEEE standard,

- the material properties may be adequately described by the set of linear piezoelectric equations, (the behaviour is independent of applied field),
- all materials properties are constant with frequency,
- the materials are poled polycrystalline ceramics with cylindrical symmetry.

Methods for measuring losses in piezoelectric materials are described in a separate section. The imaginary coefficients derived from complex fitting of the dielectric, mechanical and piezoelectric coefficients to the resonance impedance spectrum is undertaken in the PRAP software. Alternative methods of directly measuring these losses were suggested and results compared.

The results indicates:

- a) PRAP yields loss values that are broadly consistent with our alternative measurements but significant differences exist.
- b) PRAP assumes that the materials behave in a linear fashion with zero frequency dispersion. Our non-resonant experiments were conducted in a non-linear regime and the material parameters will almost certainly exhibit frequency dependence.
- c) More work is required to understand the origins of loss, to adequately measure these losses independently and accurately and to understand the interdependence of these losses in piezoelectric materials.

5 Worked Example

The sample is a length mode resonator 15mm long and 3mm in diameter of a soft PC 5H composition, with silver frit type fired on electrodes. The sample diameter is measured at three points along the length, and the three length readings are made. The average readings are:-

$$\begin{array}{lcl} \text{Diameter} & = & 2.987\text{mm} \\ \text{Length} & = & 15.063\text{mm} \end{array}$$

The mass of the sample is needed for the density measurement, and although the electrodes are on the sample they are only a small fraction of the overall thickness in this length resonator. The removal of electrodes is a somewhat destructive process, and so for thin discs it is often better to use density values from similar samples. The sample mass is:-

$$\text{Sample Mass} = 0.79005\text{g}$$

The volume of the sample could be measured by measuring the sample mass in water, however since the geometry of the sample is simple the volume can be calculated from the sample dimensions. This gives a value for the density of:-

$$\text{Sample Density} = 7485 \text{ kg/m}^3$$

The sample is now placed in the impedance analyser in the sample jig that has been corrected for open and short circuit conditions (Figure 21).



Figure 21: Piezoelectric sample placed between electrodes in the HP sample jig.

An initial sweep from 1 kHz to 500kHz is made to discover where the fundamental length mode resonance peak is. After this a refined sweep is performed over the range 70kHz to 150kHz. In this instance, the previous sample measured was a 0.5mm thick sample that was measured at an applied oscillator voltage level of 10mV. However, when this was used on the 15mm long sample there was some noise around the anti-resonance curve. This is because under these conditions the high impedance at resonance reduces the current signal. When the oscillator voltage was increased to 100mV this noise disappeared. The impedance sweep is shown in Figure 22. The minimum and maximum values for this curve respectively are the values used for the resonance and anti-resonance frequencies. The resonant frequencies are taken as the maximum and minimum values of the measured data, i.e. there is no curve fitting performed. Obviously these values depend on the frequency step of the impedance sweep, in this case 100Hz, which represents a resolution of around 0.1%.

$$\begin{aligned} f_r &= 92500 \\ f_a &= 124000 \end{aligned}$$

Using the following formula the coupling coefficient k_{33} can be determined:-

$$k_{33}^2 = \frac{\pi}{2} \frac{f_r}{f_a} \cot \left[\frac{\pi}{2} \frac{f_r}{f_a} \right]$$

$$k_{33} = 0.7029$$

The open circuit elastic compliance s_{33}^D is calculated using the following formula:-

$$s_{33}^D = \frac{1}{4 \cdot \rho \cdot f_p^2 \cdot l^2} = 9.574e-12 \cdot \left(\frac{m^2}{N} \right)$$

The closed circuit compliance coefficient can now be determined using:-

$$s_{33}^E = \frac{s_{33}^D}{1 - k_{33}^2} = 1.89e-11 \cdot \left(\frac{m^2}{N} \right)$$

In order to determine the piezoelectric constant d the dielectric constant under constant (or zero) stress condition is needed. Although the capacitance has already effectively been measured in the impedance sweep these have been carried out near resonance and the condition of zero stress is not satisfied. Normally the 'free' capacitance, C^T , measurement is carried out at 1kHz leading to the free permittivity through:-

$$\epsilon_{33}^T = C^T \frac{t}{A} = 2.77e-8 \cdot (F/m)$$

where t is the thickness and A the area.

The piezoelectric coefficients can then be determined using:-

$$d_{33} = k_{33} \sqrt{\epsilon_{33}^T s_{33}^E} = 509e-12 \cdot (C/N)$$

And

$$g_{33} = \frac{d_{33}}{\epsilon_{33}^T} = 0.01837 \cdot \left(\frac{Vm}{N} \right)$$

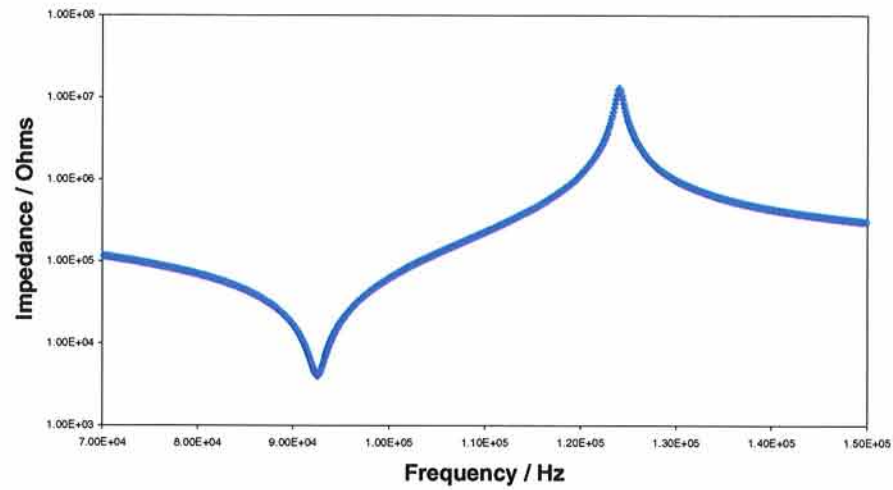


Figure 22: Worked example for piezoelectric long thin rod resonance and anti-resonance scan.

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