

2.1 The piezoelectric effect in ceramic materials

The **piezoelectric effect** was discovered by Jacques and Pierre Curie in 1880. They found that if certain crystals were subjected to mechanical strain, they became electrically polarized and the degree of polarization was proportional to the applied strain. The Curies also discovered that these same materials deformed when they were exposed to an electric field. This has become known as the inverse **piezoelectric effect**.

The piezoelectric effect is exhibited by a number of naturally-occurring crystals, for instance quartz, tourmaline and sodium potassium tartrate, and these have been used for many years as electromechanical transducers. For a crystal to exhibit the piezoelectric effect, its structure should have no centre of symmetry. A stress (tensile or compressive) applied to such a crystal will alter the separation between the positive and negative charge sites in each elementary cell leading to a net polarization at the crystal surface. The effect is practically linear, i.e. the polarization varies directly with the applied stress, and direction-dependent, so that compressive and tensile stresses will generate electric fields and hence voltages of opposite polarity. It's also reciprocal, so that if the crystal is exposed to an electric field, it will experience an elastic strain causing its length to increase or decrease according to the field polarity.

2.2 Piezoelectric materials

Besides the crystals mentioned above, an important group of piezoelectric materials are the piezoelectric ceramics, of which PZT is an example. These are polycrystalline ferroelectric materials with the perovskite crystal structure - a tetragonal/rhombohedral structure very close to cubic. They have the general formula $A^2+B^1+O^{2-}_3$, in which A denotes a large divalent metal ion such as barium or lead, and B denotes a tetravalent metal ion such as titanium or zirconium. It's these materials that are the subject of the present book (Ref. 1).

Materials such as PZT can be considered as a mass of minute crystallites. Above a temperature known as the Curie point, these crystallites exhibit simple cubic symmetry, the elementary cell of which is shown in Fig.2.1(a). This structure is centrosymmetric with positive and negative charge sites coinciding, so there are no dipoles present in the material (which is said to exhibit paraelectric behaviour). Below the Curie point, however, the crystallites take on tetragonal symmetry in which the positive and negative charge sites no longer coincide (Fig.2.2(b)), so each elementary cell then has a built-in electric dipole which may be reversed, and also switched to certain allowed directions by the application of an electric field. Such materials are termed ferroelectric because this electrical

behaviour presents a physical analogy with the magnetic behaviour of ferromagnetic materials. They don't necessarily contain iron as an important constituent. The analogy can, in fact, be carried further, since to some extent the polarization of ferroelectric materials exhibits hysteresis, and their dielectric constants are very high and temperature-dependent (as are the permeabilities of ferromagnetic materials).

The dipoles are not randomly oriented throughout the material. Neighbouring dipoles align with each other to form regions of local alignment known as Weiss domains. Within a Weiss domain, therefore, all the dipoles are aligned, giving a net dipole moment to the domain, and hence a net polarization (dipole moment per unit volume).

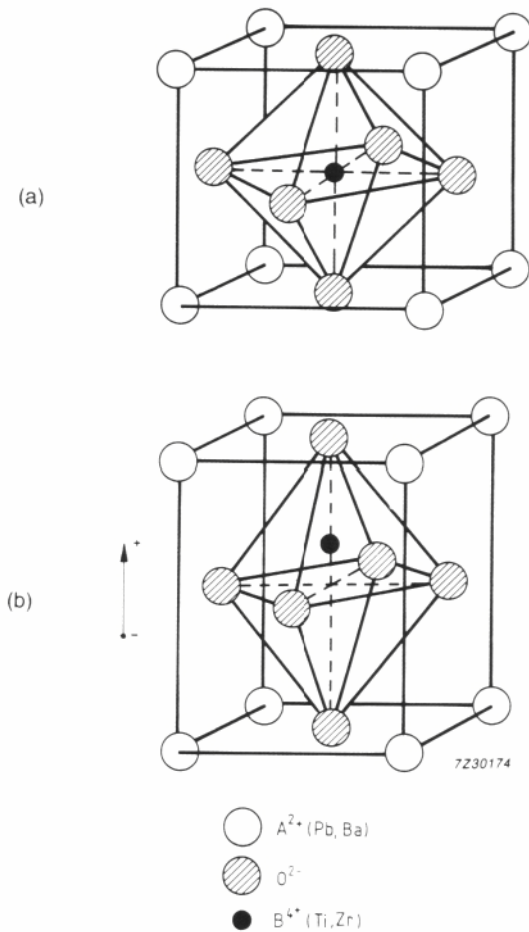


Fig.2.1 PZT elementary cell.

(a) cubic lattice (above Curie temperature);

(b) tetragonal lattice (below Curie temperature)

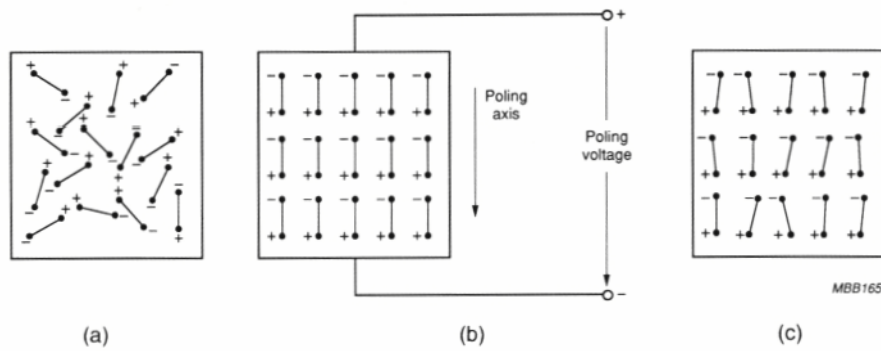


Fig.2.2 Electric dipole moments in Weiss domains.

- (a) before polarization;
- (b) during polarization;
- (c) after polarization

The direction of polarization between neighbouring Weiss domains within a crystallite can differ by 90° or 180° , and owing to the random distribution of Weiss domains throughout the material (Fig.2.2(a)), no overall polarization or piezoelectric effect is exhibited. The ceramic may be made piezoelectric in any chosen direction by a poling treatment which involves exposing it to a strong electric field at a temperature slightly below the Curie point (Fig.2.2(b)). Under the action of this field, domains most nearly aligned with the field will grow at the expense of other domains. The material will also lengthen in the direction of the field. When the field is removed (Fig.2.2(c)), the dipoles remain locked in approximate alignment, giving the ceramic material a remanent polarization and a permanent deformation (i.e. making it anisotropic). The poling treatment is usually the final treatment of PZT component manufacture.

2.3 Dielectric hysteresis

The electric field E and the polarization P are connected in a dielectric medium by the relation:

$$D = \epsilon_0 E + P \quad (2.1)$$

in which ϵ_0 is the permittivity of free space and D is the electric displacement. For a ferroelectric material like PZT, however, P is itself a function of E as shown in Fig.2.3. In this figure, the hysteresis effect, familiar from ferromagnetics, is quite evident. If an initially unpolarized sample of PZT is subjected to an increasing electric field at a temperature slightly below its Curie point, the dipoles become increasingly aligned with the field and the polarization will follow the 'initial curve' shown in Fig.2.3. When the field has increased beyond a certain value, no further increase in polarization will be observed because the dipoles are then all aligned with the field. The material is then said to have reached its saturation polarization P_{s^*} .

If the field is now reduced to zero, the dipoles become less strongly aligned, since in the absence of an external field they're bound to **certain preferred directions within** the individual crystallites. They do not, however, return to their original alignment (i.e. the alignment before the field was applied) since there are several preferred directions within the crystallites and the dipoles remain in the ones most closely aligned with the original field. Since there is still, therefore, a very high degree of alignment (as can be seen from Fig.2.2(c)), the polarization does not fall back to zero but to a value somewhat lower than the saturation polarization known as the remanent polarization P_r .

If the field is now increased in the opposite direction, the polarization of the sample initially falls to zero and then increases in the negative direction until it reaches a saturation polarization $-P_{s^*}$. If the field is again reduced to zero, the polarization falls to the remanent polarization $-P_r$ and finally, if the field is increased in the positive direction again, the polarization will fall to zero and then eventually return to P_{s^*} .

The curve thus traced out is known as the hysteresis curve. Its shape varies for the different PZT materials (Fig.2.3 is the hysteresis curve for a 'soft' PZT) but the remanent polarization is generally around 0.3 C/m^2 for all PZT materials.

The variation of electric displacement D as a function of electric field strength follows very closely the curve for polarization. For example, at the peak of the hysteresis curve ($E = 1.6 \text{ kV/mm}$), D is only around 0.014 C/m^2 higher than P . At $E = 0$, D and P are equal, i.e. $D = P_r$.

The lower part of Fig.2.3 shows the variation of the sample's relative extension S_3 (i.e. in the direction of polarization) with electric field, and it can be seen that this also exhibits a hysteresis effect corresponding precisely with the effect observed for polarization.

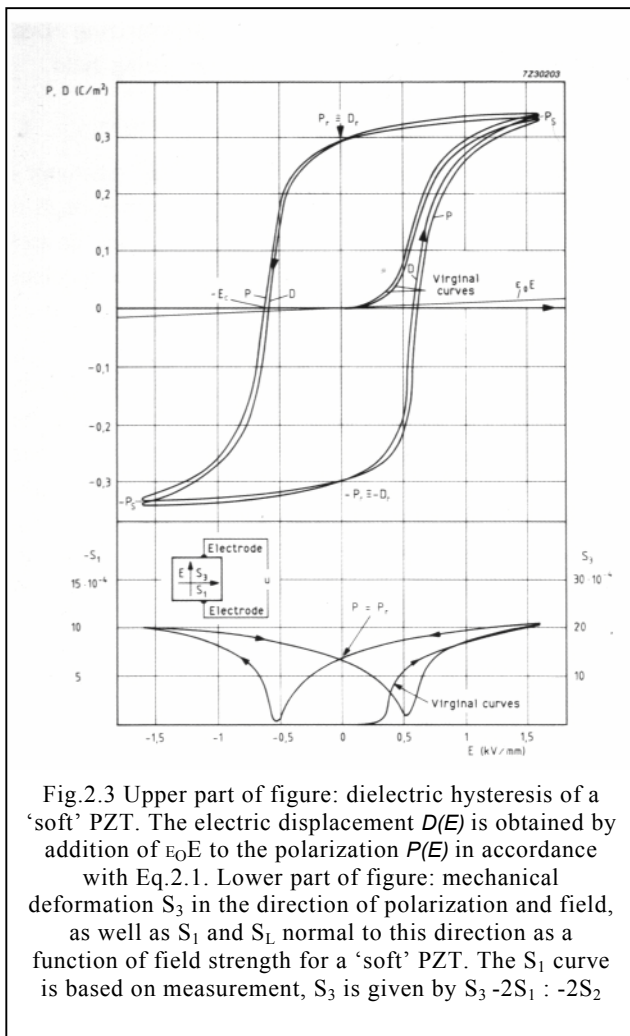


Fig.2.3 Upper part of figure: dielectric hysteresis of a 'soft' PZT. The electric displacement $D(E)$ is obtained by addition of $\epsilon_0 E$ to the polarization $P(E)$ in accordance with Eq.2.1. Lower part of figure: mechanical deformation S_3 in the direction of polarization and field, as well as S_1 and S_2 normal to this direction as a function of field strength for a 'soft' PZT. The S_1 curve is based on measurement, S_3 is given by $S_3 - 2S_1 : -2S_2$

Since the volume of the sample remains roughly constant, a relative increase (or decrease) in S_3 will be accompanied by a relative decrease (or increase) in the sample's dimension perpendicular to the field (S_1 and S_2) equal to about half the change in S_3 (the left hand scale in the lower part of Fig.2.3). This is also true, incidentally, for compressive and tensile forces exerted by the sample.

Finally, Fig.2.4 shows how S_1 varies with electric displacement, and again shows the hysteresis effect.

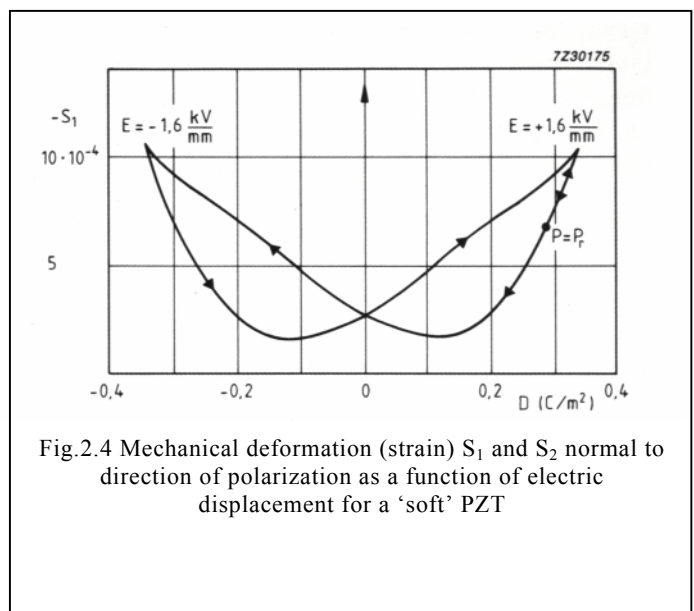


Fig.2.4 Mechanical deformation (strain) S_1 and S_2 normal to direction of polarization as a function of electric displacement for a 'soft' PZT

2.4 Basic behaviour of a piezoelectric ceramic body

Figure 2.5 illustrates the behaviour of a PZT cylinder polarized along its axis. For clarity, the magnitude of the effect has been exaggerated.

Figure 2.5(a) shows the cylinder under no-load conditions. If an external force produces compressive or tensile strain in the material, the resulting change in dipole moment causes a voltage to appear between the electrodes. If the cylinder is compressed so that it resumes its original form, i.e. before poling, the voltage will have the same polarity as the poling voltage (Fig.2.5(b)). If it is stretched, the voltage across the electrodes will have opposite polarity to the poling voltage (Fig.2.5(c)). These are examples of **generator action**: the conversion of mechanical energy into electrical energy. Examples of piezoelectric induced generator action can be found in cigarette and gas lighters, gramophone pick-ups, accelerometers, hydrophones and microphones.

If a voltage of opposite polarity to the poling voltage is applied to the electrodes, the cylinder will shorten (Fig.2.5(d)). If the applied voltage has the same polarity as the poling voltage, the cylinder will lengthen (Fig.2.5(e)).

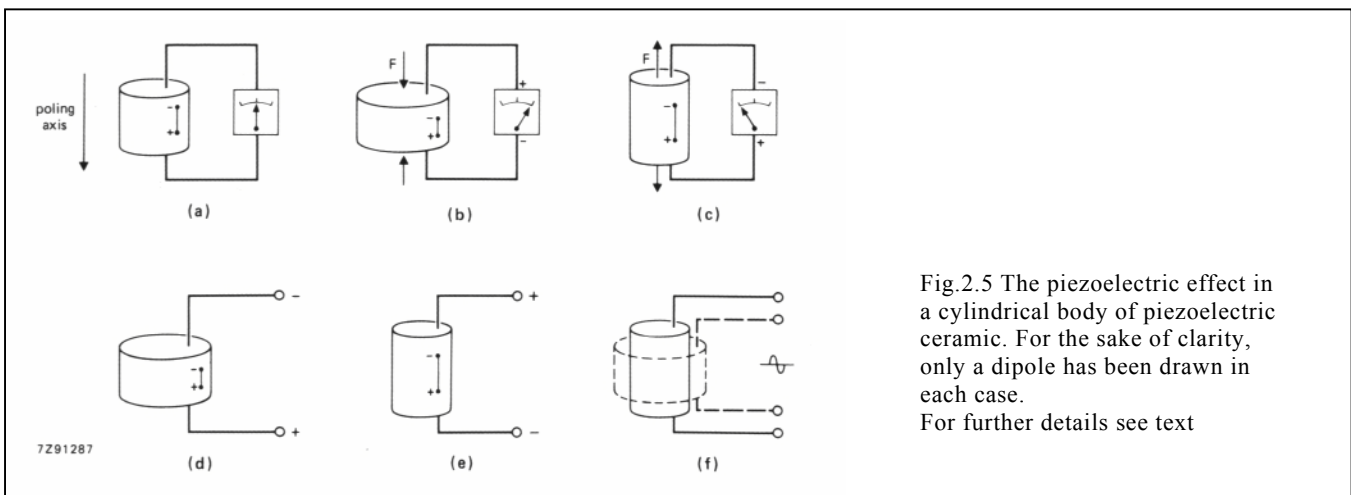
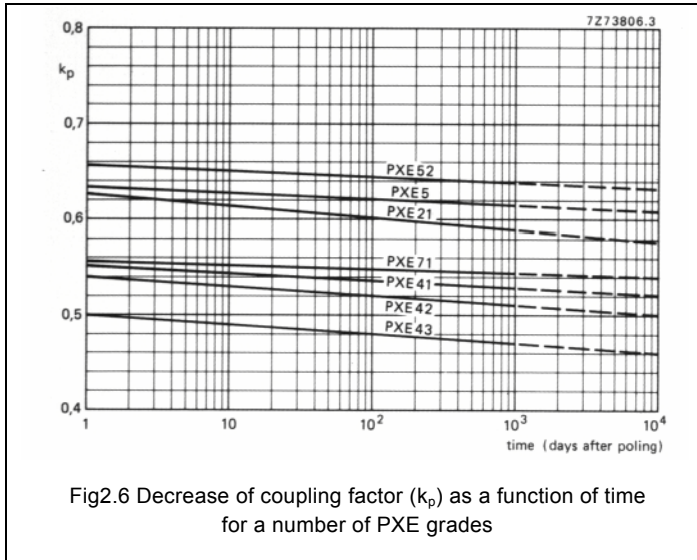


Fig.2.5 The piezoelectric effect in a cylindrical body of piezoelectric ceramic. For the sake of clarity, only a dipole has been drawn in each case.

For further details see text

Finally, if an alternating voltage is applied to the electrodes, the cylinder will grow and shrink at the same frequency as that of the applied voltage (Fig.2.5(f)). These are examples of **motor action**: conversion of electrical energy into mechanical energy.



2.5 Stability

The properties of piezoelectric elements are more or less temperature dependent and time dependent. The stability as a function of time is of particular interest. Fortunately the poling ages approximately logarithmically so that the rate of change in permittivity, coupling factor, frequency constant and so on (Section 2.11), decreases rapidly in the course of time. Powerful ambient influences are likely to change the original ageing pattern. This applies particularly to the permittivity, the mechanical Qfactor and the dielectric loss factor $\tan\delta$.

2.6 Depolarization

As already mentioned, after its poling treatment a PZT ceramic will be permanently polarized, and care must therefore be taken in all subsequent handling to ensure that the ceramic is not depolarized, since this will result in partial or even total loss of its piezoelectric properties. The ceramic may be depolarized electrically, mechanically or thermally.

2.6.1 Electrical depolarization

Exposure to a strong electric field of opposite polarity to the poling field will depolarize a piezoelectric element. The field strength required for marked depolarization depends, among other things, on the material grade, the time the material is subjected to the depolarizing field and the temperature. For static fields, it's typically between 200 and 500 V/mm.

An alternating field will also have a depolarizing effect during the half cycles that it opposes the poling field.

2.6.2 Mechanical depolarization

Mechanical depolarization occurs when the mechanical stress on a piezoelectric element becomes high enough to disturb the orientation of the domains and hence destroy the alignment of the dipoles. The safety limits for mechanical stress vary considerably with material grade.

2.6.3 Thermal depolarization

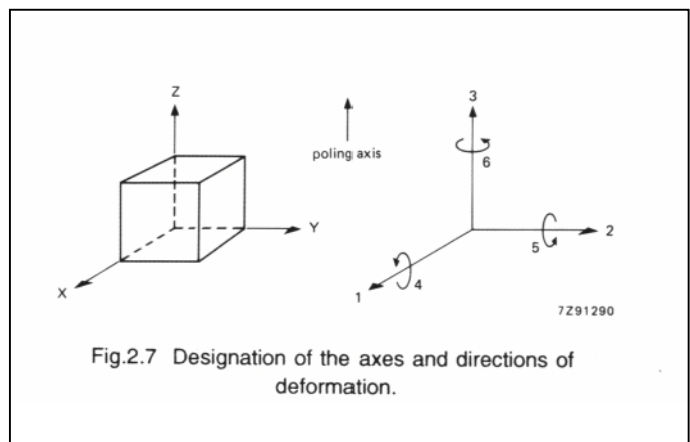
If a piezoelectric element is heated to its Curie point, the domains become disordered and the element becomes completely depolarized. A piezoelectric element can therefore function for long period without marked depolarization only at temperatures well below the Curie point. A safe operating temperature would normally be about half way between 0 °C and the Curie point.

2.7 Piezoelectric constants

Since piezoelectric ceramics are anisotropic, their physical constants (elasticity, permittivity etc.) are tensor quantities and relate to both the direction of the applied stress, electric field etc., and to the directions perpendicular to these. For this reason the constants are generally given two subscript indices which refer to the direction of the two related quantities (e.g. stress and strain for elasticity, displacement and electric field for permittivity). A superscript index is used to indicate a quantity that's kept constant (Ref.2).

The direction of positive polarization is usually chosen to coincide with the Z-axis of a rectangular system of crystallographic axes X, Y, Z. If the directions of X, Y and

Z are represented by 1, 2 and 3 respectively, and the shear about these axes by 4, 5 and 6 respectively, the various constants may be written with subscripts referring to these (Fig.2.7).



This system will now be illustrated with a few examples for the main piezoelectric constants.

Permittivity E

The (absolute) permittivity (or dielectric constant) is defined as the dielectric displacement per unit electric field. The first subscript gives the direction of the dielectric displacement, the second gives the direction of the electric field. For example:

ϵ_{11}^T is the permittivity for the dielectric displacement and electric field in direction 1 under conditions of constant stress, and

ϵ_{33}^S is the permittivity for the dielectric displacement and electric field in direction 3 under conditions of constant strain.

The tables in our Data handbook give values for the relative permittivity ϵ/ϵ_0 , i.e. the ratio of absolute permittivity to the permittivity of free space (8.85×10^{-12} F/m).

Compliance s

The compliance s of a material is defined as the strain produced per unit stress. It's the reciprocal of the modulus of elasticity. The first subscript refers to the direction of strain, the second to direction of stress. For example:

s_{11}^E is the compliance for a stress and accompanying strain in direction 1 under conditions of constant electric field, and

s_{36}^D is the compliance for a shear stress about axis 3 and accompanying strain in direction 3 under conditions of constant electric displacement.

Piezoelectric charge constants d

The piezoelectric charge constant is defined as the electric polarization generated in a material per unit mechanical stress applied to it. Alternatively, it is the mechanical strain experienced by the material per unit electric field applied to it. The first subscript refers to the direction of polarization generated in the material (at $E = 0$) or to the applied field strength, the second refers respectively to the direction of the applied stress or to the direction of the induced strain. For example:

d_{33} is the induced polarization per unit applied stress in direction 3. Alternatively it is the induced strain per unit electric field in direction 3.

d_{31} is the induced polarization in direction 3 per unit stress applied in direction 1. Alternatively it is the mechanical strain induced in the material in direction 1 per unit electric field applied in direction 3.

Piezoelectric voltage constant g

The piezoelectric voltage constant is defined as the electric field generated in a material per unit mechanical stress applied to it. Alternatively, it is the mechanical strain experienced by the material per unit electric displacement applied to it. The first subscript refers to the direction of the electric field generated in the material or to the applied electric displacement, the second refers respectively to the direction of the applied stress or to the direction of the induced strain. For example:

g_{31} is the induced electric field in direction 3 per unit stress applied in direction 1. Alternatively it is the mechanical strain induced in the material in direction 1 per unit electric displacement applied in direction 3.

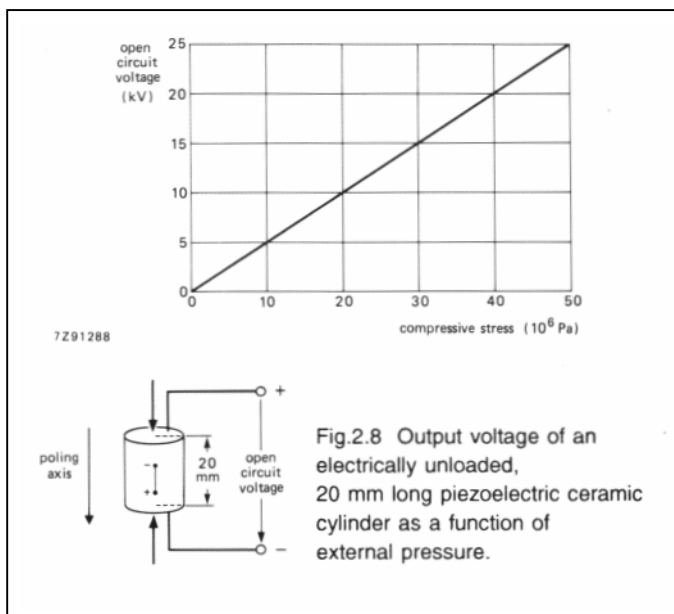
g_{15} is the induced electric field in direction 1 per unit shear stress applied about axis direction 2. Alternatively it is the shear strain induced in the material about axis 2 per unit electric displacement applied in direction 1.

2.8 Examples

To give an indication of the stresses, strains, voltages etc. that accompany piezoelectric transducer action, let's consider the example of a piezoelectric cylinder 20 mm long and 1 cm^2 in cross-section subject to an external stress. This is an example of generator action, i.e. the conversion of mechanical energy into electrical energy. Provided the ends of the cylinder are not connected together, no current flows and the dielectric displacement D is zero.

Figure 2.8 shows that the open-circuit voltage V (and hence the field strength E) is proportional to compressive stress T up to a maximum of 25 kV, which occurs at a stress of 50 MPa ¹⁾ (see Eq.A in the Appendix).

1) 10^6 N/m^2



This can be expressed as:

$$E = -gT \quad (2.2)$$

or, since $V = El$ and $T = F/A$,

$$V = -g \frac{l}{A} F \quad (2.3a)$$

in which F is the force applied to the ends of the cylinder of cross section A and length l , and g is the piezoelectric voltage constant defined in Section 2.7 (dimension m^2/C or Vm/N). Note: by definition, the voltage or electric field generated is said to be positive if its polarity is the same as that of the original poling voltage.

With $g = d/E^T$ (see Appendix, Eq.A), Eq.2.3a can be rewritten as:

$$U = -d \frac{l}{\epsilon^T A} F = -d \frac{F}{C} \quad (2.3b)$$

In which C is the capacitance of the piezoelectric cylinder and E^T is the dielectric constant at (constant) pressure T . So the charge $Q = CV$ on the cylinder (compare Fig.2.8(b)) is given by:

$$Q = -dF = -g\epsilon^T F \quad (2.4)$$

The induced charge therefore is completely independent of cylinder dimensions and hence of its tolerances (in contrast to the induced voltage). In this example, the induced charge is about 2 pC, but this depends heavily on temperature since g and E^T are temperature dependent (with temperature coefficients of opposite sign).

Stresses of 50 MPa are easily obtained with simple presses. Even the bare hand can produce forces of some tens of newtons, and it only takes about 25 N to generate 100 V with the above cylinder. The electrical energy this generates, however, is far too low to be hazardous.

Examples where mechanical energy (movement) is converted into electrical energy or into an electrical signal include: gas cigarette lighters and various domestic gas-ignition devices, gramophone pickups, accelerometers, microphones and hydrophones.

The conversion of electrical energy into mechanical movement is governed by the equation (corresponding to equation A in the appendix):

$$S = dE = d \frac{U}{l} \quad (2.5)$$

in which S is the mechanical strain (Fig.2.9) generated by electric field E or voltage V across the cylinder. The dimensions of the piezoelectric charge constant d are C/N or m/V . Since $S = \Delta l/l$

$$\Delta l = dU \quad (2.6)$$

from which we can deduce that Δl is independent of the dimensions of the PZT cylinder. For a PZT 5A cylinder subject to 16 kV ($E = 800$ V/m), Δl equals about 10 μm .

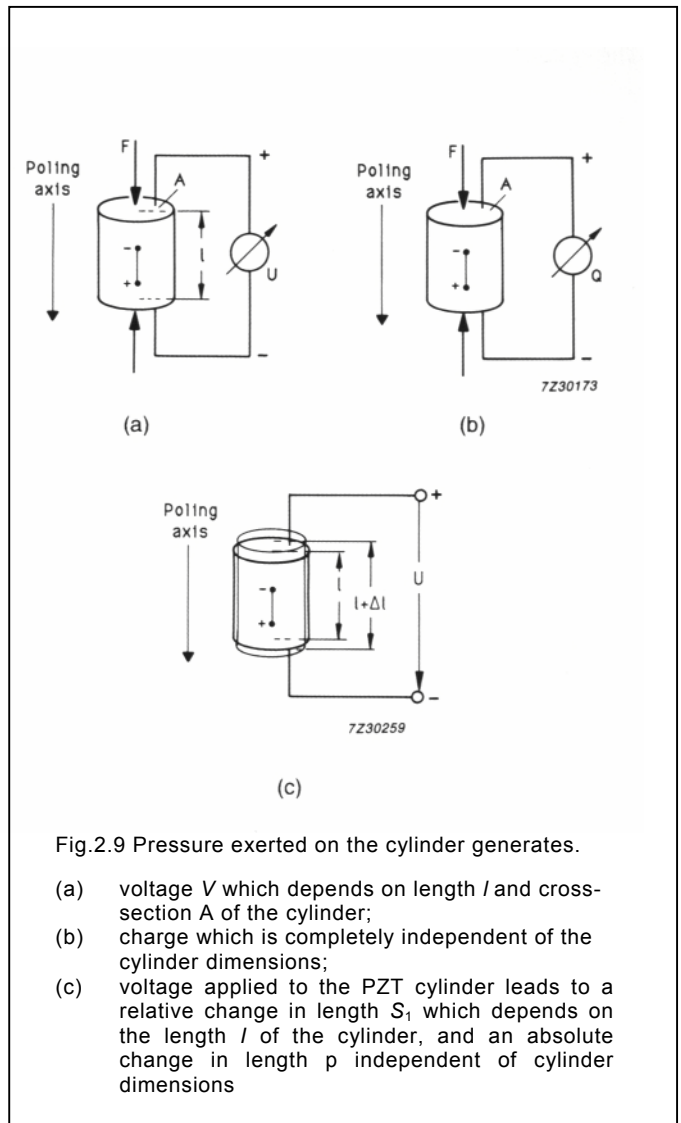


Fig.2.9 Pressure exerted on the cylinder generates.

- (a) voltage V which depends on length l and cross-section A of the cylinder;
- (b) charge which is completely independent of the cylinder dimensions;
- (c) voltage applied to the PZT cylinder leads to a relative change in length S_1 which depends on the length l of the cylinder, and an absolute change in length p independent of cylinder dimensions

The figures quoted here refer to static loads; an alternating field generally yields different results. In particular, at the mechanical resonant frequency, the amplitude of oscillation can be expected to be much greater than the static changes. For relatively large mechanical movement (> 1 mm say) special flexional elements are available.

Examples where electrical energy is converted into mechanical energy can be found in atomizers and equipment for ultrasonic cleaning, welding, soldering and ultrasonic drilling.

2.9 Dynamic behaviour of PZT transducers

When exposed to an alternating electric field, a piezoelectric element periodically changes its size in accordance with the frequency of the field. In other words it oscillates and, if the frequency lies in the vicinity of its series resonant frequency (see below for definition) its behaviour can be described by the equivalent circuit of Fig.2.10.

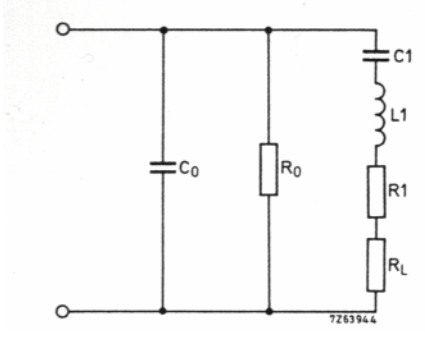


Fig.2.10 Equivalent circuit diagram of a PZT transducer.
 C_0 is the capacitance of the transducer below the resonant frequency minus capacitance C_1 ,
 R_1 is the resistance caused by mechanical losses
 R_L the resistance of the working load due to the radiated energy: in vacuum $R_L = 0$,
 C_1 the capacitance of the mechanical circuit and L_1 is the inductance of the mechanical circuit

For such an oscillating system, Fig.2.11 shows the variation of admittance $|Y|$ and impedance $|Z|$ with frequency. The frequency f_m at which the admittance becomes maximum (minimum impedance frequency) lies close to the series resonant frequency

$$f_s = \frac{1}{2\pi} \sqrt{\frac{1}{L_1 C_1}} \quad (2.7)$$

(The frequency at which the impedance in the equivalent circuit becomes zero when R_L is neglected).

The frequency f_n at which the admittance becomes minimum (maximum impedance frequency) lies close to the parallel resonant frequency

$$f_p = \frac{1}{2\pi} \sqrt{\frac{C_0 + C_1}{L_1 C_0 C_1}} \quad (2.8)$$

(The frequency at which the parallel resistance in the equivalent circuit becomes infinite, again neglecting R_1).

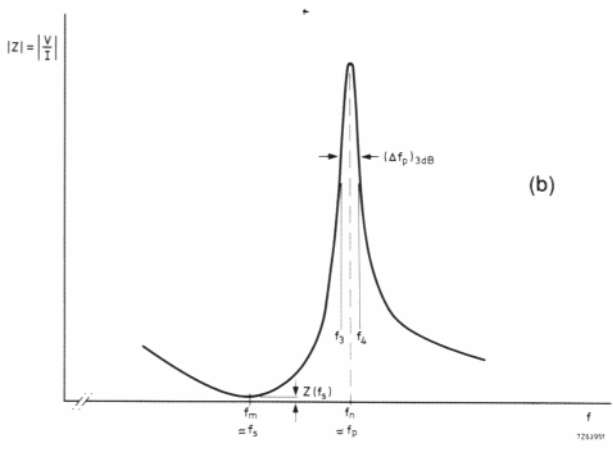
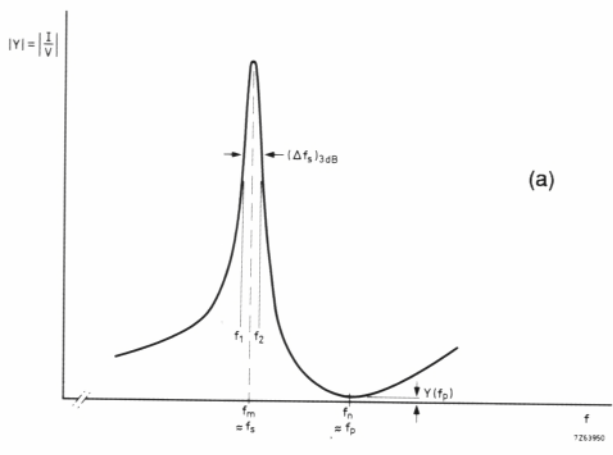


Fig.2.11 Admittance and impedance as functions of frequency. The series resonant frequency f_s lies in the vicinity of the minimum impedance frequency f_m the parallel resonant frequency f_p lies in the vicinity of the maximum impedance frequency f_n . Below f_m and above f_n the transducer behaves capacitively, between f_m and f_n it behaves inductively

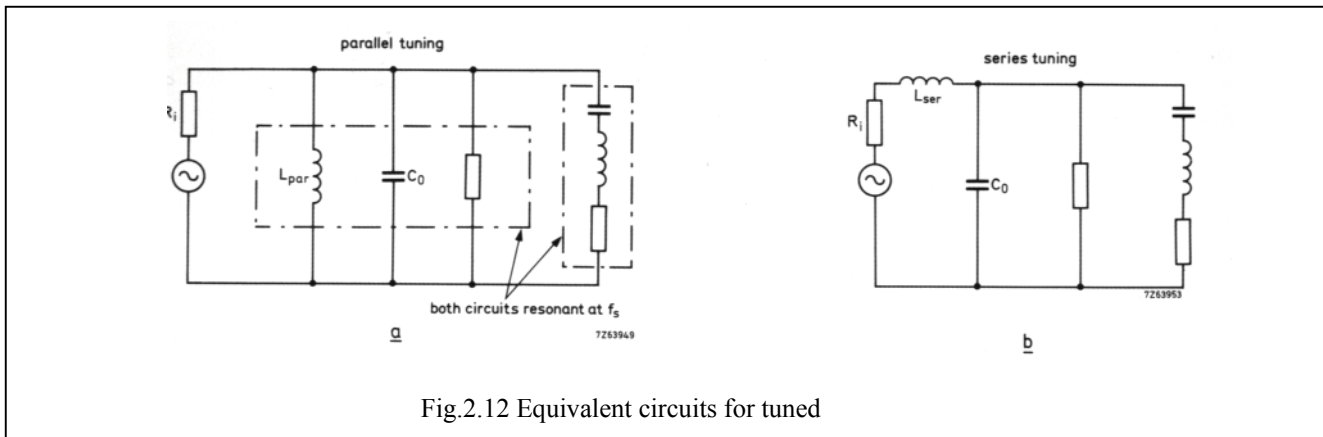


Fig.2.12 Equivalent circuits for tuned

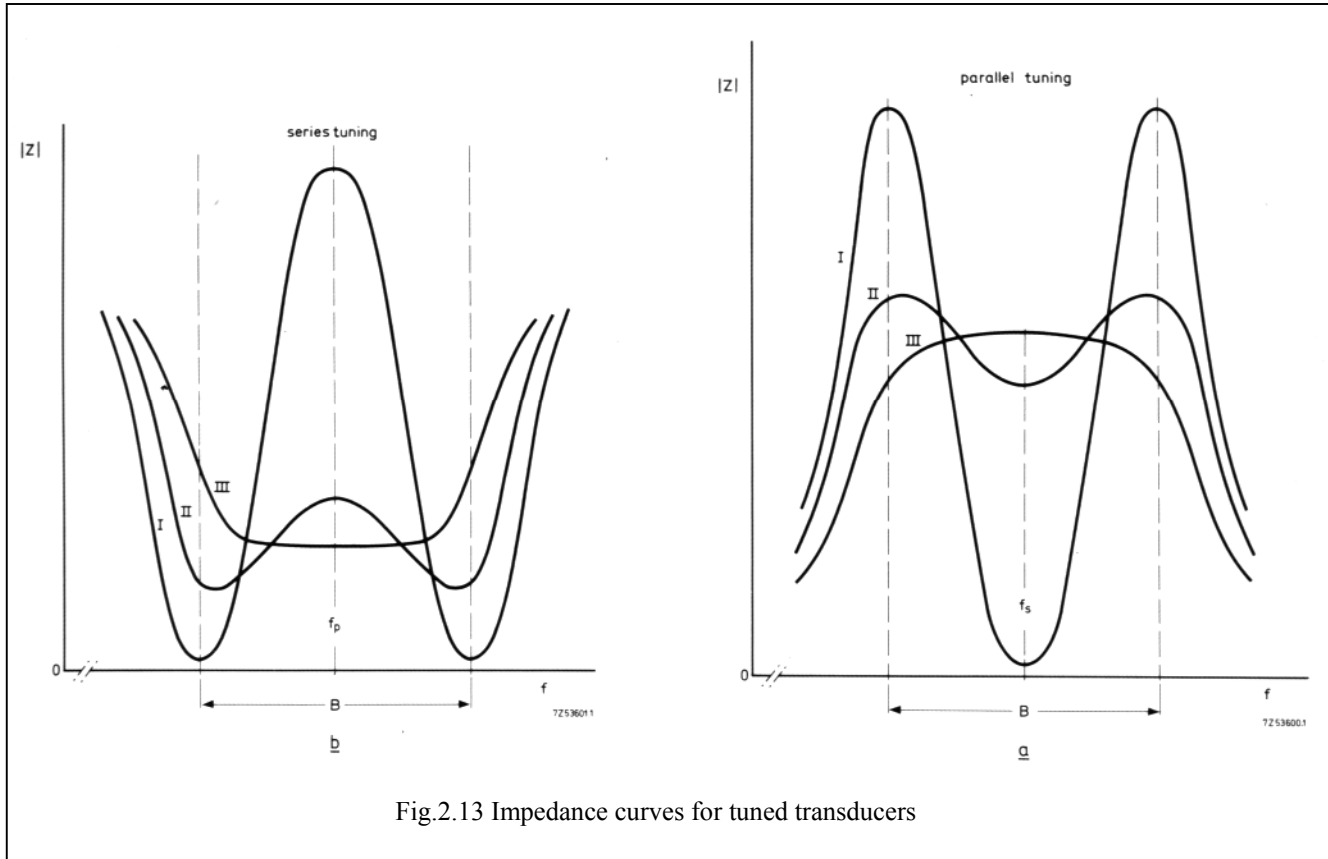


Fig.2.13 Impedance curves for tuned transducers

It's often advisable to tune the transducer with a series or parallel inductance, L_{par} or L_{ser} given by:

$$L_{par} = \frac{1}{\omega_s^2 C_0} \quad (\omega_s = 2\pi f_s) \quad (2.9)$$

$$L_{ser} = \frac{1}{\omega_p^2 C_0} \quad (\omega_p = 2\pi f_p) \quad (2.10)$$

In this way, two coupled resonant circuits are obtained: one mechanical, governed by L_1 , C_1 and R_1 , the other electrical, governed by L_{par} (or L_{ser}), C_0 and the resistor R of the AC voltage generator. The frequency response of such a coupled system resembles that of a band-pass filter.

Figure 2.12 shows the equivalent circuit for a tuned system (series and parallel tuning) and Fig.2.13 shows the

variation of impedance with frequency. Curve I applies to an acoustically unloaded oscillator, curves II or III to an oscillator in which the loading is average or strong.

The impedance of the parallel-tuned system at f_s , is real, and that of the series-tuned system is real at f_p . Although the frequency-response curve depends to some extent on the electrical termination resistance and mechanical load, the effect on bandwidth B , and on f_s and f_p is not great. The bandwidth obtained by electrical tuning is roughly the product of the effective coupling coefficient k_{eff} (see. section 2.11) and the series or parallel resonant frequency, i.e

$$B = k_{eff} f_{sp} \quad (2.11)$$

2.10 Frequency constant N

The resonant frequencies referred to in the previous section depend, of course, on the dimensions of the PZT sample, and experience indicates that they vary inversely with these dimensions. Figure 2.14, for example, shows the variation of impedance with frequency for a PZT5A disc, 1 mm thick and 25 mm in diameter. An impedance-minimum occurs at a series-resonant frequency f_s of

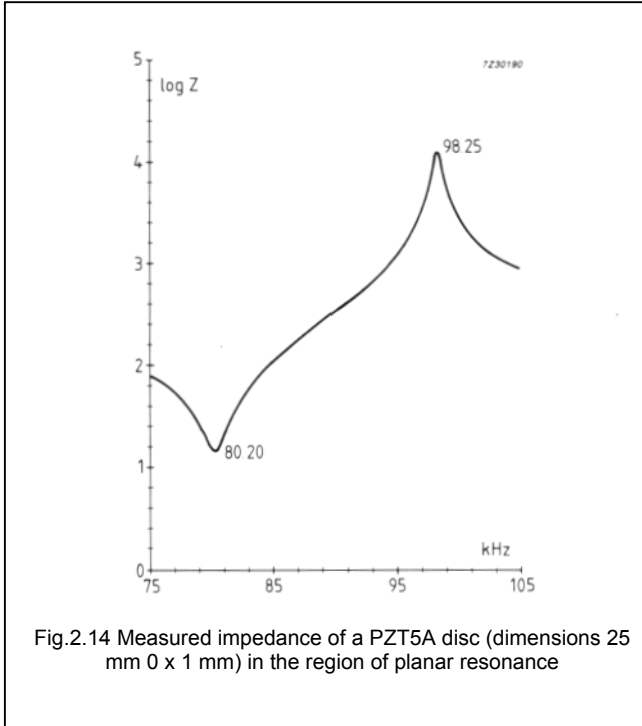


Fig.2.14 Measured impedance of a PZT5A disc (dimensions 25 mm \varnothing x 1 mm) in the region of planar resonance

Known as the planar or radial resonant frequency, it's related to the disc diameter D by

$$f_s = \frac{N_p^E}{d} = \frac{2000}{25 \times 10^{-3}} \approx 80 \text{ kHz} \quad (2.12)$$

N_p^E , which for PZT5A material equals 2000 m/s is known as the planar or radial frequency constant.

Figure 2.15 is similar to Fig.2.14 but with the frequency scale extended to 3 MHz to show higher resonances. The impedance minimum at about 2 MHz is known as the axial resonance, and its frequency is related to the thickness h of the disc by

$$f_s = \frac{N_3^D}{h} = \frac{1850}{1 \times 10^{-3}} \approx 2 \text{ MHz} \quad (2.13)$$

N_3^D is known as the thickness frequency constant and for PZT5A material it equals 1850 m/s ($\approx 1 \times 10^3 \text{ m} \times 2 \times 10^6 \text{ Hz}$).

So the frequency constant is the product of the series resonant frequency f_s and the dimensions governing that frequency. The subscript indicates the type of oscillation at resonance: p for planar oscillations, 3 for oscillations in the Z or axial direction.

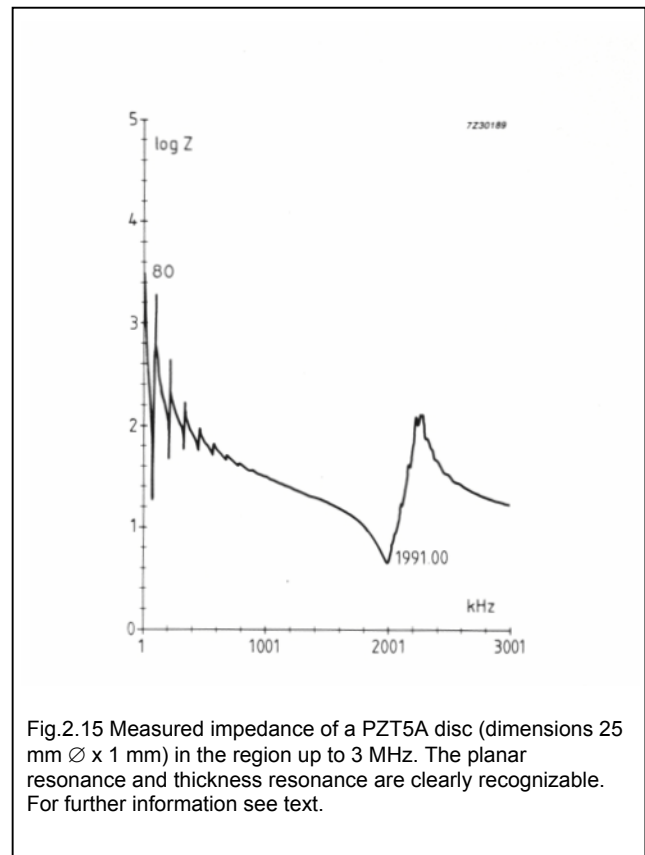


Fig.2.15 Measured impedance of a PZT5A disc (dimensions 25 mm \varnothing x 1 mm) in the region up to 3 MHz. The planar resonance and thickness resonance are clearly recognizable. For further information see text.

Frequency constants are always quoted in our data sheets and data handbook (MA03) on PZT materials, so using the above relations, it's an easy matter to calculate the series resonant frequency of a PZT oscillator. The frequency constant can, in fact, be shown to equal half the sound velocity in the ceramic material (with the exception of N_p).

Figures 2.14 and 2.15 relate to freely oscillating PZT bodies. Behaviour changes quite dramatically if the bodies are constrained. Figure 2.16, for example, shows how the impedance of a diaphragm on which a PZT disc is glued varies with frequency (for details see caption to figure).

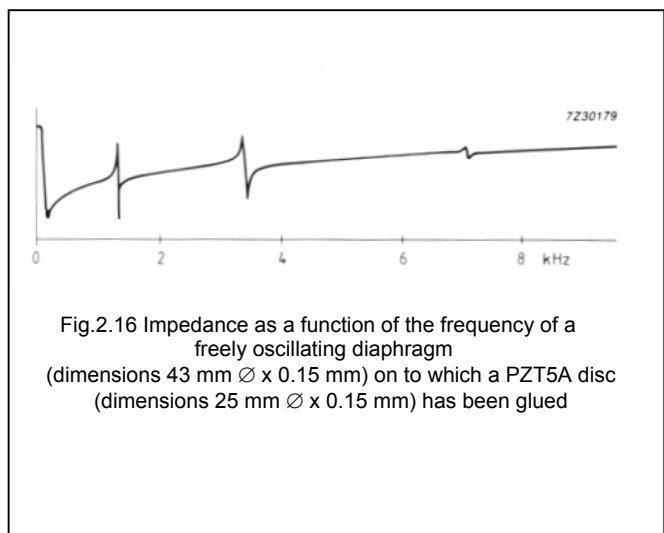


Fig.2.16 Impedance as a function of the frequency of a freely oscillating diaphragm (dimensions 43 mm \varnothing x 0.15 mm) on to which a PZT5A disc (dimensions 25 mm \varnothing x 0.15 mm) has been glued

2.11 Coupling factor k

Another important constant for piezoelectric materials is the coupling factor k_{eff} which is a measure of the effectiveness with which electrical energy is converted into mechanical energy and vice versa. At frequencies well below the resonant frequency of the piezoelectric body, k_{eff} is given by the expression

$$k_{eff}^2 = \frac{\text{energy converted}}{\text{input energy}}$$

(see appendix for derivation).

This expression holds for both electromechanical and mechano-electrical conversions.

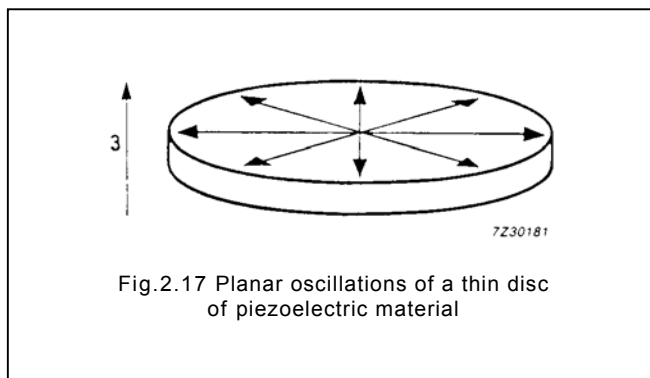
A study of the values of k_{eff} shows that for modern piezoelectric ceramics, up to 50% of the stored energy can be converted at low frequencies. The values of k_{eff}^2 quoted in tables, however, are usually theoretical maxima, based on precisely defined vibrational modes of ideal (i.e. unrealistic) specimens of the material. In practical transducers, the coupling factors are usually lower.

As with other piezoelectric constants, coupling factors carry subscripts. k_{33} , for instance, is the coupling factor for longitudinal vibrations of a very long, very slender rod (in theory infinitely long, in practice, with a length/diameter ratio > 10) under the influence of a longitudinal electric field. k_{31} is the coupling factor for longitudinal vibrations of long rod under the influence of a transverse electric field, and k_{15} describes shear mode vibrations of a piezoelectric body.

Special cases of the coupling factor are the planar coupling factor k_t , and the thickness coupling factor k_r . The planar coupling factor k_p of a thin disc represents the coupling between the electric field in direction 3 (parallel to the disc axis) and simultaneous mechanical effects in directions 1 and 2 (Fig.2.17) that result in radial vibrations. This is known as radial coupling.

The thickness coupling factor k_r represents the coupling between an electric field in direction 3 and the mechanical vibrations in direction 3 of a -thin, planar object of arbitrary contour (i.e. an object whose surface dimensions are large compared with its thickness).

The resonant frequency of the thickness mode of a thin planar object is far higher than that of its transverse mode.



What's more, since its overall volume remains substantially constant, expansion/contraction in thickness must always be accompanied by corresponding contraction/expansion in the transverse directions, so the strongly attenuated transverse vibrations at the higher resonant frequency of the thickness mode tend to increase the apparent stiffness of the material. Hence k_t is lower than k_{33} - the coupling factor for longitudinal vibrations of a slender rod (whose longitudinal resonant frequency is much lower and matches more closely its transverse resonant frequency).

Although a high k_{eff}^2 is usually desirable for efficient transduction, it should not be thought of as a measure of efficiency, since the unconverted energy is not necessarily lost (converted into heat) and can in many cases be recovered.

The real efficiency is the ratio of the converted useful energy to the energy taken up by the transducer, and a tuned and well-adjusted transducer working in its resonance region could be more than 90% efficient. Well outside its resonance region, however, its efficiency could be very low.

2.12 Comparison of piezoelectric ceramic and crystalline quartz

This section details some of the important differences between PZT and crystalline quartz, differences that in many instances account for their use in quite widely differing application areas. As we said earlier, the ferroelectric properties of PZT mean that it has a very much higher dielectric constant than quartz (see Table I). Likewise, the coupling factor and piezoelectric charge constant of PZT are considerably higher than those of quartz, and hence volume-for-volume, its performance as a transducer is far superior to that of quartz, allowing expensive amplifiers to be dispensed with.

On the other hand, quartz has a Q factor several times higher than that of PZT.

	Symbol	Unit	Quartz	PZT5A (Navyll)	PZT4(Navyli)
Dielectric Constant	$\epsilon_{33}^T/\epsilon_0$		4.5	1800	1300
Coupling Factor	k_{33}		0.09	0.66	0.60
Charge Constant	D_{33}	10-12C/N	2.0	460	300
Voltage Constant	G_{33}	10-3 Vm/N	-50	28	25
Quality Factor	Q		10^4-10^6	80	600

For significance of indices see section 2.6

These differences in material properties naturally lead to PZT and quartz being used in different application areas. Quartz, for example, is ideal for high-Q, high precision mechanical resonators, as used for frequency stabilizers in clocks and watches.

PZT materials, on the other hand, are less popular as resonators, their main application areas being in, for example, actuating systems (stacked elements) in which they operate well below their natural resonances and in which the ability to generate high force or large displacements is more important. In other applications (for example high-performance ultrasonic transducers), high conversion efficiency and design versatility are important, and here PZT is ideal thanks to the ease with which it can be fashioned into almost any shape, and, in contrast to quartz, its ability to be polarized in any desired direction.

2.13 Pyroelectric effects

The polarization in piezoelectric materials is temperature dependent. The oriented structure of the electric dipoles gradually disappears with rising temperature. Within the safe operating temperature range the changes are reversible. When exposed to excessive heat permanent loss of polarization will occur. Changes in the alignment of the dipoles lead to charge displacements and electric fields.

In most applications this phenomenon is an unwanted side-effect which causes measuring errors or even failure of sensitive electronic components like MOSFETS by overvoltage.

In other applications the effect is very useful, for instance in infrared detectors.

Infrared radiation heats up the ceramic, the resulting voltage or charge is a measure for the level of the radiation.

In most cases however it is a nuisance. The interference mainly occurs in very low frequency or quasi-static applications. To suppress it parallel resistors are used to allow the charge to flow away. In sensors this causes an unwanted uplift of the lower cut-off frequency. In this section a qualitative as well as a quantitative overview of the pyroelectric effect will be given.

A measure for the effect are the so-called pyroelectric coefficients dP/dT and dE/dT .

For our PZT range the following values are typical:

$$\frac{dP}{dT} \approx 400 \times 10^{-6} \text{ C}/(\text{m}^2\text{K})$$

$$\frac{dE}{dT} \approx 20 \times 10^3 \text{ V}/(\text{mK})$$

Fig.2.19 and 2.20 show the results of measurements on PZT5A discs.

Room temperature was taken as a reference and temperature cycles were carried out at a rate of 3 K/min. When a specimen is heated to 100 °C for the first time a considerable irreversible change in polarization takes place. After a few cycles the changes become almost purely reversible.

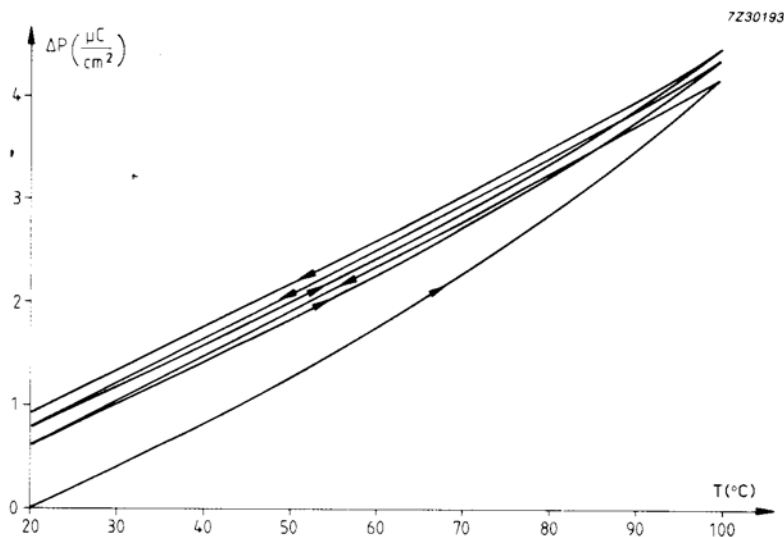


Fig.2.19 The polarization of PZT5A during temperature cycling

From Fig.2.20(a) it is clear that ΔP is almost a linear function of temperature. The curve for ΔE however deviates from being linear because the dielectric constant (E) is also a function of temperature.

The following example clearly demonstrates the importance and danger of the pyroelectric effect:

$$\Delta T = 10\text{K}$$

PZT5A disc of $\varnothing 10 \times 1 \text{ mm}$.

$$\Delta E = 20 \times 10^3 \text{ V/(mK)} \times 10 \text{ K} = 200 \times 10^3 \text{ V/m}$$

$$\Delta V = \Delta E \cdot h = 200 \times 10^3 \text{ V/m} \times 10^{-3} \text{ m} = 200 \text{ V}$$

Clearly this voltage would destroy a MOSFET amplifier stage immediately.

Figure 2.21 shows measured values of $(dP)/(dT)$ as a function of temperature for several PZT material grades. The average of all curves confirms the value of $400 \times 10^{-6} \text{ C/(m}^2\text{K)}$ mentioned before. The liberated pyroelectric charge for a temperature change can be calculated with the formula:

$$Q = \frac{1}{2} \left(\frac{dP}{dT} T_1 + \frac{dP}{dT} T_2 \right) \cdot (T_2 - T_1) \cdot A \quad (2.14)$$

where A is the surface area of the PZT-element.

Given a possible rate of temperature change, the leakage resistor necessary to keep the interference within limits can now be calculated. In critical applications material grades with the highest ratio between piezoelectric (d_{33}) and pyroelectric charge constant (dP/dT) should be used. PZT5A is the best grade in this respect.

Figure 2.22 provides information about the pyroelectric constants of field-strength (dE/dT) for the range of PZT grades. These constants are important to predict their behaviour under open circuit conditions, as is the case in spark generators and often in acceleration sensors.

The generated pyroelectric voltage is given by:

$$U = \frac{dE}{dT} \cdot \Delta T \cdot h \quad (2.15)$$

h - height of PZT-element

In this case a measure for material quality is the ratio between the piezoelectric voltage constant (g_{33}) and the pyroelectric field strength constant (dE/dT).

