

*Measurement
Good Practice Guide*

**Piezoelectric
displacement in
ceramics**

*Mark Stewart, Markys Cain
& Mark Gee*

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Piezoelectric Displacement in Ceramics

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Abstract:

This Good Practice Guide is intended to aid a user to perform displacement measurements on piezoelectric ceramic materials such as PZT (lead zirconium titanate) in either monolithic or multilayer form. The various measurement issues that the user must consider are addressed, and good measurement practise is described for the four most suitable methods.

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Piezoelectric Displacement in Ceramics

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1. Scope

These guidelines are intended to enable a user to perform displacement measurements on piezoelectric ceramic materials such as PZT (Lead Zirconium Titanate) in either monolithic or multilayer form. As a general rule of thumb these types of material will generate approximately 1 μm of displacement for a voltage of 1000 volts across a 1 mm thick sample, and these guidelines are intended to cover this regime of displacement. The guidelines are intended to cover a quasi static range, that is around 1kHz and below, which implies the device is operating off resonance. Although much in these guidelines is pertinent at frequencies above this range, there are extra considerations which are not dealt with here.

2. Theoretical description

Due to their inherent non centro-symmetric crystalline structure, piezoelectric crystals possess the ability to become electrically polarised following mechanical pressure, with each surface becoming oppositely charged. Quartz and Rochelle salt are two early examples. The charge generated is proportional to the pressure exerted. This is called the direct piezoelectric effect. The converse (or indirect) analogue is when the crystal expands (or contracts) along one axis when subjected to an external electrical field. It is generally thought that the two effects are synonymous - vis. the direct and converse effect are determined by the same physics and described by the same materials parameters. When piezoelectric materials are utilised as actuators or any positioning device, the converse piezoelectric effect is used to describe the materials effectiveness in positional motion. The mechanical strain, S_j , in response to an applied electric field, E_i , is described by the tensor equation:

$$S_j = d_{ij} E_i$$

The d_{ij} is known as either the piezoelectric charge coefficient or (as in this case) the piezoelectric strain coefficient and has units V/m (or C/N). For any arbitrary stress system then a large number of tensor related piezoelectric coefficients may need to be considered. However, it can be readily shown that when simple geometrical shapes are used and when the electrical field vector is suitably chosen then this reduces to a much smaller set of tensor values that need be considered. Additionally, since piezoelectric ceramics have fairly simple uniaxial symmetry, the d_{ij} tensor reduces to only 3 non-zero coefficients: d_{33} , d_{31} and d_{15} (since $d_{31}=d_{32}$, $d_{15}=d_{24}$).

The measurement of this mechanical strain, following the application of an arbitrary electric field, is the subject of this Good Practice Guide. Various factors need to be accounted for when deciding which tensor property is the one measured in your experimental set-up. The methods which will now be described can be used to measure potentially any of the coefficients. It is only important to understand the changes in geometry needed to adequately

separate the effects of one piezoelectric strain from combining with another which would otherwise cloud the issue. These details are discussed later and it is certainly worth obtaining copies of the standards, cited following the references section in this guide.

3. Factors influencing measurement

3.1 Sample dimensions

Although the measurement of piezoelectric displacement can be carried out on almost any sample shape or dimension *it is recommended that discs or cylinders are used*, as this will minimise clamping effects at the corners. The length to diameter ratio is a trade off between the advantages and disadvantages of either extreme. For long cylindrical shapes there will obviously be a larger, more easily measured, displacement for a given field, however it may sometimes be difficult to generate the required voltages. For disc type dimensions it is easier to generate high fields. However, for very thin samples bending, caused by the clamping mechanism adopted, may introduce problems. Also considering the porosity content and fragility of thin samples *it is recommended that monolithic samples not less than 0.5 mm are used*. In the DTI-supported 'Characterisation of Advanced Materials (CAM)7' project successful measurements have been carried out on a number of 10 mm diameter discs, ranging from 0.5mm to 10mm thick. Whilst no measurements of greater aspect ratio than 1:1 have been carried out, they should be possible provided that care is taken over sample alignment.

Sample thickness measurements should be taken as the average of four measurements one at the centre and three around the outside. This is particularly important if measurements of displacement are later averaged over the samples' surface - such as when using interferometric techniques. If point displacement techniques are used then it is the thickness at the point at which displacement is measured that is important. Generally, measurement of thickness is only important when we wish to cite the electric field applied to the sample. However, when subjecting piezoelectric ceramics to high electric fields it is important to realise that many of the material properties no longer can be idealised as being simply linear with field. The non-linear nature of ferroelectric materials is well documented and beyond the scope of this guide.

3.2 Sample holding methods

The requirements for a sample holder for these types of measurement are that they provide suitable electrical contact to the sample, and apply minimal mechanical constraints to the sample. In the most common case where the measurement is with respect to a reference plane, it must be able to secure one face of the sample to this reference plane, again with minimal constraints.

Several methods of sample fixing have been used including, mechanical fixing, high viscosity grease, double sided adhesive tape, and vacuum chucking.

Mechanical fixing by means of springs or otherwise can give rise to unwanted mechanical resonances and so is not recommended without performing a frequency sweep to determine the position and extent of these resonances. Adhesive tape and vacuum grease provide a reasonable sample fixing method, although care must be taken with the grease method to apply the minimum thickness of grease possible to hold the sample. A disadvantage of both these methods is that they introduce an insulating barrier which must be bypassed by the electrical connections, usually by soldering a wire to the sample surface.

A more controlled method is to hold the sample down to the high voltage electrode by a vacuum provided by a small peristaltic pump. Figure 1 shows a schematic of a typical vacuum based sample holder. The sample is held onto the high voltage electrode by atmospheric pressure and the ground electrode can be made by either a spring loaded contact or soldering a wire contact. The only disadvantage of the vacuum holding method is that the sample must be reasonably flat, which is usually the case for commercial lapped discs, and the holder may need to be adapted for different shaped samples. There is also a possibility that the peristaltic

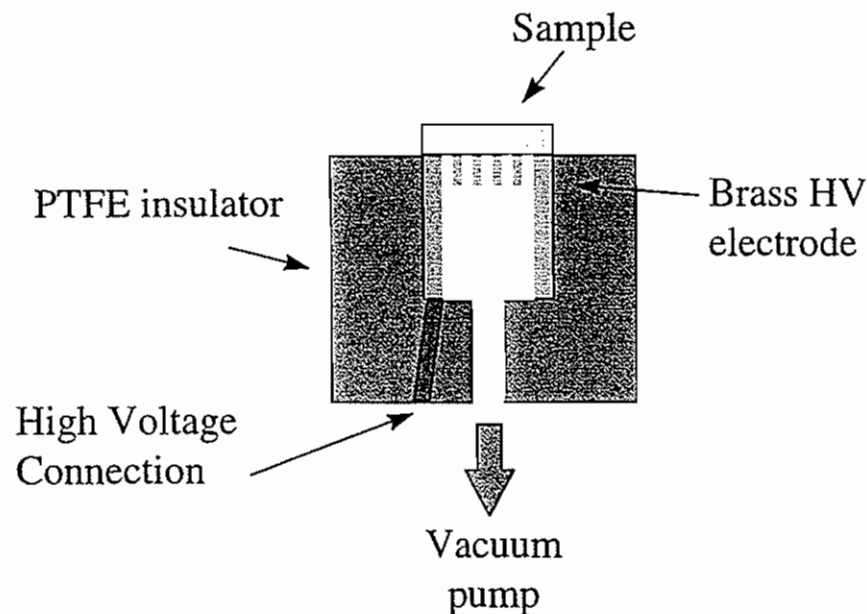


Figure 1 Vacuum holder for sample location

pump may introduce fluctuations in the holding pressure, but since these are much lower than the general laboratory vibrations, should not give rise to any concerns.

3.3 Poled samples

Most commercial PZT samples will have been poled, and the +ve direction marked with either a dot or a cross. When taking measurements, it does not really matter how the sample is oriented, although it is good practice to decide on its direction and maintain this for all

experiments. It is important to relate the sign of the polarisation with the sign of the applied voltage in order to correctly determine the sign of the d coefficient. There are some advantages in having the +ve poled direction on the face furthest from the high voltage electrode. Firstly the top face and therefore the manufacturer's marking can be seen when the sample was placed in the holder. Secondly since the displacement measurement device measures the gap between sample and sensor, a +ve voltage on the electrode causes the sample to contract, and the gap to expand. This means the applied voltage and displacement sensor signal are in phase.

3.4 Recommended driving levels

In order to produce repeatable measurements it is desirable that the measurement process itself does not change the sample. A simple method to detect any changes in the sample brought about by the application of a high voltage is to measure the capacitance and loss, normally at 1 kHz, before and after the experiment. The percentage change depends on the type of material, but in general there will be a small *increase* in capacitance after the application of a high field which depends on the aged condition of the sample, and for conditions which cause depoling, such as high fields or temperatures, a much larger *decrease* in the sample capacitance will be detected.

There are two main causes of sample 'degradation' brought about by high field measurements. Firstly high enough quasi static fields can cause depoling, and secondly sample self heating due to dielectric losses in the material. In practice for typical PZT materials there will be little change in the sample if the peak to peak voltage is kept to below approximately 1 kV/mm. This, of course, would be halved for using unipolar voltages, and for hard materials this value could be doubled to 2 kV/mm. For the soft materials the dielectric losses will cause significant sample heating at frequencies of 1 kHz and above.

Figure 2 gives an indication of the changes in a soft material after the application of a high field on a well aged sample. After the first measurement the low field value has increased slightly and subsequent measurements are very repeatable, indicating that the initial measurement has brought about some sort of deaging.

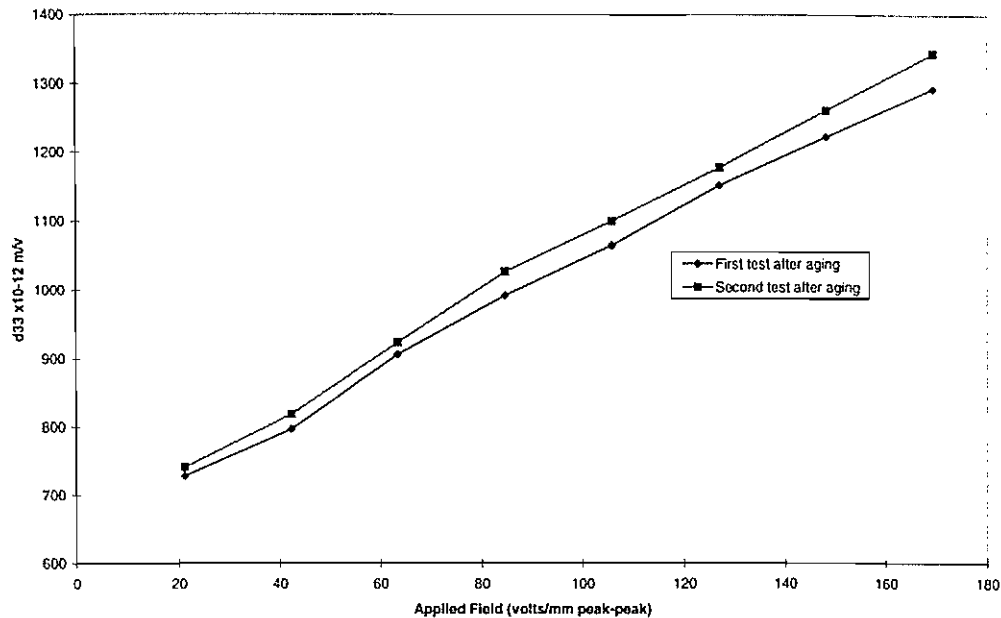


Figure 2 Changes in aged soft material after application of high fields

3.5 Frequency

The guidelines are intended to cover quasi static behaviour and as such cover frequencies below 1 kHz. At higher frequencies the sample holding issues become more critical as it is difficult to maintain the stability of the reference plane, and also the bandwidth of the displacement measurement systems becomes more critical. The measurement of piezoelectric displacements at frequencies higher than 1 kHz will be covered in a future Good Practice Guide.

3.6 Temperature and humidity

It is always good practice to measure temperature and humidity in piezoceramic testing since some of the properties are known to be affected by variations in these parameters. However, in practice, changes in humidity have little effect on the *piezoelectric* properties but mainly affects the *breakdown strength* of the surrounding air. The change in ambient laboratory air temperature has *less* effect on the measured values of piezoelectric activity than that caused by *sample self heating*, often occurring when the materials are 'driven' hard. Measurement of the sample surface temperature is thus desirable, but the attachment of thermocouples is often incompatible with the high voltage associated with these tests.

3.7 High voltage amplifier requirements

In order to generate enough displacement to measure with most of the available measurement devices, a voltage of the order of hundreds of volts, or even kilovolts needs to be applied to the sample. Typical gains for amplifiers used for these types of experiment are 100, and 1000 times, and are usually controlled by a function generator capable of only 10 volt outputs.

Depending on the capacitance of the device and the required frequency, the maximum current output of the amplifier can quickly become limiting. The gain of the amplifiers is often fixed, but when the sample begins to draw too much current the gain is reduced. Normally this is not a problem, as the actual voltage is measured by means of a resistor divider network incorporated in the amplifier, which is fixed at the amplifier gain setting. However clipping of the amplifier as the device pulls too much current introduces unwanted harmonics, and is sometimes difficult to detect. A divide by 10 or 100 oscilloscope probe can be used to double check the voltage at the sample. This can also highlight poor connections to the sample. This is important since with high voltages any small air gap can quickly break down.

The operating frequency is usually much lower than the bandwidth of the amplifier, the limiting factor is usually the current limit, consequently there is a possibility of introducing high frequency noise from driving the saturated amplifier. In acoustic emission experiments on piezoelectrics this noise can be a problem as the high bandwidth detector can pass these frequencies on to the measurement system. This high frequency component is removed by adding a resistor in series with the sample (capacitor) [5], with a value chosen such that the time constant is much longer than the driving frequency. However, since the frequency response of the commonly used displacement measurement devices is much lower than acoustic emission detectors, the mechanical noise generated by the amplifier is less of a problem than the much lower frequency environmental mechanical vibration.

A list of suitable amplifier manufacturers is given in the appendix to this guide.

3.8 Sample breakdown/flashover

When dealing with thick monolithic materials it is often necessary to apply several kilovolts to obtain even modest applied fields. Sample breakdown is always a possibility, but this is unlikely since most PZT materials (depending on material porosity) will have a breakdown strength in excess of 5 kV/mm and driving the materials at these levels will produce very hysteretic displacement behaviour. A more likely scenario is flashover due to air breakdown around the sample. Depending on the humidity level, air breakdown can occur at fields of around 2 kV/mm which could easily damage sensitive measuring equipment if flashover were to occur.

It is important to keep this in mind when designing the sample holding arrangement so that there are no gaps between the high voltage and ground small enough to cause air breakdown. Sometimes, even with careful design, it is easy to overlook things such as poorly defined electrodes on ceramic samples.

3.9 Safety

Potential equipment and personal safety hazards can be caused by applying a much higher voltage than intended. This can easily can occur when adding *1000 volt amplification to

systems designed for low voltage operation. Potential pitfalls are incorrect sequencing of switching equipment causing momentary application of high voltages, or breakage in the feedback system of the high voltage generation. To avoid these instances it is good practice to run the test sequence without the high voltage amplification in place and to monitor the signal to the high voltage generator with an oscilloscope set to trigger just above the maximum applied field. This will highlight any untoward applied voltages.

It is recommended, and depending on the local regulations maybe a legal requirement, that some form of safety interlock is incorporated into the measurement system that prevents any possible handling of the high voltage components whilst the high voltage is applied.

3.10 Strain measurement under stress/load

Since piezoelectric actuators will typically have to do some work in moving a load it is useful to know the displacement capability of an actuator under varying loads. The load required to nullify the piezoelectric displacement is termed the blocking force and is usually determined by measuring the maximum displacement under free conditions and then multiplying by the stiffness of the device. The displacement output of a device is assumed to be linear from the maximum at zero stress down to zero at the blocking force (Figure 3). The stiffness of the device is usually determined by a resonance method, rather than a static measurement of stress-strain characteristics.

It would be useful to measure the actual displacement performance under load, however because of the small displacements this is difficult to achieve. The difficulty lies in the application of load to a small device, and evenly distributing that load across the device.

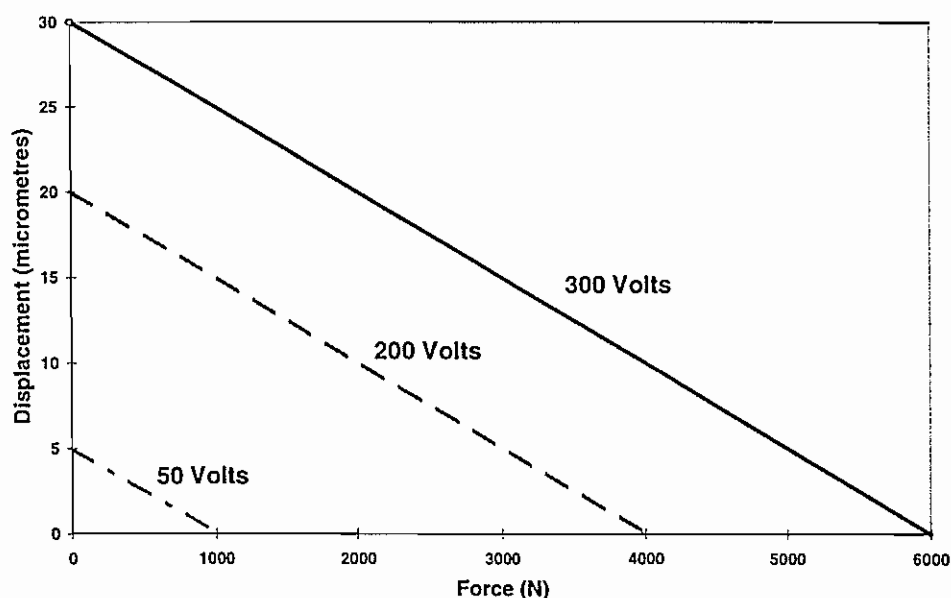


Figure 3 Ideal linear behaviour of a piezoelectric device. These are derived without making the intermediate measurements.

Consider the measurement of a thin disc under a static load. If this load is applied over only half of the area because of misalignment, then the stress under that area will be doubled. If the piezoelectric displacement is measured at some point remote from the ceramic, which is usually the case since the loading mechanism will be covering the ceramic, then it is possible that the stressed area will not move because of the blocking stress, and the unstressed area will expand into the gap. The net result is that there is no displacement registered on the measurement device and a much lower blocking force is determined. An illustration of this problem is shown in Figure 4.

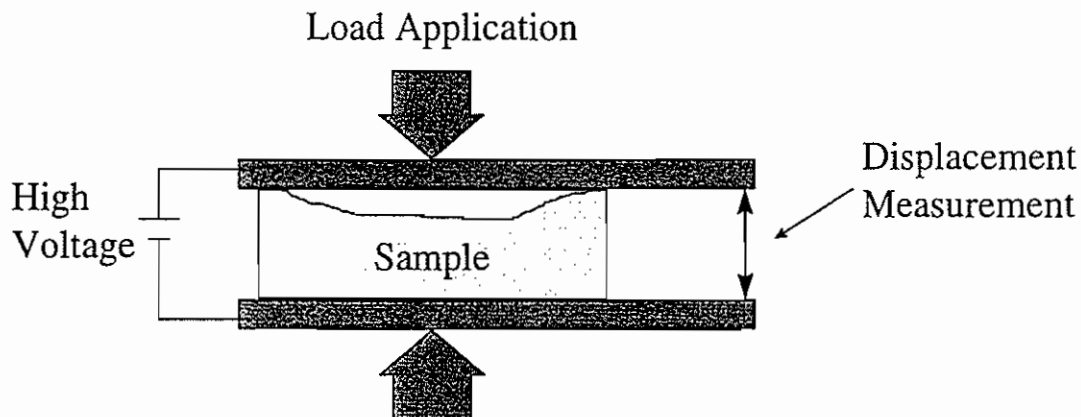


Figure 4 Illustration of possible errors due to measuring displacement under load. (Sample roughness has been exaggerated for clarity).

To overcome this it is recommended that these experiments are carried out with long cylindrical samples and that the displacement measurement is carried out by strain gauges. This has several advantages: the stress distribution in longer samples is more uniaxial, the strain is the actual strain in the sample, and it enables constant monitoring of the strain before, during and after the loading. Potential disadvantages are: the necessity of long samples to accommodate relatively large strain gauges; and the lack of an easy method of calibrating the strain gauge measuring system.

3.11 Determining d_{33}

The piezoelectric charge constant d_{33} can be measured by either the direct method where the charge developed for a given stress is measured, sometimes called the Berlincourt method, or as in this case the indirect method. Here the d_{33} is defined as:

$$d_{33} = \text{resultant strain} / \text{Applied Field (m/V)}$$

For PZT type materials it is usual to describe the d_{33} in units of pico-m/V for convenience. Strictly speaking the d_{33} should be determined under conditions where the stresses within the plane perpendicular to the poling and applied field are negligible. This implies that samples with a cylindrical aspect ratio rather than discs should be used, because of the greater

uniaxiality. In practice the clamping effect of surrounding material is more of a problem in the direct method than in the indirect.

The amplitude of the strain and field waveform can be expressed as either rms. or peak to peak, and for most cases the d_{33} determined by either method should be the same. However if there is significant non linearity then the values determined by the two methods can start to differ. As users are often interested in the maximum displacement that can be generated *it is considered good practice to describe the values in terms of peak to peak*. This also holds for the applied field which should also be expressed as a peak to peak value.

3.12 Multilayers

So far the guide has dealt with measurements on monolithic piezoelectric samples, and with only minor exceptions all the recommendations hold for multilayer samples. The voltages required for displacement are much lower, but the higher capacitance of the device requires a larger current output from the high voltage amplifier. Additionally, it is easier to set-up displacement measurement sensors around multilayer actuators because of their inherent lower operating voltages, and also because they normally have insulating pieces affixed to the top and bottom of the multilayer device.

The most important difference with multilayers is that it is very difficult to determine a d_{33} value since this depends on knowing the exact internal structure and dimensions of the multilayer. This may be proprietary and even if given by the manufacturer these measurements are done on a sampling basis and cannot be guaranteed for every sample. Therefore *it is recommended that the output is reported in terms of strain for a given voltage, rather than a d_{33} value*.

This also has an impact on the measurement verification methods, as it is possible to get large variation in multilayer output through manufacturing defects such as delaminations, electrodes open or short circuiting etc. Some of these defects can be highlighted by capacitance measurements and resonance analysis of the frequency sweeps.

3.13 Improving signal-to-noise ratio

For most displacement measurement systems the piezoelectric strain levels will be such that the measurement system will be operating at or near its resolution limit. This added with general laboratory mechanical vibrations means there is considerable noise superimposed on the strain output. The individual outputs can be filtered, although this can cause errors if the filter frequency is not coupled with the signal generation frequency. It is preferable to use either a lock-in amplifier, or gain-phase analyser to generate the driving voltage/frequency, and to determine the amplitude at the driving frequency. These systems can also give

information on the relative phase of the voltage and strain signal, which corresponds to the mechanical loss.

There are two points to bear in mind when using these signal-to-noise reduction methods. Firstly the software/electronics in these systems will assume linear behaviour, and determine results based on rms. values. *This noise reduction method is not recommended when significant non linearity occurs, such as soft materials at high drive levels.* This can be checked by simultaneously viewing the outputs on an oscilloscope. Secondly the gain-phase analyser will apply many cycles to perform the noise reduction, which could lead to problems such as sample heating and ageing.

4. Displacement measurement methods

4.1 Fibre optic probe

The fibre optic probe consists of a bundle of fibres (Figure 5) where one end of the bundle sees and illuminates the target. The other end of the bundle is split in two such that one half goes to a light source for the illumination, and the other half goes to a photodetector to measure the reflected light intensity [1,2].

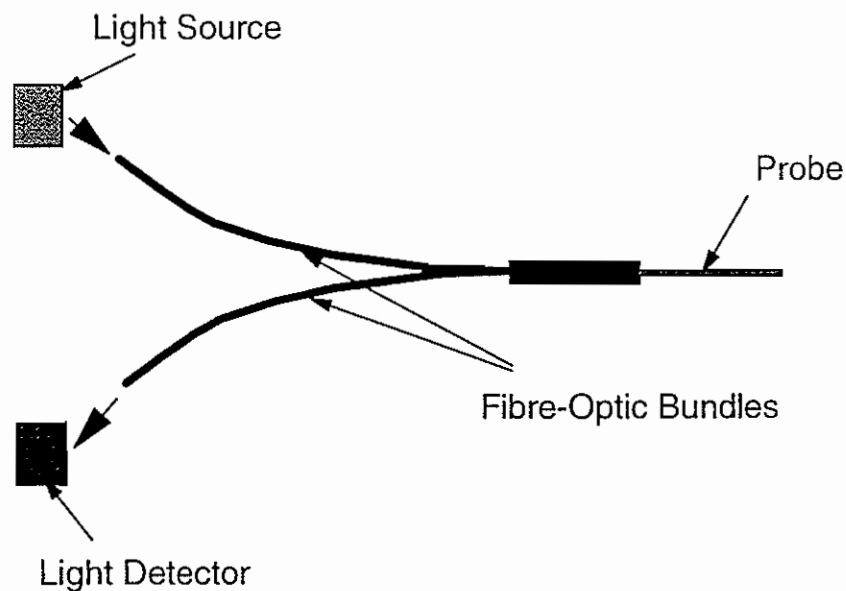


Figure 5 Fibre optic displacement measurement probe.

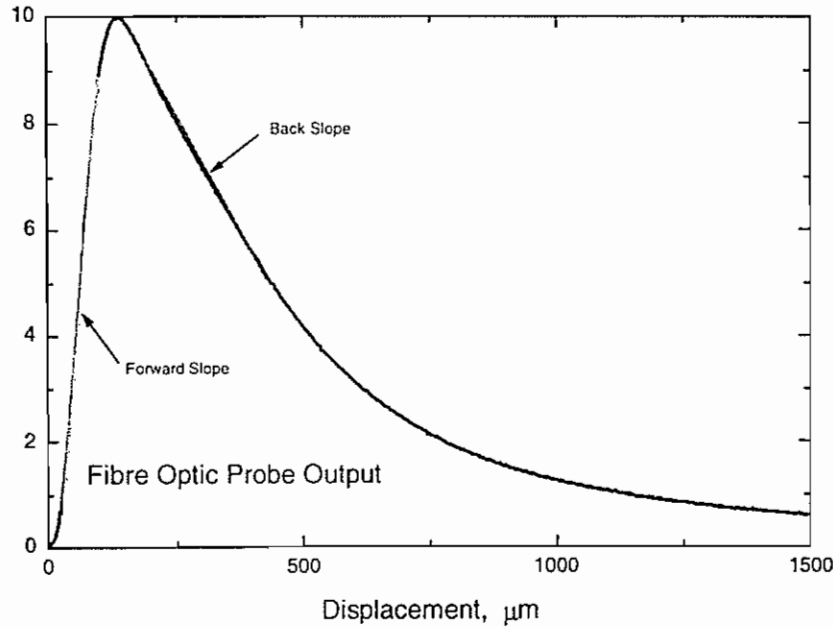


Figure 6 Characteristic curve of a typical fibre optic probe

The displacement of the target from the end of the fibre optic probe is measured by monitoring the amount of light returned. The characteristic curve (Figure 6) shows an initial region of increasing light intensity with displacement which peaks and then asymptotically decreases to zero as the displacement increases further. The lower displacement region of the characteristic curve is termed the front slope region, and the higher displacement region of the characteristic curve the back slope region. Both regions are close to linear over restricted but useful ranges of displacement, and can be used for displacement measurement. For piezoelectric materials the forward measurement region is normally used, as this has the necessary high sensitivity for measurement.

The fibre optic probe is sensitive to the reflectivity of the target and the system needs to be calibrated for each target by moving the target to find the optical peak and adjusting the output to some predetermined level, usually the maximum output. For experiments on piezoceramics the electrode can be polished to improve reflectivity of the target, although in practice it is simpler to attach a small mirror with double sided adhesive tape. The probe is also sensitive to tilt of the target, and it is important that the target surface does not tilt during operation [3].

The major advantages of using fibre optic probes for piezoelectric displacement measurement are its simplicity, the fact that it is non contact, and the high bandwidth. The bandwidth can go into the 100 kHz range and speed is limited by the amplification electronics. However as a consequence of the fast acquisition the signal to noise decreases, and so the signal must be filtered or larger samples must be used.

The major functional capabilities and limitations of fibre optic probes are given in Table 1.

Attribute	Comment
Resolution	at best around 1 nm
Traceability	By comparison to other traceable calibrated device
Lateral resolution	200 µm but depends on sensor
Frequency range	Up to 200 kHz
Ease of use	Easy
Mounting	Easy
Cost	Moderate
Other points	Somewhat noisy, limiting effective resolution and usefulness

Table 1: Limitations and attributes of fibre optic probe

4.2 Capacitance probe

The principle of the capacitance displacement probe is very simple [4]. Two metal plates are mounted on either side of the gap whose separation is to be measured. The plates act as a capacitor whose capacitance is inversely proportional to the gap between the plates according to the normal relationship

$$C = \frac{\epsilon_r \epsilon_0}{d} A$$

To reduce errors from edge effects, the probe plates are normally fitted with guard rings to eliminate errors from edge effects.

If a constant alternating current is passed through the capacitance probe, then since

$$V = \frac{I}{j\omega C}$$

then the amplitude of the voltage generated is proportional to the gap distance as

$$V = \frac{dI}{j\omega \epsilon_r \epsilon_0 A}$$

In commercial devices the capacitance gauge can be realised by either making two isolated sensors, one which is attached to the piezoceramic, or having one sensor with the sample being the ground electrode. The former is usually the more accurate as it improves the signal to noise ratio, but it does have the disadvantage that a sensor needs to be attached to the sample. The latter method is non contact as one face of the ceramic can be used as the ground electrode.

Capacitance probes have excellent resolution particularly for small gaps. They offer a cost effective solution, but the bandwidth can be limited because of the excitation signal needed to measure the capacitance. Also the small stand off which is used to measure the displacement can in failure conditions cause flashover damaging the sensitive electronics of the capacitance gauge.

Attribute	Comment
Resolution	< 1 nm
Traceability	By comparison to other traceable and calibrated device
Lateral resolution	Few mm → few cm
Frequency range	Up to about 5 kHz
Ease of use	Easy
Mounting	Some care required
Cost	Moderate cost
Other points	Averaging measurement, mounting needs some care

Table 2: Limitations and attributes of capacitance probe

4.3 Laser interferometry

There are many variants of laser interferometric measurement systems but most are based on the Michelson interferometer. The displacement is measured by splitting a monochromatic light source, usually a helium neon laser, where a reference beam follows a fixed path, and the measuring beam goes to the sample and returns to join the reference beam. The interference fringes created are used to determine the displacement. Usually the output from the interferometer is in the form of two signals, a sine and cosine, which describe a circle as the sample is moved, and this corresponds to some integer multiple of the laser wavelength. For small movements it is sufficient to use analogue to digital conversion to determine the displacement. However, for fast movements over greater distances it is necessary to use counting techniques to determine the number of revolutions as well as each part of the circle. For greater velocities still laser doppler vibrometers can be used, but the frequencies these are usually used for are outside the scope of this guide.

Laser interferometers probably have the highest resolution of the four measurement techniques, and almost infinite range. However they tend to be expensive and very difficult to set up. For piezoelectric ceramics it will be necessary to attach a mirror to the sample which can sometimes cause problems at higher frequencies. The small lateral size and high resolution of the measurement system will be able to detect any movement in the mirror if it is not firmly attached to the ceramic, and if it is very firmly attached will detect the movement caused by the d_{31} motion.

Most Michelson interferometers are sensitive to mechanical vibrations and air movements between the measurement head and the sample. One way to overcome this is to use a common path set-up, such as a Jamin interferometer, where the reference beam closely follows the sample beam. This means any noise or air movement is also experienced by the reference beam and the noise is cancelled out.

Rather than measure the movement of just one face of the piezoceramic, a differential set-up can be devised whereby the interferometer interrogates the sample with two beams, one on either face, thus measuring the change in thickness. Although this is obviously preferable, in practice these systems are even more expensive and difficult to set up.

Attribute	Comment
Resolution	< 1 nm
Traceability	By calibration of laser wavelength
Lateral resolution	tens of microns
Frequency range	Dependant on measurement electronics up to several MHz
Ease of use	Difficult
Mounting	Difficult
Cost	Expensive
Other points	Very high frequency vibrations can be measured with laser doppler technique.

Table 3: Limitations and attributes of laser interferometry

4.4 Strain gauges

Strain gauges use the change in resistance of fine wires as they are strained to determine the strain in the material to which they are bonded. The change in resistance is very small, and to

form a useable measurement system the change in resistance of the gauge is measured using a Wheatstone bridge. As the change in resistance is also sensitive to temperature often all four arms of the bridge are made with strain gauges, where three gauges perform the temperature compensation, and only one gauge sees the strain.

Strain gauges are mostly used in static applications, but with suitable amplification they can be used in more dynamic situations into the kHz region. The large size of even the smallest strain gauges makes it difficult to measure strain in samples less than 5 mm thick, which for piezoceramic samples can be a problem, and tend to make them more useful for measuring strain in the d_{31} mode. Sample preparation for strain gauges can also be difficult, and incorrect placement can lead to considerable errors.

Attribute	Comment
Resolution	at best around 0.05 microstrain
Traceability	Difficult, using manufacturers gauge factor
Lateral resolution	Several mm
Frequency range	Usually less than 100 Hz, but can be improved with specialised electronics
Ease of use	Easy
Mounting	Easy
Cost	Cheap
Other points	Care must be taken with gauge installation, measures strain so insensitive to vibrations, need sample surface at least 5 mm ²

Table 4: Limitations and attributes of strain gauges

5. General reporting requirements

The measured values of many of the properties of piezoelectric materials are also a function of the samples history. That is, previous loading and stressing environments (fatigue), temperature (depoling) and time (ageing). Thus, it is recommended that when reporting any values, be they d_{33} or other piezoelectric property, the samples *history* must also be recorded.

In summary, the following table gives a minimum requirement for reporting the results of a d_{33} measurement, for example.

Test Details

Sample Details			
Sample History			
Sample dimensions		Poling Date	
thickness (mm)		Date Tested	
diameter (mm)		Temperature (°C)	
Frequency (Hz)		Relative Humidity (%)	
Applied Field (p-p) (V/m)		d_{33} p-p (m/V) $\times 10^{-12}$	

6. Calibration issues

Of the four methods discussed laser interferometry offers the simplest and most rigorous path to traceable calibration. The sine and cosine output from the interferometer gives rise to a circle and the displacement is simply an integer multiple of the wavelength of the laser illumination and the arc of the circle. Of course for traceability the wavelength of the laser radiation must be independently calibrated. For fibre optic probes and capacitance gauges the situation is more complex and the user must rely on the manufacturer's calibration, which is usually determined by comparison with a laser interferometer system. Additionally both these methods can be affected by angular misalignment of the sample to the probe.

The calibration of the strain gauge is the most difficult of the four methods to perform traceable measurements. Usually calibration is provided by the manufacturer in the form of a gauge factor, which is the average calibration of a sample of gauges of a similar batch. There are many reasons why the calibration can be different from the manufacturer's quoted gauge factor, such as temperature, gauge alignment, and the stress state of the sample. Individual gauges can always be calibrated *in situ* by comparison with a traceable method, however if this can be done it makes using the strain gauge redundant.

7. Verification of measurement system

So far the calibration of the voltage and displacement measurements as independent parameters have been discussed. However, it is still easy to introduce measurement inaccuracies which might go undetected. The following section discusses a number of methods by which the system as a whole could be checked out.

In order to check out the complete measurement system it would be useful to have some sort of reference material/artefact that could be guaranteed to give the specified displacement for a given voltage. A material such as quartz would have the necessary stability and robustness under high voltages, but since the d_{33} is almost 100 times smaller than most PZT materials it is impractical. The use of PZT as a reference material is hindered by their time and

temperature dependence and susceptibility to change under high fields. However, work is underway to determine the boundaries under which they might be used as reference materials. Other candidates, under consideration for standard reference materials, include a hard PC8 PZT ceramic and lithium niobate ceramic.

A more pragmatic method of verification is to compare the d_{33} value obtained by the indirect method to values obtained with the Berlincourt or resonance method. If the indirect value is lower then it is likely there is something wrong with the method. If the value is more than twice the Berlincourt value then, unless the material is very soft and being driven at high fields, it would be wise to examine the measurement system. For d_{33} values that fall between these boundaries it is useful to measure the d_{33} as a function of applied field. For most PZT materials there is a reasonably linear increase in d_{33} with applied field until saturation is reached. For soft materials this increase could be of the order of a two fold increase, whereas for hard materials this is more likely to be around 10-20%. A decrease in output with increasing field or any massively non linear behaviour is likely to be caused by measurement error.

Since the piezoelectric strain is brought about by dipole movement, changes in piezoelectric strain should be matched by changes in dielectric displacement. So if the polarisation of the sample is measured simultaneously with the mechanical displacement, there should be a one-to-one correspondence between the change in permittivity and d_{33} .

Another cross check on the measurement system is to measure the frequency responses of a hard and a soft material and compare. The soft material will usually show a linear increase in d_{33} with decreasing frequency going from around 1 kHz, whereas by comparison the hard material response will be much flatter.

8. Suppliers of equipment

This list is intended to give a novice possible sources of instrumentation for performing the tests described in this guide, and is not intended to be exhaustive. The inclusion of a manufacturer does not imply recommendation by NPL, neither does the exclusion imply a product is unsuitable.

8.1 High voltage amplifiers

Trek, Inc.

3932 Salt Works Road.

PO Box 728

3932 Salt Works Road

Medina, New York 14103

USA

Tel: (716) 798-3140

Fax: (716) 798-3106

Web: www.trekinc.com

Piezo Systems, Inc.

186 Massachusetts Avenue, Cambridge, MA USA

Tel: 617-547-1777

Fax: 617-354-2200

Web: www.piezo.com

Sensor Technology

P.O. Box 97, 20 Stewart Rd.,

Collingwood, Ont., Canada

L9Y 3Z4

Tel: (705) 444-1440

Fax: (705) 444-6787

Web: www.sensortech.ca

APEX

UK agents:

ASHWELL ELECTRONICS LTD.

Hertfordshire

Tel: +44 1438 364 194

Fax: +44 1438 313 461

Web: www.ashwell-hq.com

Web: www.apexmicrotech.com

8.2 Capacitance displacement probes

Automatic Systems Laboratories Limited

28 Blundells Road, Bradville, Milton Keynes, MK13 7HF, United Kingdom

Tel: +44 1908 320666

Fax: +44 1908 322564

Web: www.aslltd.co.uk

Queensgate Instruments Ltd

Queensgate House

Willoughby Road

Bracknell

Berkshire

RG12 8FB

Tel: +44 (0) 1344 350000

Fax: +44 (0) 1344 350035

Web: www.queensgate.co.uk

8.3 Strain gauges

Measurements Group UK Ltd

Stroudley Road

Basingstoke

Hants RG24 8FW

United Kingdom

Tel: (0) 1256 462131

Fax: (0) 1256 471441

Web: www.measurementsgroup.com

Techni Measure

Alexandra Buildings, 59 Alcester Road, Studley, Warwickshire B80 7NJ.

Tel: 01527 854103

Fax: 01527 853267

Web: www.techni-measure.co.uk

8.4 Fibre-optic displacement probes

Mechanical Technology Incorporated

968 Albany-Shaker Road

Latham, New York 12110

USA

Tel: 518-785-2464

Fax: 518-785-2806

Web: www.mechtech.com

Philtec Inc.

UK agents:

Scantron Industrial Products Ltd

Monarch Centre Venture Way Taunton Somerset TA2 8DE England

Tel: +44 (0)1823 333343

Fax: +44 (0)1823 333684

Web: www.philtec.com

Web: www.scantron-net.co.uk

8.5 Laser interferometers

Zygo Corporation

Laurel Brook Road

Middlefield, Connecticut

06455-0448, USA

Tel: 860-347-8506

Fax: 860-347-8372

Web: www.zygo.com

Renishaw plc

New Mills

Wotton-under-Edge

Gloucestershire

GL12 8JR

Tel: +44 1453 524524

Fax: +44 1453 524901

Web: www.renishaw.co.uk

9. References

- 1) D A Krohn. Fiber Optic Sensors, (1992).
- 2) P A Slazas. Non-contact optical displacement sensing, *Sensor Review*, 16 (1996) 33-37.
- 3) M Stewart, N J McCormick and M G Gee. Measurement of Strain in Field and Mechanical Degradation Performance of Piezoelectric Ceramics, *Ferroelectrics*, 187 (1996) 11-21.
- 4) T R Hicks and P D Atherton. The Nanopositioning Book, Published by Queensgate Instruments Limited, UK. ISBN 0 9530658 0 4 (1997).
- 5) H. Aburatami and K Uchino, *Jpn. J. Appl. Phys.* Vol. 35 (1996) L516-518.

10. Standards

1. 'IEEE Standard on Piezoelectricity', Std 176-1978.
2. 'IRE Standards on Piezoelectric Crystals, 1961', Proc. IRE, pp. 1162-1169; July 1961.
3. IEC standard publication 483, 1976. 'Guide to dynamic measurements of piezoelectric ceramics with high electromechanical coupling'.
4. European Pre-Normative Standard, 'Piezoelectric properties of ceramic materials and components: part 1 and part 2', CENELEC, BTTF 63-2, Advanced Technical Ceramics working group, 1999.

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