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Ferroelectric Hysteresis Measurement & Analysis

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Summary

It has become increasingly important to characterise the performance of piezoelectric materials under conditions relevant to their application. Piezoelectric materials are being operated at ever increasing stresses, either for high power acoustic generation or high load/stress actuation, for example. Thus, measurements of properties such as, permittivity (capacitance), dielectric loss, and piezoelectric displacement at high driving voltages are required, which can be used either in device design or materials processing to enable the production of an enhanced, more competitive product. Techniques used to measure these properties have been developed during the DTI funded CAM7 programme and this report aims to enable a user to set up one of these facilities, namely a polarisation hysteresis loop measurement system.

The report describes the technique, some example hardware implementations, and the software algorithms used to perform the measurements. A version of the software is included which, although does not allow control of experimental equipment, does include all the analysis features and will allow analysis of data captured independently.

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1. Polarisation-Field (P-E loops) and Strain-Field (S-E) measurements for Piezoelectric Ceramics

1.1 Introduction

Since there is little explicit information on how to perform and interpret P-E loop measurements there has been a tendency to regard the measurement as somewhat academic and difficult. In fact the method is remarkably simple, and there is a lot of valuable information that can be gained from the measurements that can be applied by all users of piezoelectric ceramics.

A P-E loop for a device is a plot of the charge or polarisation[*] (P) developed, against the field applied to that device (E) at a given frequency. The significance of this measurement can be more easily understood by examining the P-E loops for some simple linear devices. The P-E loop for an ideal linear capacitor is a straight line whose gradient is proportional to the

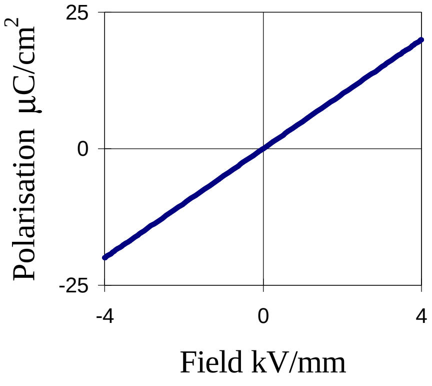

Figure 1a): Ideal linear capacitor response

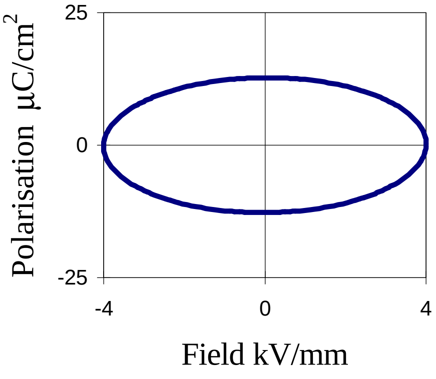

Figure 1b) Ideal resistor response

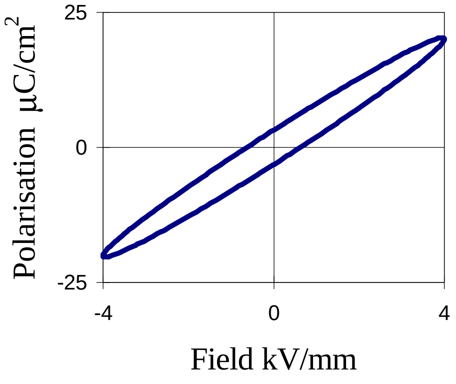

Figure 1c): Lossy capacitor response

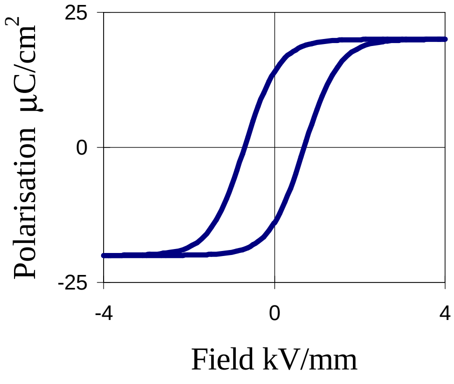

Figure 1d): Non-linear ferroelectric response

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[*] Charge and Polarisation are strictly speaking different but for materials with a high relative permittivity we can assume they are equal.

capacitance (figure 1a). This is because for an ideal capacitor the current leads the voltage by 90 degrees, and therefore the charge (the integral of the current with time) is in phase with the voltage. For an ideal resistor the current and voltage are in phase and so the P-E loop is a circle with the centre at the origin (figure 1b). If these two components are combined in parallel we get the P-E loop in figure 1c which is in effect a lossy capacitor, where the area within the loop is proportional to the loss tangent of the device, and the slope proportional to the capacitance. If we now consider less ideal devices such as non linear ferroelectric materials we would get a P-E loop such as figure 1d.

The nature of piezoelectric materials is that a change in its polarisation state is coupled with a piezoelectric strain, which is the most used functional response of the material. At the time that PE loop measurement systems were *first* developed, the simultaneous measurement of this strain (S) was difficult because of the limited availability of data capture and sensitive strain measurement techniques. More recently, with modern computer based data acquisition and a plethora of highly sensitive displacement measurement devices, the measurement of strain field (S-E) loops is more common, as is simultaneous polarisation-strain-field, (P-S-E).

1.2 Piezoelectric characterisation

So what can the P-E loop tell us about the behaviour of a piezoelectric ceramic or device? The IEEE standard 180 defines several reference points on the curve which enable numeric comparisons of materials. Figure 2 shows some of these; E_c, the Coercive field, P_r remanent polarization, and P_s saturation polarisation. For a better understanding of these terms a more complete description of ferroelectric terminology is needed, see for example [1,2]. These parameters are most likely to be of interest to the material manufacturer and will give them some indication of the poling conditions to use for the ceramic, and a better understanding of the material behaviour.

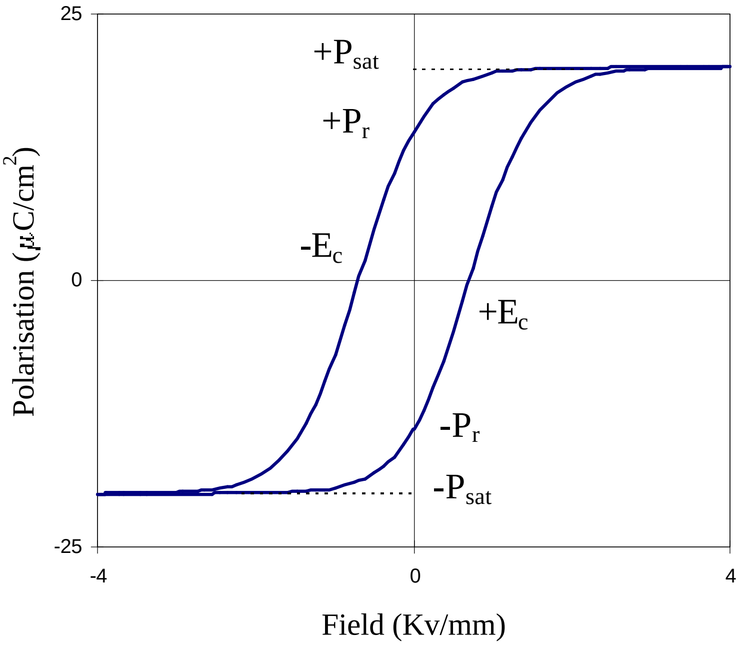


Figure 2. P-E hysteresis loop parameters for a ferroelectric material

For the piezoelectric ceramic user there is much to be learnt from a qualitative look at the PE loop. For example the degree of non linearity of behaviour can be seen. At low fields the P-E loop will resemble that of figure 1c for a lossy capacitor, but the loops will only begin to open out at much higher drive fields as saturation is neared (figure 1d). For achieving a controlled displacement with a piezoelectric actuator it may be better to confine the fields to values where the behaviour is less hysteretic. The polarisation is related to the strain and since small currents are somewhat simpler to measure than small displacements the P-E loop can provide a means of investigating displacement behaviour. Indeed the charge can be used in a feedback loop to drive the piezoelectric with a non linear field to give a linear displacement [3].

The measurement of strain field loops S-E is obviously important for actuation applications. The slope of the S-E loop is the piezoelectric coefficient, d_{33}, one of the most important design parameters for use as actuators. The behaviour of many piezoelectric materials with respect to applied field is highly non linear and this phenomenon can be studied with a S-E measurement system. The S-E loop can also show the amount of hysteresis in the strain output which is important when using the materials for accurate positioning applications. For high levels of hysteresis this might mean having to use a biopolar rather than unipolar drive to return the actuator to the zero position. Measurement of S-E loops also allows investigation of the onset of massive non linearity in the strain with the appearance of the ‘butterfly loop’, figure 3.

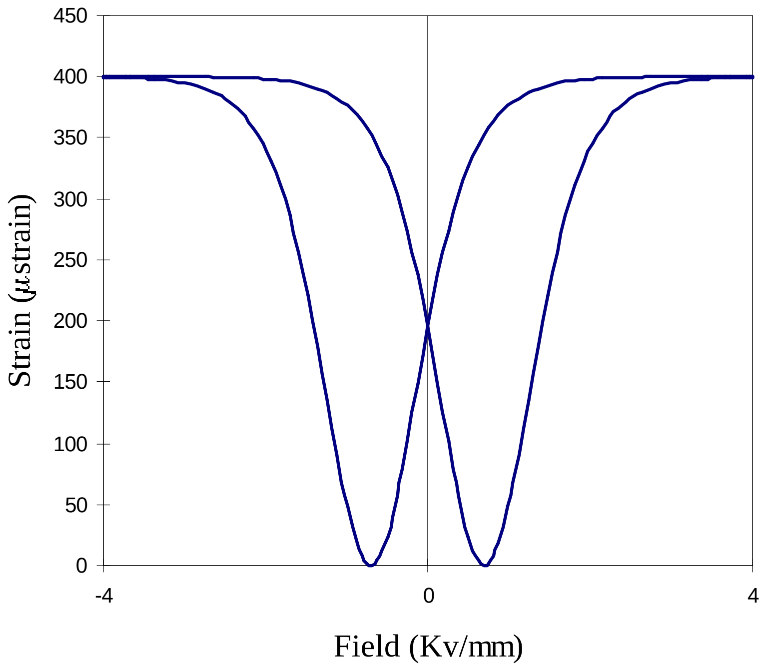


Figure 3 Schematic of a S-E loop exhibiting a butterfly loop. This schematic was simply derived by squaring the Polarisation data from figure 2. (The strain is often, but not always, proportional to the square of the polarisation)

Using a more quantitative approach to the P-E loop it is possible to derive the capacitance and loss of the device at high fields and at different frequencies - information that is needed for tuning the drive electronics and determining the self heating effect of components. Examination of S-E loops also gives the opportunity to quantify the hysteresis in a manner similar to the dielectric loss, giving in effect the mechanical loss.

In some applications, such as thin film ferroelectric memories the hysteresis of the material is put to good use, and measurement of the P-E loop helps define the drive parameters and can be used to investigate the long and short term performance.

There is an implication from definitions of parameters such as P_s, and E_c that in hysteresis measurements the field must always be driven to saturation. However, we have seen that valuable information can be gained from measurements at fields well below this. Conversely, measurements need not stop at saturation, and the field can be increased until breakdown occurs. This gives the opportunity to study breakdown behaviour, and it may even be possible to determine a pre-breakdown characteristic.

The origin of the ‘ferro’ in ferroelectric comes from the similarity in hysteresis loop behaviour between ferroelectric and ferromagnetic materials, and not because they contain iron. Ferromagnetic materials can be classified as either hard or soft, dependent on their hysteresis loop behaviour. This terminology has also transferred to ferroelectric materials, where a soft PZT is characterised by its low coercive field and a squareish hysteresis loop, whereas a hard PZT has a much higher coercive field and is consequently more difficult to pole and de-pole.

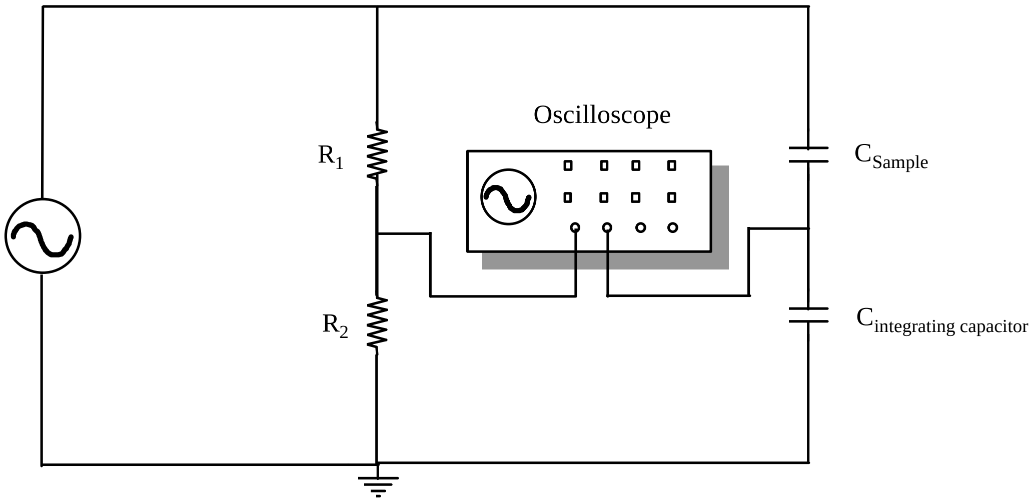


Figure 4 Schematic of a Sawyer Tower circuit for P-E loop measurements

1.3 P-E loop measurement

So far we have discussed the properties and significance of a hysteresis loop, but not how to make the measurements. The measurement methods used have been developed over the years with advances in electronics hardware and software. The most often quoted method of hysteresis loop measurement is based on a paper by Sawyer and Tower [4] which included some seminal measurements on Rochelle salt. A schematic of the experimental setup is shown in figure 4. Here the field applied across the sample is attenuated by a resistive divider, and the current is integrated into charge by virtue of a large capacitor in series with the sample. Both these voltages are then fed into the X and Y axes of an oscilloscope to generate the P-E loop. The applied voltage was usually a sinusoid at mains frequency as this was the simplest method to generate the required voltage and current. Recording these traces using photographs of the oscilloscope screen meant that subsequent numerical analysis was difficult. As a result, several years later, this circuit was modified by Diamant et al [5] to include variable resistive and capacitative components to compensate for sample conductivity and capacitance, leaving only the non linear part. Although the use of this method proliferated the adjustment of the variable components was often subjective and results unreliable.

With the advent of modern integrated circuitry the method of charge measurement has changed from using a large capacitor, to using a virtual ground operational amplifier as a current to voltage converter with an integrating capacitor to convert the current to charge [6] (a more detailed examination of charge measurement methods are given later). Also, around this time, the introduction of microprocessors meant that the acquisition and control was made much simpler, and the compensation was carried out in software rather than hardware [7]. Concurrent advances in solid state high voltage electronics has meant there are commercially available high voltage amplifiers which allow frequencies other than those tied to the mains frequency and also enabled waveforms other than sine waves to be used. Sine waves are most often used since these are easily produced, however a triangle wave drive is more attractive for frequency dependent measurements since dE/dt is constant.

The availability of cheap PC hardware, in particular digital data acquisition, has meant that the measurement of the P-E loops has become simpler and more attention can be paid to the data analysis using software routines. However, there have been a few recent innovative approaches to the measurement of P-E loops that are worth noting. Firstly, Dickens et al [8] used a non standard drive field to isolate the non-linear components. The approach uses bipolar and unipolar fields and relies on the fact that switching only occurs in bipolar fields when the field is reversed. By comparison of the various P-E loops, the resistive, capacitative and non-linear terms can be calculated. A similar method has been used by Dias and Das-Gupta [9] but using hardware rather than software subtraction and addition of the terms. They use three nominally identical samples, one sees the full bipolar field, whereas the other two samples see respectively a positive and negative unipolar field.

The IEEE 180 standard comes the closest to defining a standard procedure for making P-E loops but since it is only a definition of terms it is not very explicit. Most of the current ferroelectric workers describe their measurement setup for P-E loops simply as a modified Sawyer-Tower circuit and rarely detail the compensation methods if any are used.

2. Hardware for P-S-E loop measurements

2.1 Introduction

A system for performing simultaneous P-S-E measurements is shown schematically in figure 5. This modular system has been assembled using commercially available measurement instrumentation so the construction is simply a matter of connecting these units together. Table 1 at the end of this section lists the various component parts used in the system, as well as some similar instruments that could be used.

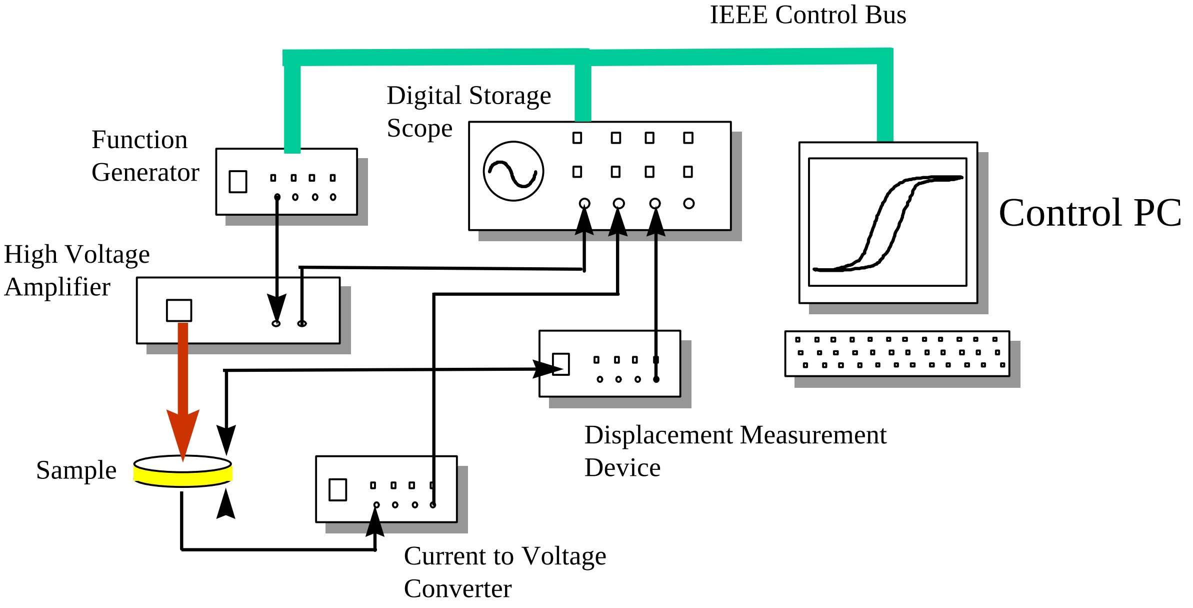


Figure 5. Schematic of building blocks in the NPL P-S-E loop system

The software control and analysis for the system is achieved through a series of LabView routines which is included with this report. Some of the instrumentation control software routines were prototyped at NPL, and David Hall at the University of Manchester has ported a series of analysis routines developed in Turbo Pascal to Labview. The advantage of the Labview based approach is that sub-systems can be easily replaced and if the hardware has a Labview driver the software integration is even simpler.

2.2 Hardware system

The operation of the NPL system is based around IEEE bus controlled instrumentation and capture on a digital storage oscilloscope (DSO). Although the DSO option is more expensive than using a PC based analogue acquisition card it does mean that acquisition can take place independent from the PC and its processor, leaving the PC free for other tasks. The DSO can also be used without computer control, which can be useful in identifying triggering and signal level problems which often arise when setting up an experiment.

For the acquisition of a P-E loop the initial wave shape is formed by the function generator, which is then amplified by the high voltage amplifier, which sends the amplified waveform to the sample. Again the external function generator can be replaced by an internal PC digital to analogue converter to reduce the cost. The computer control of the function generator is mainly for convenience, and for the timed ageing experiments, but it is possible to trigger the PE loops manually.

The current passing through the sample is then converted to a voltage, which is captured on a digital storage oscilloscope, along with the monitor output from the high voltage amplifier, and waveforms from any displacement measuring devices connected. The captured waveforms are then sent to the PC for subsequent analysis.

2.3 Choosing HV amplifiers

The choice of high voltage amplifier must be made based on several factors:

- high voltage specification
- maximum drive frequency that can be maintained at the power amplification stated (thus the transfer characteristics are important)
- maximum current that can be delivered into a resistive and capacitative load
- amplification linearity and distortion
- input and output impedance
- circuitry protection
- cost

The typical operating fields of ceramic piezoelectric materials can extend to 500V/mm and even 1kV/mm for some hard compositions, and so, depending on the sample thickness, voltages in excess of several kV are necessary. For strain measurements in order to generate sufficient displacement that can be measured using most of the commercially 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 experiments 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 of the amplifier can quickly become limiting. The gain of the amplifiers are often fixed. However, 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 the clipping of the amplifier as the device pulls to much current introduces unwanted harmonics, and is sometimes difficult to spot. 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, as with high voltages it is possible to create a small air gap which quickly breaks 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), with a value chosen such that the time constant is much longer than the driving frequency. For strain experiments the mechanical noise generated by the amplifier is less of a problem than the much lower frequency environmental mechanical vibration. Care must be taken to exclude the effect of this additional component in the measurements, i.e. the voltage drop is measured across the sample only.

2.4 Choosing displacement measurement systems for S-E measurements

The displacement generated by the piezoelectric effect on typical sized piezoceramic samples is of the order of micrometres, or perhaps tens of micrometres for large multilayer stacks. Consequently, the displacement measurement method chosen must be capable of measuring these small displacements with the necessary resolution and accuracy. Four methods that have routinely been used for these types of measurements are discussed further; fibre optic probe, capacitance probe, laser interferometry and strain gauges.

2.4.1 Fibre optic probe

The fibre optic probe consists of a bundle of fibres 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.

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 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.

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. A consequence of fast data acquisition is that the signal to noise ratio decreases, and so the signal must be filtered or larger samples must be used.

2.4.2 Capacitance probe

The principle of the capacitance displacement probe is very simple. 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. 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 the amplitude of the voltage generated is proportional to the gap distance.

In commercial devices the capacitance gauge can be realised by either making two isolated sensors, with one 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 to displacement measurement, but the bandwidth is limited due to 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.

2.4.3 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) into two beams. One beam acts as a reference beam following a fixed path, and the second 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. 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 setup, 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 setup 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.

The traceable calibration of a laser interferometer is in essence very simple, all that is needed is a traceable measurement of the laser wavelength. This calibration factor is then included in the measurement software associated with the interferometer.

2.4.4 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 5mm 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.

The calibration of the strain gauge can be difficult in order 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.

2.5 Charge measurement for P-E loop measurements

For a P-E hysteresis loop system the measurement of field is very simple, usually needing no more than a resistive potential divider. The measurement of charge is not very difficult but there are several options that present themselves.

The simplest method is to use a large capacitor in series with the sample as in the conventional Sawyer-Tower circuit. This integrates the current and so the voltage measured across this capacitor is proportional to the charge. The only problem with this method is in choosing the correct value low loss capacitor for the particular conditions of voltage, current and frequency.

Another approach is to use operational amplifiers used as current to voltage converters which have a capacitor in the feedback loop to integrate the current, to get the charge. This

technique is used in many commercial charge amplification systems. The main drawback is that the system is liable to drift if there is a zero offset and some careful design is needed for these systems.
Since the data collection will be carried out by computer and there is bound to be some further data manipulation, a simpler method is to measure the current rather than the charge, and use the *computer* to integrate the current with respect to the time. This means that in the simplest case, the current can be determined by measuring the voltage drop across a resistor placed in series with the sample. This is usually only practical for currents in the mA range and for lower currents some further amplification systems are needed.

For simple self build construction it is easier to use an operational amplifier current to voltage converter and perform the integration to charge at a later stage, usually in software. Figure 6 shows the setup for an op amp current to voltage converter, where the current input goes to the inverting input and the gain of the converter depends on the value of the feedback resistor, such that the current at any instant I is:

$$I = \frac{V_{out}}{R_{st}}$$

(where R_{st} = reference, or 'standard', resistor).

In this configuration, without the integrating capacitor, the zero offset does not present such a problem. This means that a general purpose operational amplifier such as a 741 will prove equal to some of the more expensive high quality op amps. Depending on the gain of the circuit a great deal of noise can be introduced into the output, and although the integration to charge removes some of this, it is often found a capacitor is needed in the feedback loop. This capacitor acts as a filter to remove some of the high frequency noise that is often present, the value of this capacitor depends on the gain resistor. Usually the time constant of this filter $C_{st}R_{st}$ must be adjusted to at least two orders of magnitude smaller than the period of the applied voltage. Too large a value of C_{st} can lead to a spurious phase shift in the current waveform, leading to an apparently lossy P-E loop.

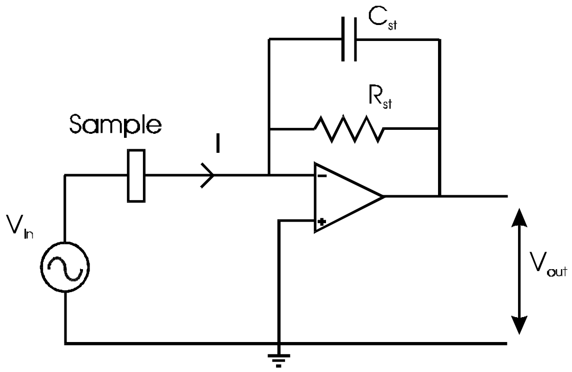


Figure 6 Operational Amplifier Current-to-Voltage Converter

Although this circuit is simple to build there is only one gain setting. It is a simple matter to introduce various gain settings by switching in various resistors. It is also necessary to add switchable filtering capacitors when changing gain or frequency. If it is necessary to control these settings via a PC, in the case of PC acquisition systems, it is probably more cost effective to purchase a purpose built current amplifier which produce a voltage output proportional to the current flowing through them.

One minor drawback with the current to voltage converter approach is that should there be a fault condition such as sample breakdown or flashover, then the converter will receive a high voltage spike which, without protection, will destroy the circuitry. For the case of the self built 741 based amplifier this will simply cost the few pence for the replacement IC. However, for the commercial kit this may involve the cost of external repair and recalibration of the unit. In order to prevent this a protection circuit consisting of two back to back diodes connected between the input and ground, and an optional current limiting resistor can be incorporated (figure 7). The critical characteristics of these diodes are they should be able to withstand the high voltage and that the reverse current leakage should be as small as possible so as not to affect the measured current. Suitable diodes, which have been used successfully are 1N4007 although it is always best to compare P-E curves with and without protection to establish the effect of the additional components.

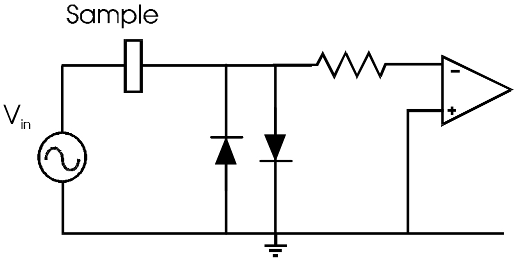


Figure 7 Protection Circuitry for Current-to-Voltage converter

2.6 Summary

The modular approach, using commercial equipment and Labview software means that the system is versatile and can be used with a variety of different building blocks. Proving tests have shown that the system gives very similar results to those obtained using a commercial piezoelectric test system, and with the addition of capacitance and loss measurements at high voltage is in fact more capable. The main drawback in going for this modular approach will be in the safety and electrical noise pollution aspects. This must be investigated by the builder of such a system which is already catered for in a commercial system.

Function	Type	Comments
Function Generator	HP33120A	IEEE control of function generator is not necessary if continuous applied waveform is used.
	Thurlby Thandar TG1304	Can be used manually to trigger loops.
	PC analog output card	For example most National Instrument Boards
Current-to-Voltage Converter	Keithley 428	
	Stanford Research SR570	RS232 controlled only
	Virtual earth 741 op amp	
Displacement measurement system	MTI Fotonic 2000 fibre optic	Any device allowed, with the constraint that it produces a voltage output linearly proportional to displacement
High Voltage Amplifier	TREK	A number of models available for example 609A, 50/750
	Chevin Research HVA1B	Custom built
Data Acquisition	Gould Datasys 840 DSO	Four channel
	Tektronix DSO TDS 420	
	Any PC data acquisition board with LabView driver	For example most National Instrument Boards

Table 1 List of Equipment

Connection 1	**Connection 2**	**Comments**
PC (IEEE)	**Digital Storage Scope (IEEE)**	**This can be replaced by an internal A/D PC card**
PC (IEEE)	**Function Generator (IEEE)**	**Could be replaced by manual function generator**
PC (Serial Port)	**Current to Voltage Converter**	**Not necessary for manual gain change system**
Function Generator (OUT)	**High Voltage Amplifier (signal input)**	
High Voltage Amplifier (HV OUT)	**High voltage side of sample**	**High voltage cable needed**
High Voltage Amplifier (Remote)	**High voltage cut out switch**	**This safety switch only operates the amplifier when the enclosure is closed.**
High Voltage Amplifier (Monitor)	**Channel 1 of DSO or A/D card**	**Measures the applied voltage**
Sample (low voltage side)	**Current to Voltage converter input**	**The low voltage side of the sample should be isolated.**
Current to Voltage Converter (Signal output)	**Channel 2 of DSO or A/D card**	
Displacement Measurement Device (analogue output)	**Channel 3 of DSO or A/D card**	

Table 2 Connections for P-S-E setup

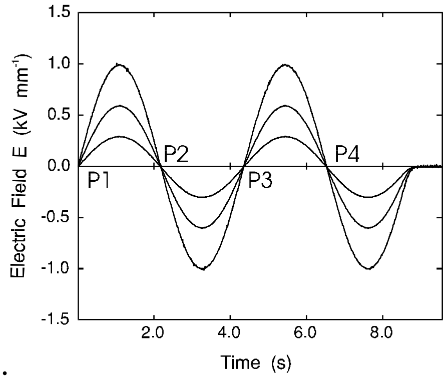
3. Theoretical basis for P-E loop analysis software

3.1 Introduction

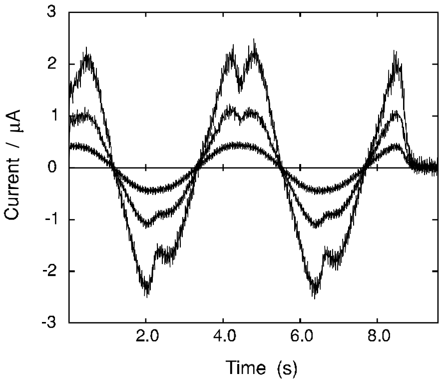
This section covers some of the theoretical basis for the software in order to help understand and use it. For further information on the development of this software and the behaviour of ferroelectric ceramics under high field conditions see references [10-12].

3.2 Measurement routines

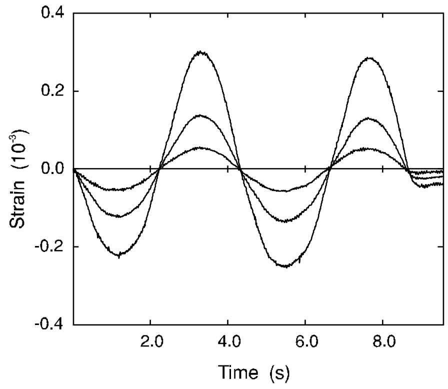
The raw voltage waveforms representing the applied electric field *E*, induced current *I*, and induced displacement *x* are downloaded to memory within the PC either by means of a DSO (digital storage oscilloscope) or via an A/D card. Conversion factors for voltage gain, current gain, and displacement gain are set by the user in order to allow conversion of the waveforms to absolute values. These gain factors are dependent on the high voltage amplifier (typically x1000), the current amplifier (typically 1 µA / Volt) and the displacement measurement device (typically 1 µm / Volt) being employed for the measurements. The electric field *E* is calculated as the applied voltage divided by the specimen thickness *d* and the induced strain as the displacement divided by *d*. Typical electric field, current, and strain waveforms obtained at high field levels are illustrated in figure 8



(a)



(b)



(c)

Figure 8. (a) Electric field, (b) current and (c) strain waveforms obtained for PZ26 ceramic with an applied electric field amplitude of 3.5 kV mm^{-1}.

3.3 Construction of *P-E* and *S-E* hysteresis loops

It is necessary to select a set of data representing a single cycle of the electric field waveform, which can then be used to construct the *P-E* and *S-E* loops. The data points corresponding to the start and end points of the loop are identified using a 'threshold' routine, which detects when the electric field waveform crosses the horizontal time axis with either a positive or negative slope. Thus, various zero positions can be identified, denoted as points *P1*, *P2*, *P3*, etc in figure 8(a). The user has the option of specifying which of these zero points will be used to define the range of data used to construct the *P-E* and *S-E* loops. For example, for the data shown above in figure 8(a) the loops could be plotted using the data range from points *P1* to *P3* or points *P2* to *P4*. For measurements made using a 'burst' waveform (as shown here), it is usually advisable to avoid the first half cycle of data since irreversible effects can give rise to incomplete hysteresis loops. The zero points and the threshold level can be set in the "Analysis Options" subroutine of the software. The threshold is initially set from the configuration file PECONFIG.TXT, usually set at 1%, although the value depends on the level of noise on the field signal. The greater the noise the larger the value of this threshold value needs to be to correctly identify the crossover points.

Once the required data points have been identified, the charge *Q* stored by the test specimen at any given time *t* is calculated by numeric integration of the current data *I*:

$$Q(t) = \int_{t1}^{t2} I dt \tag{1}$$

The *dielectric displacement D* is calculated as the surface charge density:

$$D(t) = \frac{Q(t)}{A} \tag{2}$$

where *A* = specimen surface area.

It is assumed that the specimen is cylindrical in shape and so:

$$A = pr^2 \tag{3}$$

where r = specimen radius.

In most cases, for high permittivity ferroelectrics, the polarisation P at a given time is very nearly equal to the dielectric displacement D. However, a small correction is needed in order to give accurate results for low permittivity dielectrics:

$$D(t) = P(t) + e_0 E(t) \tag{4}$$

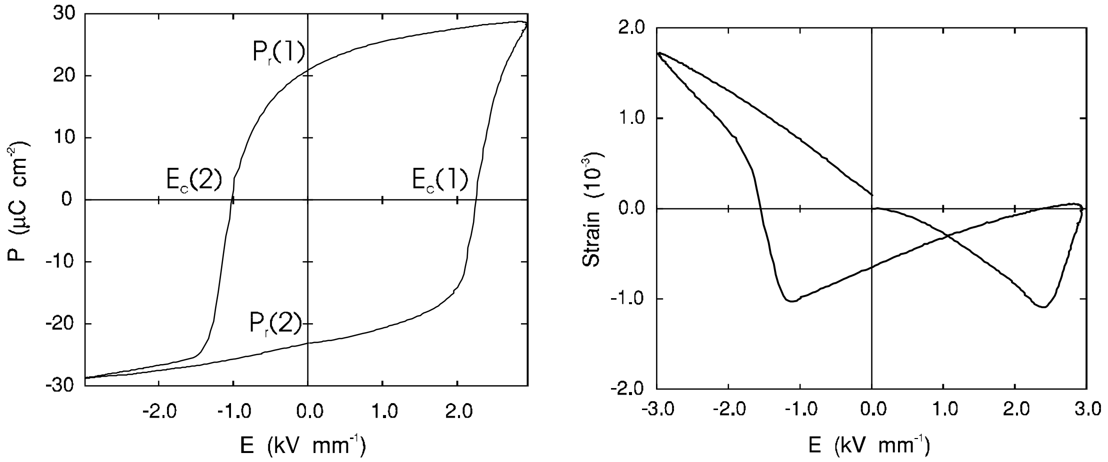
and so:

$$P(t) = D(t) - e_0 E(t) \tag{5}$$

The remaining problem is to define the baseline for the polarisation values. It is very difficult in practise to determine the absolute value of polarisation, since only changes in charge (and hence polarisation) are measured. The polarisation at zero electric field strength is not always zero, since this can represent a positive or negative *remanence* P_r. As a simple solution to this problem, it is assumed that the maximum and minimum polarisation values, P_{max} and P_{min} respectively, should be equal in magnitude

$$\text{i.e.} \qquad |P_{\max}| = |P_{\min}| = P_0 \tag{6}$$

where P_0 is the amplitude of the polarisation waveform.



(a) (b)

Figure 9. (a) *P-E* and (b) *S-E* loops for PZ26 ceramic measured with an applied electric field amplitude of 3.5 kV mm^{-1}.

The *P-E* and *S-E* loops can now be plotted, as illustrated in figure 9. The *coercive field* values $E_c(1)$ and $E_c(2)$ are determined as the intersections of the P-E loop with the electric field axis, while the *remanent polarisation* values $P_r(1)$ and $P_r(2)$ are found from the intersections of the loop with the polarisation axis. The 'shift' of the *P-E* loop along the electric field axis caused by domain stabilisation effects during ageing is quantified as the *internal bias field* E_i:

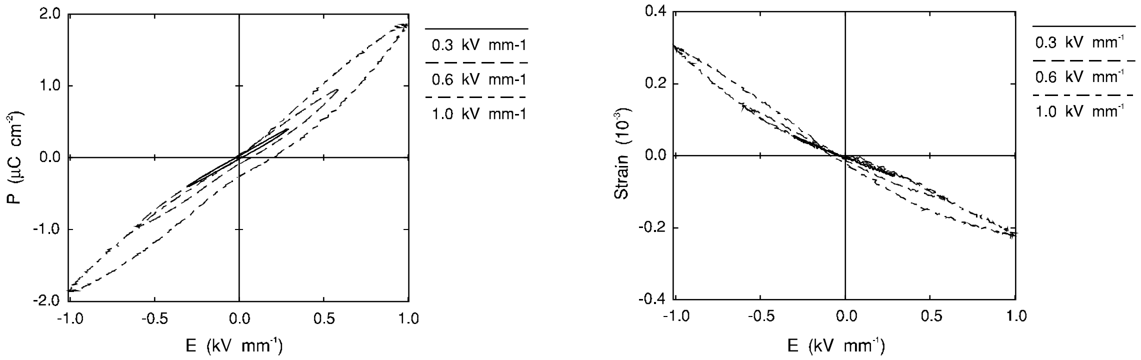
$$E_i = \frac{E_c(1) + E_c(2)}{2} \tag{7}$$

Finally, the *hysteresis loss* U_H is determined as the area enclosed within the *P-E* loop by numerical integration:

$$U_H = \int_{t1}^{t2} PdE \tag{8}$$

3.4 Determination of equivalent high field dielectric coefficients

For most practical applications, the ‘working’ electric field strength for a piezoelectric device is well below that which would cause ferroelectric domain switching and hysteresis. A comparison between *P-E* and *S-E* loops obtained at various drive amplitudes is shown in figure 10 to illustrate the relatively low levels of nonlinearity and hysteresis which are obtained in typical usage (relative to the full hysteresis curve shown above in figure 9).



(a) (b)

Figure 10. (a) *P-E* and (b) *S-E* loops for PZ26 hard PZT ceramic measured with an applied electric field amplitude of 0.3, 0.6, and 1.0 kV mm^{-1}.

The *P-E* sub-loops shown in figure 10(a) can be analysed to yield the high field dielectric coefficients $\varepsilon_r^{/}$, $\varepsilon_r^{//}$ and the loss tangent tanδ. Although linear dielectric theory cannot be strictly applied to a non-linear ferroelectric material at high field strengths, it is possible to calculate effective dielectric coefficients which represent the total charge stored and power dissipated within the dielectric. It has been found in practice that the deviations from linearity are usually small in the practical working range of most piezoelectric transducers, and so the dielectric coefficients determined in this manner do not deviate significantly from those found by other measurement methods (e.g. high field dielectric bridge measurements).

In order to calculate the dielectric coefficients $\varepsilon_r^{/}$ and $\varepsilon_r^{//}$ for a lossy dielectric, it must be recognised that the magnitude of the polarisation waveform will be influenced to some extent by the dielectric loss

i.e. $$P* = e_0 e_r * E * \tag{9}$$

(where * indicates a complex quantity).

The magnitude of ε_r^* is found from the amplitude of the polarisation and electric field waveforms as follows:

$$|\varepsilon_r^*| = \frac{|P^*|}{\varepsilon_0 |E^*|} \tag{10}$$

The well-known expression for the power dissipated in a lossy capacitor is:

$$\textit{Power dissipated} = \tfrac{1}{2}\omega C V_0^2 \tan\delta \tag{11}$$

where ω = angular frequency
C = capacitance
and V$_0$ = amplitude of applied voltage waveform.

By introducing the specimen dimensions and substituting the electric field *E* for the applied voltage *V*, this expression is modified to give:

$$\textit{Power dissipated} = \pi f \varepsilon_0 \varepsilon_r'' E_0^2 \tag{12}$$

where *f* is the frequency of the applied AC signal.

This equation yields the energy loss per cycle, which is the hysteresis loss U_H:

$$U_H = \pi \varepsilon_0 \varepsilon_r'' E_0^2 \tag{13}$$

Subsequently, the real part of permittivity ε_r' is found from these two values :

$$\varepsilon_r' = \sqrt{(|\varepsilon_r^*|)^2 - (\varepsilon_r'')^2} \tag{14}$$

The dielectric loss tangent tanδ is simply the ratio of ε_r'' to ε_r' :

$$\tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'} \tag{15}$$

The relationship between the applied electric field E^* and the induced strain S^* is analogous to the dielectric relationship given above (equation 9), with the piezoelectric strain coefficient d^* replacing the absolute dielectric permittivity $\varepsilon_0\varepsilon_r^*$. Therefore, the values of d', d'' and the *piezoelectric loss tangent* $\tan\delta_d$ are found as follows:

$$|d^*| = \frac{|S^*|}{|E^*|} \tag{16}$$

$$\textit{Piezoelectric 'loss'} \quad U_d = \int_{t1}^{t2} S\,dE = \pi d'' E_0^2 \tag{17}$$

$$d' = \sqrt{(|d^*|)^2 - (d'')^2} \tag{18}$$

and

$$\tan\delta_d = \frac{d''}{d'} \tag{19}$$

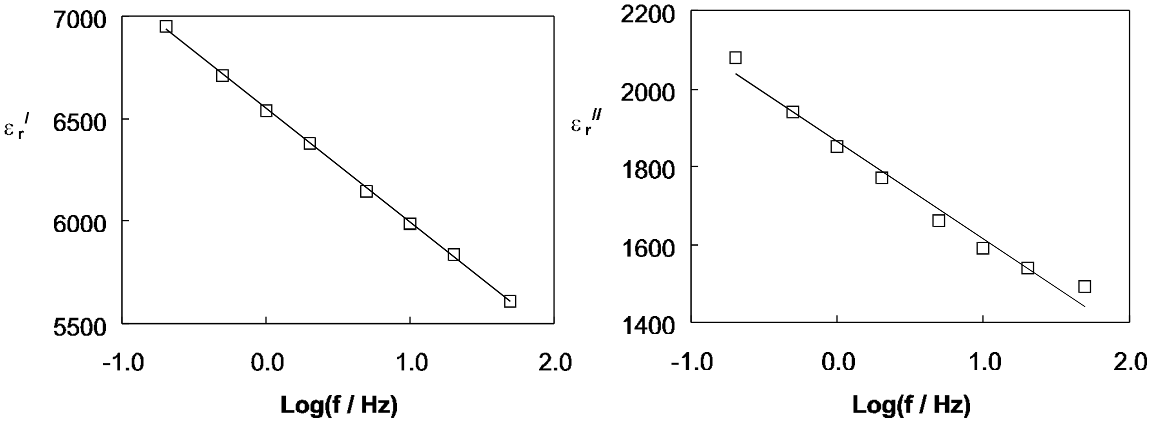
3.5 Rayleigh law representation of dielectric behaviour in piezoelectric materials

The linear nature of the $\varepsilon_r^{/}$ vs E_0 plot for PC5H is a good example of the Rayleigh law, which is a well-known phenomenon in ferromagnetic materials [13]. The application of this relationship to the direct piezoelectric effect in ferroelectric PZT ceramics has been described in some detail in a recent series of articles by Damjanovic et al. [14-16]. The form of the hysteretic relationship is thought to arise from the hindrance of domain wall motion by random defects (either lattice or microstructural defects). In the case of the dielectric behaviour, the Rayleigh law in ferroelectrics will have the form:

$$e_r^{/}(E_0) = e_r^{/}(0) + aE_0 \tag{20}$$

where $\varepsilon_r^{/}(0)$ is the value of permittivity in the low field region and α is the Rayleigh coefficient (equal to the gradient of the $\varepsilon_r^{/}$ vs E_0 plot). In more recent work the above relationship has been extended to include a threshold field limit below which the behaviour does not follow the Rayleigh Law, however this has not been taken into account in the present implementation of the software. For more information on this see [12].

Another consequence of the interactions between moving domain walls and defects is a logarithmic frequency dependence of the permeability (for ferromagnetic materials). This type of behaviour was also observed in the present case for the permittivity of PC5H, as shown in figure 11. Therefore, there is good reason to suppose that a useful analogy can be drawn between the low-field vibration of domain walls in ferromagnets and the vibration of ferroelectric domain walls in soft PZT ceramics.



(a) $\varepsilon_r^{/}$

(b) $\varepsilon_r^{//}$

Figure 11. Frequency dependence of dielectric coefficients for PC5H.

In order to explore this argument further, the P-E loops obtained for PC5H were examined in more detail. A second observation made by Rayleigh was that the slope of the B-H curve at the loop tips is the same as that of the initial B-H curve, as shown in figure 12.

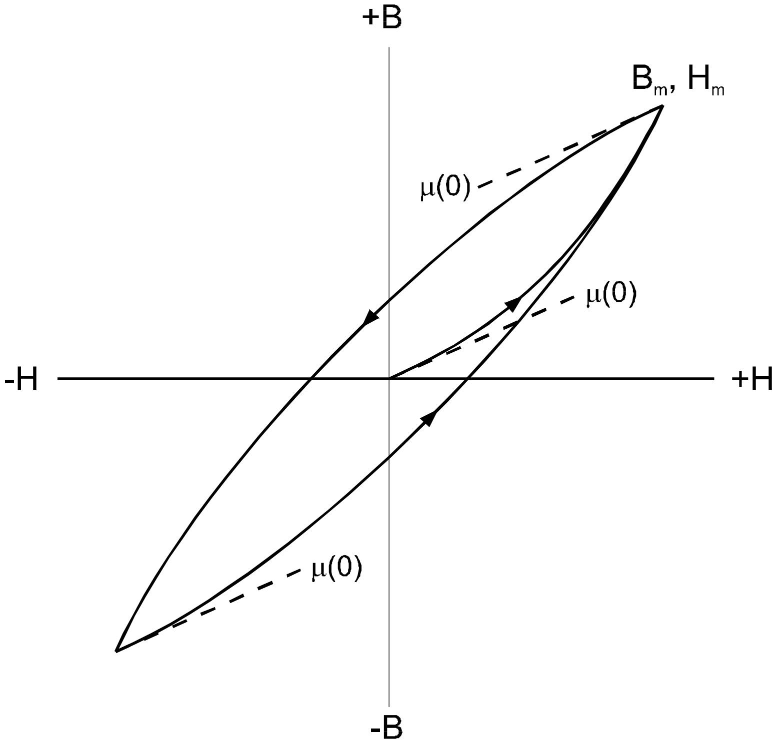


Figure 12. Ideal form of Rayleigh loop for a ferromagnetic material [13].

Given this observation, it follows that the P-E loop can be described by the following equation:

$$P = \varepsilon_0([\varepsilon_r^{/}(0) + \alpha E_0]E \pm (\alpha/2)(E_o^2 - E^2)) \tag{21}$$

This offers the possibility of predicting the P-E relationship for any given applied field level, provided that the Rayleigh relationships are valid. The hysteresis loss W_H and the $\varepsilon_r^{//}$ values can also be calculated as follows:

$$W_H = \frac{4}{3} a e_0 E_0^3 \tag{22}$$

$$e_r^{//} = \frac{4}{3p} a E_0 \tag{23}$$

The calculated P-E loops for PC5H at field amplitudes of 0.2, 0.4 and 0.6 kV mm^{-1} are shown in figure 13 together with the experimentally determined data points. The fitting parameters used in this case were $\varepsilon_r^{/}(0) = 3030$ and $\alpha = 5248$. It is clear that the calculated loops provide a good fit to the experimental data at low field amplitudes. The deviation between the calculated curve and experimental points grows more pronounced with increasing field amplitude, presumably due to the asymmetry caused by using a poled specimen.

Equation (21) above is for the calculation of a PE loop based on the Rayleigh law, that is a plot of polarisation versus field. In order to simplify the incorporation of this algorithm into the software the PE loops are converted to time, voltage and current arrays so that the data appears as if it had come from the data acquisition hardware. In order to do this a PE loop is generated using equation (21) based on an arbitrary field curve (usually a sine wave). The current at any time is determined as the derivative of the polarisation with respect to time, that is:

$$I = \frac{dP}{dt} \tag{24}$$

In the same way that the Rayleigh law has been used to predict and simulate dielectric behaviour of ferroelectrics, the piezoelectric strain S can be represented by an equation analogous to (21):

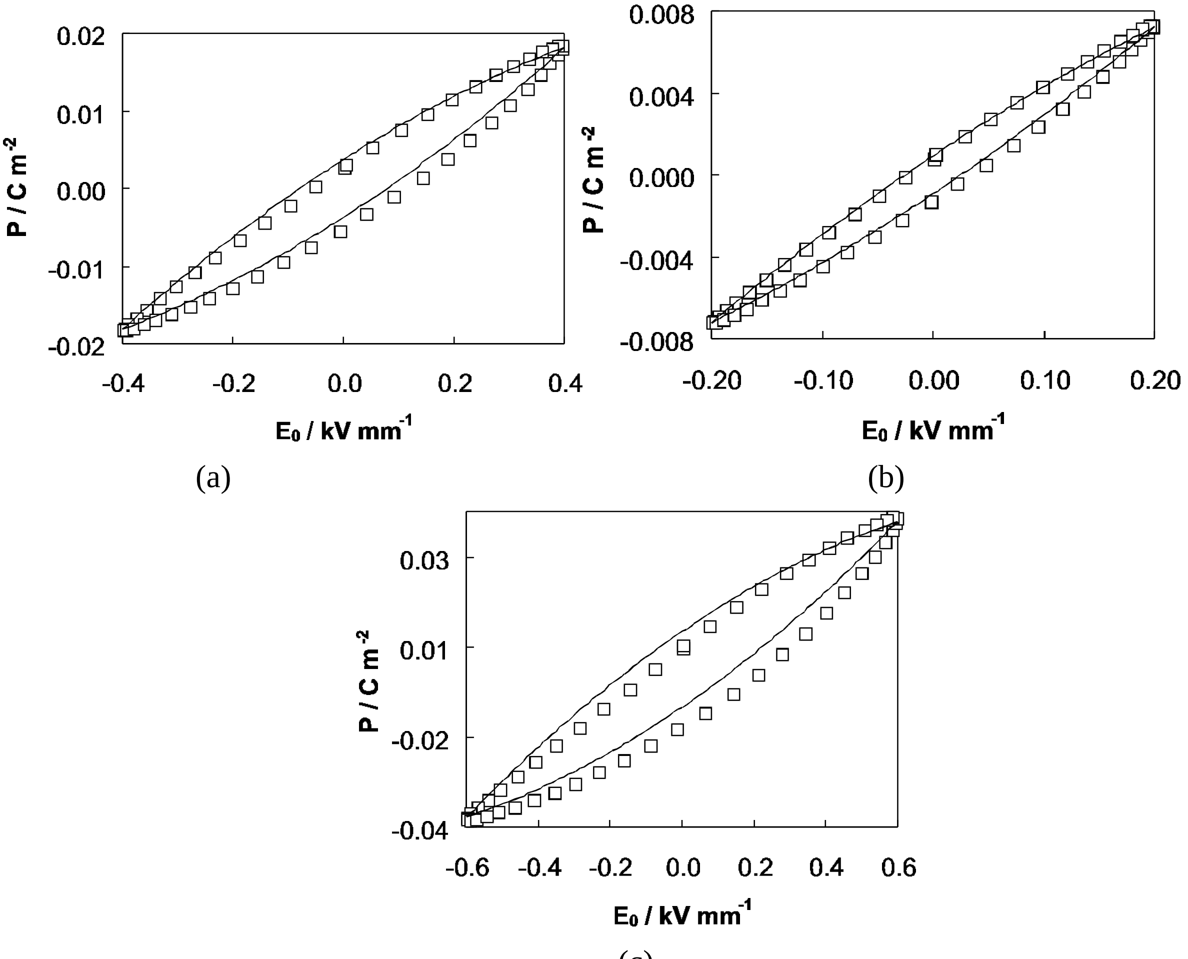


Figure 13. Comparison of calculated and experimentally determined P-E loops for PC5H at field amplitudes of (a) 0.2 kV mm^{-1} (b) 0.4 kV mm^{-1} and (c) 0.6 kV mm^{-1}. Only every 10th data point is shown for clarity.

$$S = [d_{33}^{/} + a'E_0]E \pm (a'/2)(E_o^2 - E^2) \tag{25}$$

where d'$_{33}$ is the real part of the complex piezoelectric coefficient from (18). This Rayleigh coefficient is different to the one in (21) and is represented as α' to distinguish this. Since the strain is dimensionless the units of α' must be $(m/V)^2$ rather than the m/V for the dielectric coefficient.

3.6 Representation of a lossy dielectric as a parallel CR network to model PE loops.

At fields below which ferroelectric switching occurs piezoelectric materials can be thought of as a lossy linear dielectric and can simulated by a parallel resistor capacitor (RC) network where the resistor R represents the dielectric loss across an ideal capacitor C. This means the current across the RC model can be represented by the following:

$$I = \frac{V}{R} + \frac{CdV}{dt} \tag{26}$$

The simulation subroutine of the software can create time, voltage current curves based on (26) given an arbitrary voltage waveform, and user input of C and R. This can be used as a learning tool for the understanding of the significance of PE loops, but can also be used to check the hardware system. For instance, by using a very low loss polypropylene capacitor in parallel with a high voltage resistor, measurements can be made and compared with the PE loops produced using (26). Also given that for the parallel RC circuit the dielectric loss is given by

$$\tan\delta = \frac{1}{\omega RC} \tag{27}$$

the tan δ calculated by the software can be compared with that expected from (27).

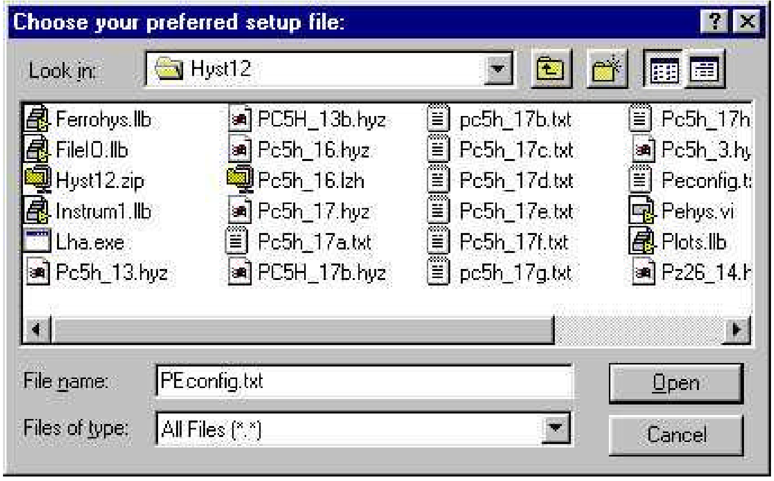
4. Overview of the software package

4.1 General information

The software was designed as a fully integrated set of measurement and analysis routines for the electrical characterisation of piezoelectric ceramic materials under high field conditions. At the outset of the CAM7 project, it was envisaged that most emphasis would be placed on determination of the effective high field dielectric properties of ferroelectric ceramics at intermediate field levels ($0<E_0<E_c$), and the saturated ferroelectric hysteresis characteristics (for $E_0<E_c$), by the acquisition and analysis of P-E (polarisation-electric field) data. During the course of the software development, it became evident that it would also be important to incorporate routines for the measurement and analysis of S-E (strain-field) data, thereby enabling a calculation of the effective high field piezoelectric coefficients. Within the program, a boolean switch (P-E/P-S-E) is used as a selector to include or exclude the strain-field data.

4.2 Startup and Main Panel

On first running the program, the preferred configuration file must be selected. The default file is named ‘PEconfig.txt’, as shown below:



Choose your preferred setup file:

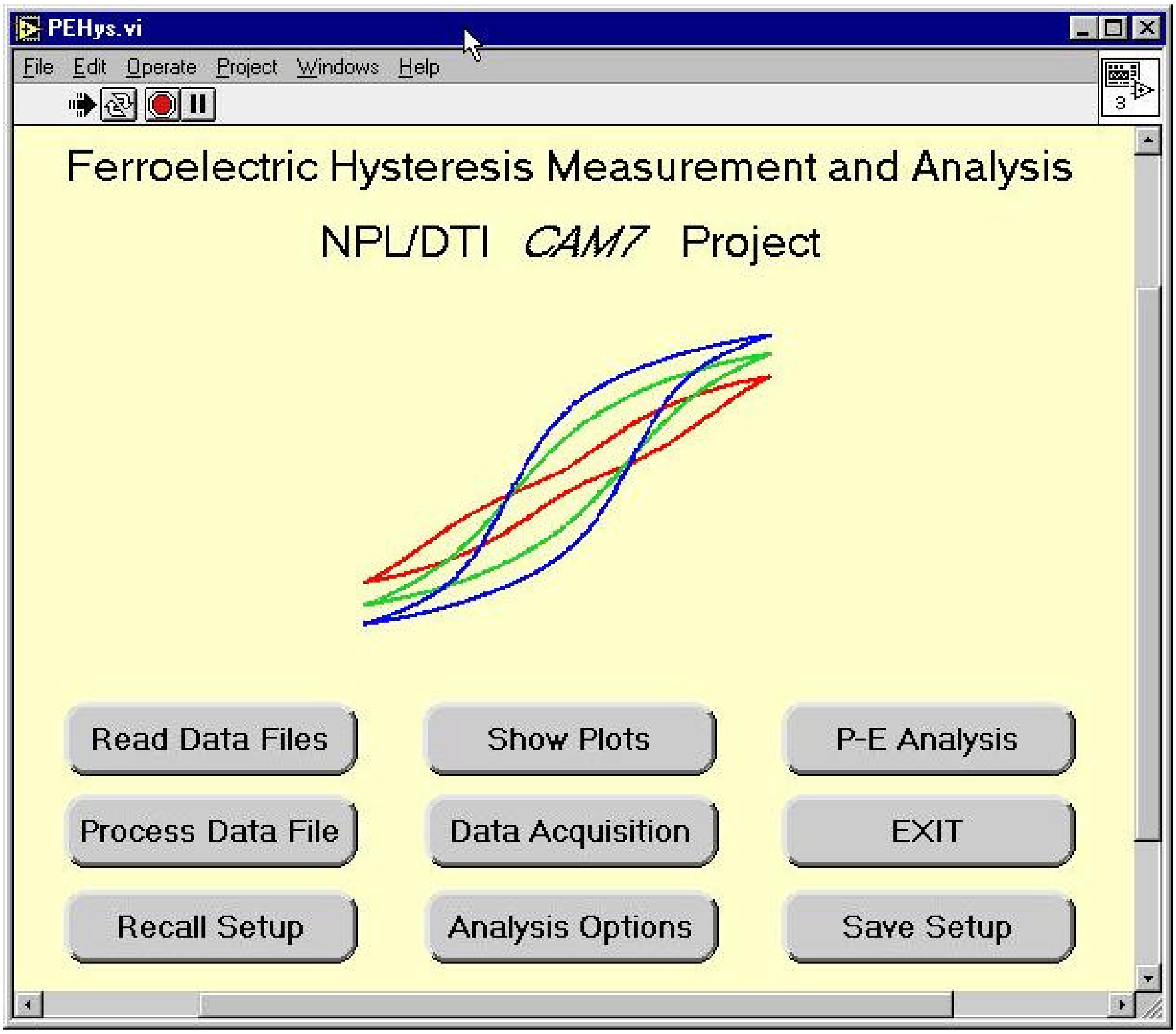
Look in: Hyst12

File name: PEconfig.txt

Files of type: All Files (*.*)

Any other ASCII file can be used as long as it conforms to the correct data format. The setup file can be edited using a standard text editor, but it is generally recommended that the *Save Setup* and *Recall Setup* options are used to create and use a customised configuration file, since this ensures that the information is saved and loaded correctly (see section 4.9 below).

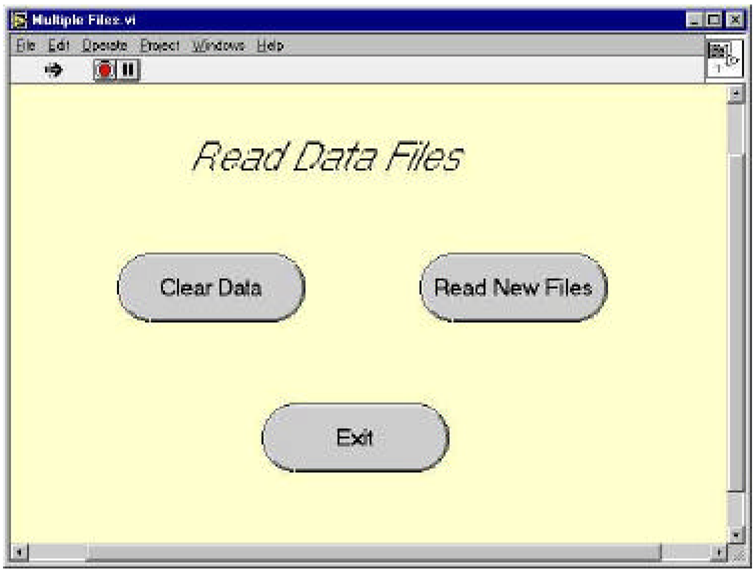
The main functions that can be accessed from the front panel of the program are illustrated below:



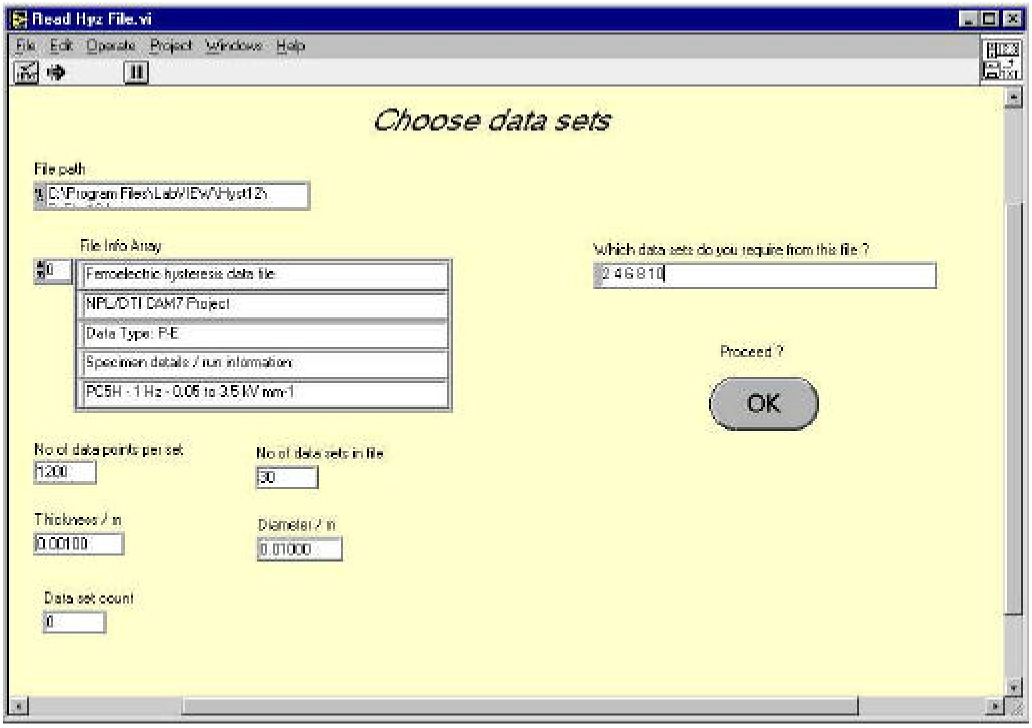
The following sections give a brief overview of the available options within each of these program modules.

4.3 Read Data Files

A large number of data sets (typically up to 30) can be imported into the program for subsequent plotting and quantitative analysis. The first window to open within this option allows the user to add data sets to those in memory, clear the memory, or return to the main panel:



Each data file will usually contain multiple data sets, from which any one or any given selection can be specified. Choosing the *Read New Files* option opens up a new window that provides the choice of data sets from within the selected file:



File path: C:\Program Files\LabVIEW\Hyst12\

File Info Array: 0
Ferroelectric hysteresis data file
NPL/DTI CAM7 Project
Data Type: P-E
Specimen details / run information:
PC5H - 1 Hz - 0.05 to 3.5 kV mm-1

Which data sets do you require from this file ? 2 4 6 8 10

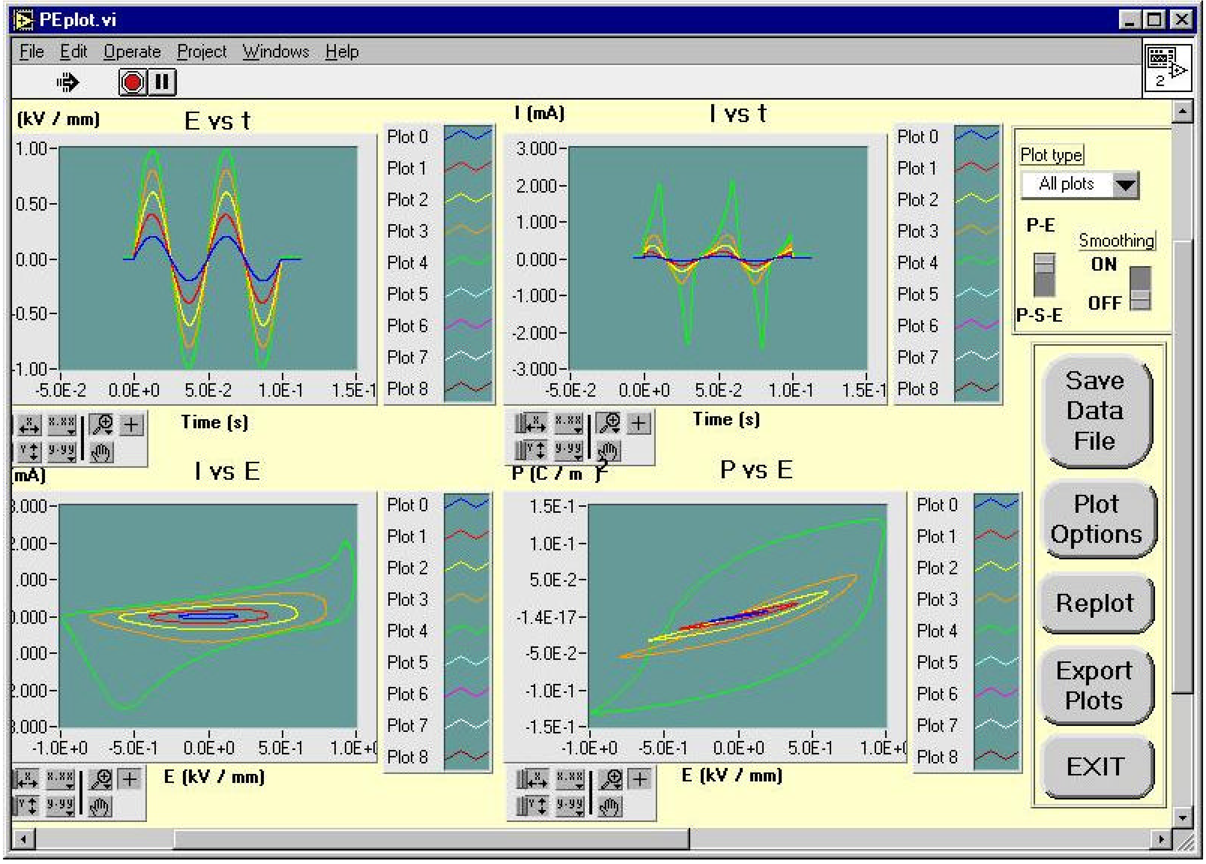
No of data points per set: 1200
No of data sets in file: 30
Thickness / m: 0.00100
Diameter / m: 0.01000
Data set count: 0

This module is very flexible in that multiple data sets (from a single one or a series of different data files) can be read into memory. Each data set comprises the raw current, voltage (and optionally strain) waveforms, together with the associated instrumentation/specimen details. On returning to the main program window, all of the data sets in memory are processed according to the subsequent actions.

4.4 Show Plots

4.4.1 Main Plot Window

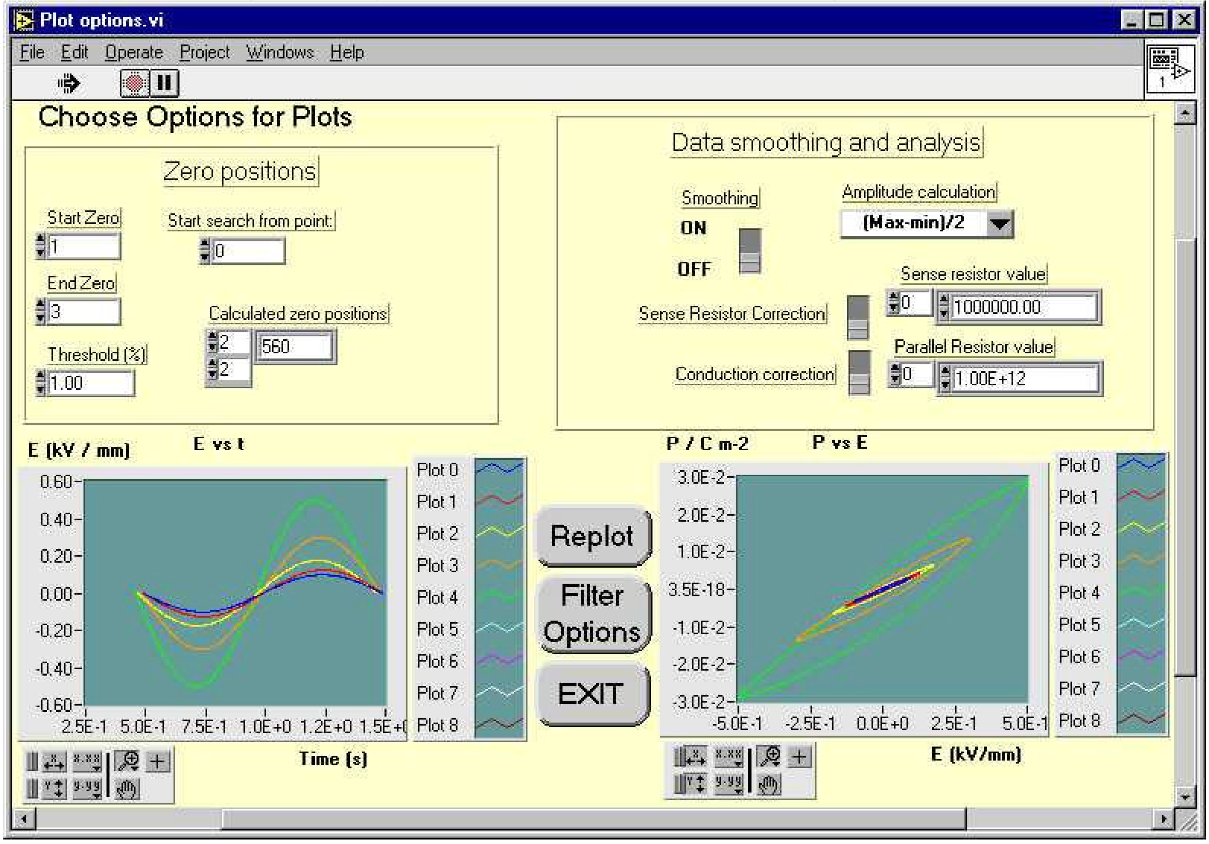
This module is used for on-screen comparison of the data in memory according to a number of different allowed formats (e.g. E vs t, I vs t, S vs t, P vs E, S vs E etc). Data scaling and axis definition is accomplished using standard LabVIEW chart types. This also enables re-scaling of the plotted data to highlight particular areas of interest. The provision of routines for obtaining a hard copy of the plot is somewhat limited in LabVIEW. Therefore, an option for exporting the plotted results as a text file (for subsequent import to a spreadsheet or graphics program) is also provided in this module.



Selecting the P-S-E option (using the boolean switch), followed by the *Replot* button provides an additional 2 graphs on the right hand side of the screen (not visible on the above figure) for S vs t (strain against time) and S vs E (strain against electric field). Similarly, selection of the smoothing option followed by *Replot* applies smoothing/filtering routines to the plotted data according to the format chosen within the *Filter Options* module (see below).

4.4.2 Plot Options

Pressing the *Plot Options* button opens up a new window within which the various options required for plotting and analysis of the current data can be configured, as shown below:


Plot options.vi

Choose Options for Plots

Zero positions

Start Zero: 1

End Zero: 3

Threshold (%): 1.00

Start search from point: 0

Calculated zero positions: 2, 2, 560

Data smoothing and analysis

Smoothing: ON / OFF

Amplitude calculation: (Max-min)/2

Sense resistor value: 0, 1000000.00

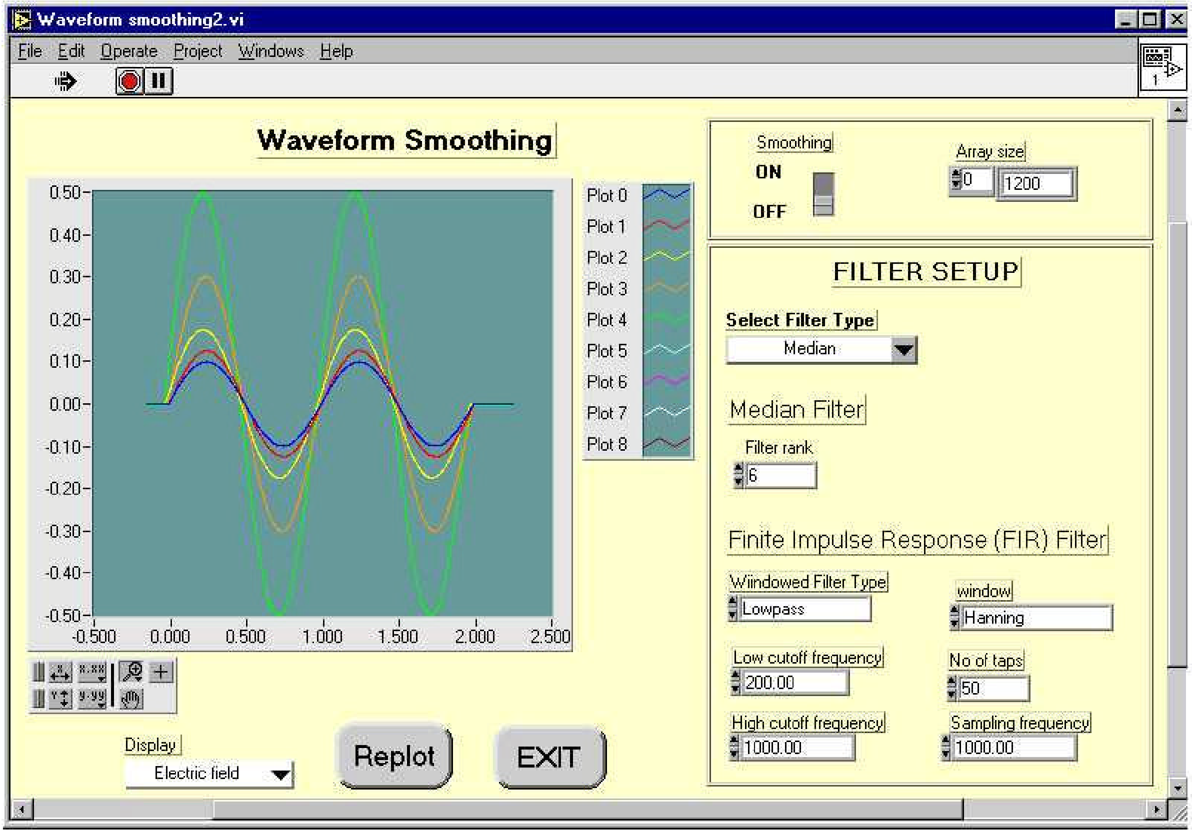
Parallel Resistor value: 0, 1.00E+12

The set of options within the *Zero Positions* box enable the user to specify how the start and end points of the data used in plotting the hysteresis loops are determined. The *Calculated zero positions* values (which cannot be changed by the user) are established as the positions at which the electric field waveform passes through the ‘threshold’ value, while *Start search from point* allows the user to ignore any noisy data which might be present prior to the beginning of the cycle. A threshold value of around 1% is usually sufficient to avoid confusion with any noise which might be present before the real data (when using a burst waveform).

Within the *Data Smoothing and Analysis* box, it is possible to specify how the amplitude of the waveforms is calculated, either from the peak-peak value or as RMS (root mean square) value. This option only seems to exert a significant influence on the calculated results when using non-sinusoidal drive signals. Correction routines are also provided for subtraction of a parallel ohmic conduction current (i.e. compensating for a finite specimen resistance) and for a series resistance (in case the current is determined using a series resistor which, depending on hardware connections, may act to reduce the voltage across the specimen). In each case, setting the switch in the ‘down’ position turns off the correction routine.

Pressing the *Replot* button allows the user to see visually the effects of changing any of the plotting options.

The *Filter Options* button opens up an additional window which enables the configuration of various options relating to smoothing/filtering of noisy data:



Smoothing: ON / OFF

Array size: 0 1200

Select Filter Type: Median

Filter rank: 6

Windowed Filter Type: Lowpass

window: Hanning

Low cutoff frequency: 200.00

No of taps: 50

High cutoff frequency: 1000.00

Sampling frequency: 1000.00

Display: Electric field

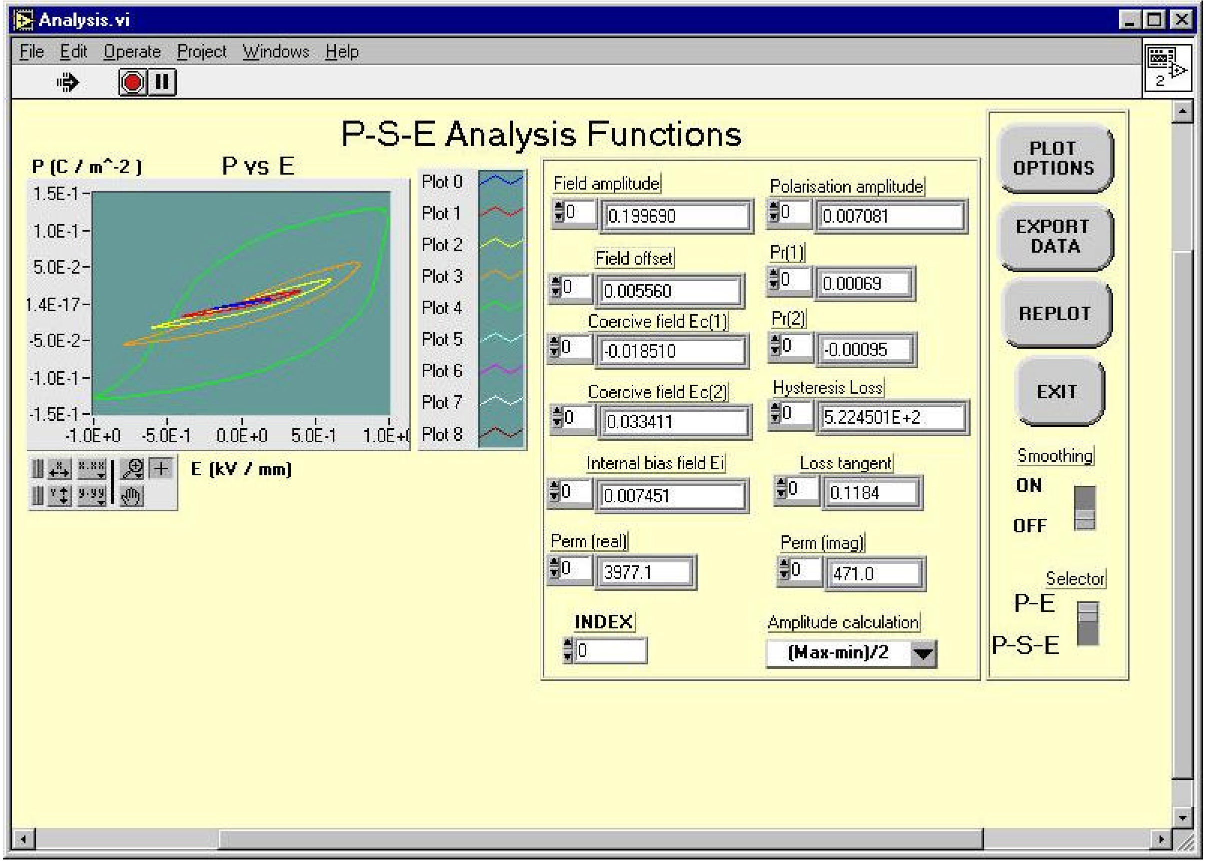
The two main types of filter available are a *Median Filter* (which uses a relatively simple averaging routine) and a *Finite Impulse Response Filter* (which can use various types of digital signal processing methods). As with the other program modules, it is necessary to press the *Replot* button to see the effects of any changes in the filter setup.

4.5 P-E Analysis

The purpose of this module is to calculate a number of functional material properties for each data set in memory. This covers the effective high field dielectric and piezoelectric coefficients ($\varepsilon_r^{/}$, $\varepsilon_r^{//}$, tan δ, $d^{/}$, $d^{//}$) as well as the characteristic parameters of the P-E and S-E hysteresis loops. An ‘index’ selector is used to cycle through the available data sets, providing an on-screen comparison of the calculated values. The *Plot Options* module can also be accessed from within this module. The calculated values for all data sets in memory can be exported as a spreadsheet file for subsequent evaluation and/or plotting.

Selecting the ‘P-S-E’ option makes visible an additional S vs E plot and a further set of values (including the real and imaginary piezoelectric coefficients) calculated from the strain-field data.

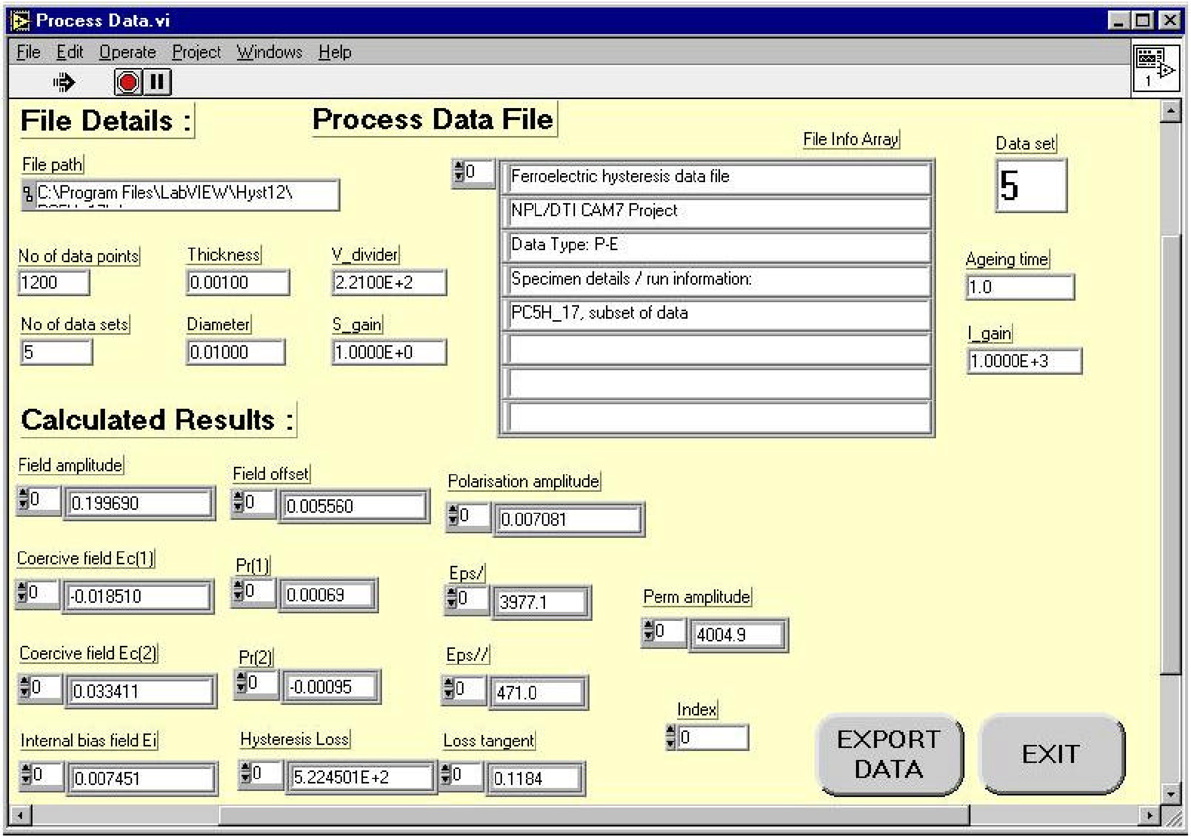
The *Export Data* button provides the option for exporting the calculated results as a text file, in standard spreadsheet format (i.e. as numbers separated by tabs). Headings are provided in the exported file to indicate the data being presented in each column.



Field amplitude	0	0.199690
Polarisation amplitude	0	0.007081
Field offset	0	0.005560
Pr(1)	0	0.00069
Coercive field Ec(1)	0	-0.018510
Pr(2)	0	-0.00095
Coercive field Ec(2)	0	0.033411
Hysteresis Loss	0	5.224501E+2
Internal bias field Ei	0	0.007451
Loss tangent	0	0.1184
Perm (real)	0	3977.1
Perm (imag)	0	471.0
INDEX	0	
Amplitude calculation		(Max-min)/2

4.6 Process Data File

This module provides a combination of the data read and analysis functions in one automated routine that acts on a single data file. All of the data sets in the file are read into memory and the associated material properties calculated according to the present analysis options. The calculated values can then be exported as described above. On exiting this module, all of the data sets remain in memory in the standard format so that plots can be obtained or further analysis carried out.



File Details :

Process Data File

File path: C:\Program Files\LabVIEW\Hyst12\

No of data points: 1200

Thickness: 0.00100

V_divider: 2.2100E+2

No of data sets: 5

Diameter: 0.01000

S_gain: 1.0000E+0

File Info Array: 0

- Ferroelectric hysteresis data file
- NPL/DTI CAM7 Project
- Data Type: P-E
- Specimen details / run information:
- PC5H_17, subset of data

Data set: 5

Ageing time: 1.0

I_gain: 1.0000E+3

Calculated Results :

Field amplitude: 0 0.199690

Field offset: 0 0.005560

Polarisation amplitude: 0 0.007081

Coercive field Ec(1): 0 -0.018510

Pr(1): 0 0.00069

Eps/: 0 3977.1

Perm amplitude: 0 4004.9

Coercive field Ec(2): 0 0.033411

Pr(2): 0 -0.00095

Eps//: 0 471.0

Index: 0

Internal bias field Ei: 0 0.007451

Hysteresis Loss: 0 5.224501E+2

Loss tangent: 0 0.1184

4.7 Data Acquisition

4.7.1 Main Data Acquisition Window

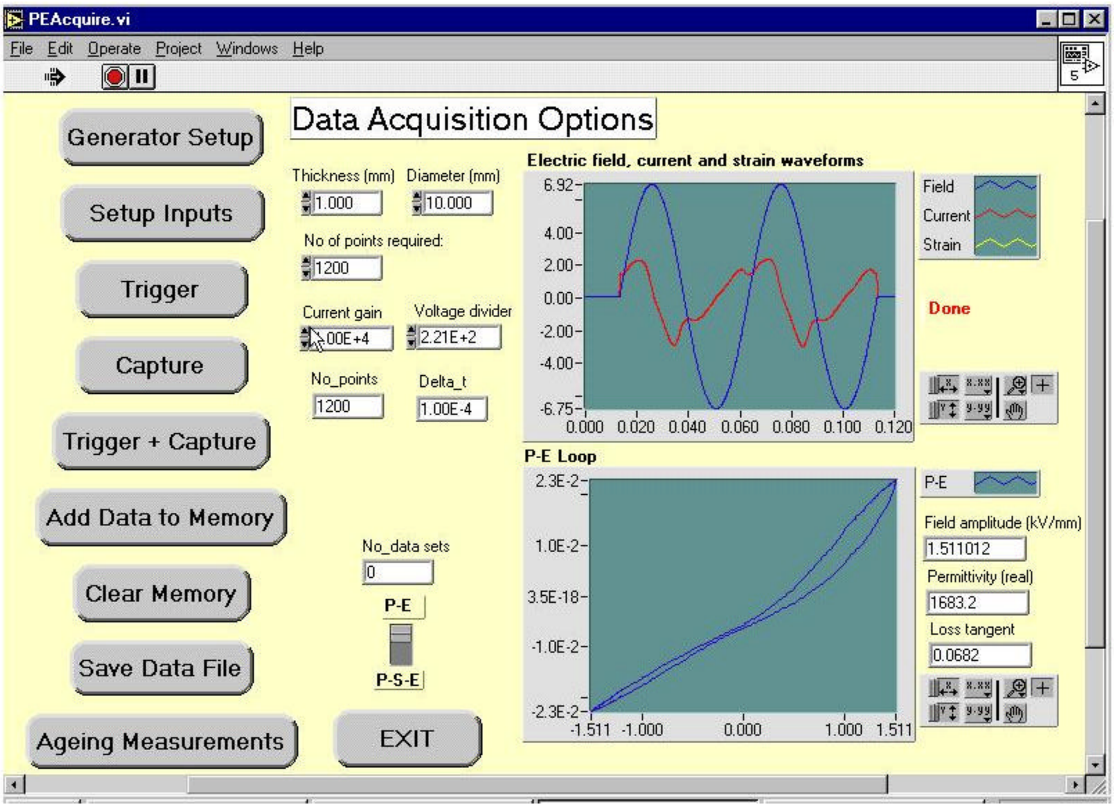
The routines for instrument control and data capture are all provided in this module, within which a wide range of instrumentation options and signal characteristics can be set up by the user. Upon ‘capturing’ a set of waveforms from an A/D card or DSO, the data set can be ‘added’ into the memory, where it can then be processed according to all of the actions described previously. Alternatively, once the required number of data sets has been added to the memory they can be saved together in a single data file. The memory can then be cleared if necessary and further data sets acquired in a similar manner. A routine is also provided for automatic acquisition of data during an ‘ageing’ experiment.

The data collection in the version of the software provided with this report has been disabled to allow it to run on all machines. Accessing some of the buttons on this menu require data collection hardware and a message noting this will appear.

The data collection routines have been replaced by the simulation routines discussed earlier. Thus selecting *Capture* or *Trigger and Capture* will lead to a screen which enables simulation based on either the Rayleigh Law or a parallel CR circuit.

The thickness and diameter of the specimen, as well as the number of data points required, should all be entered into the data boxes. Similarly, the current gain and the voltage divider of the equipment being used for data acquisition should be entered before any data sets are added to the memory. The number of data points acquired and the time interval between points are also indicated here.

Selecting the *P-S-E* option makes visible further information relating to the field-induced displacement data, and an additional plot of the strain-field data.



Thickness (mm) 1.000

Diameter (mm) 10.000

No of points required: 1200

Current gain .00E+4

Voltage divider 2.21E+2

No_points 1200

Delta_t 1.00E-4

No_data sets 0

Done

Field amplitude (kV/mm) 1.511012

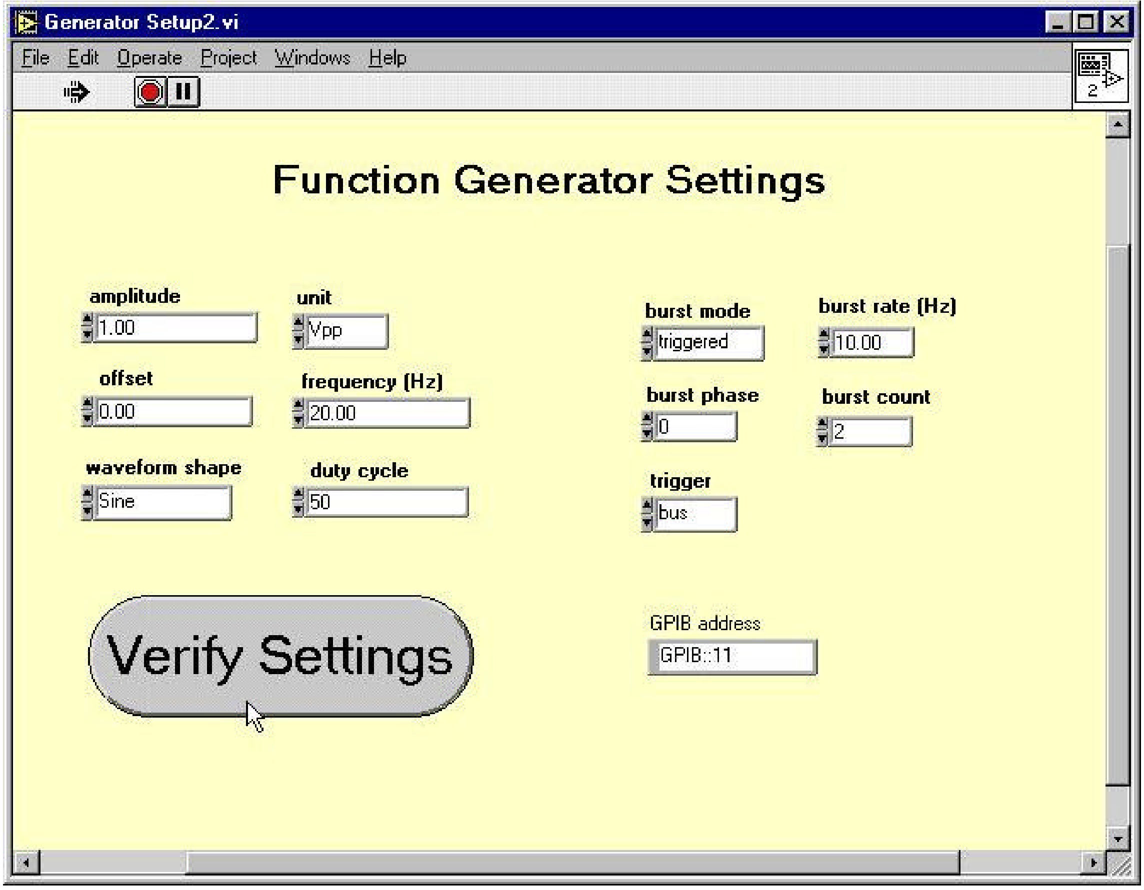
Permittivity (real) 1683.2

Loss tangent 0.0682

4.7.2 Generator Setup[**]

The *Generator Setup* module has been provided for software control of the Hewlett Packard HP 33120 Function Generator, as shown below. Any other function generator can be used for continuous signals, but the HP instrument is necessary if software control of triggering and signal characteristics is required. The amplitude level should be set with some caution, since it is usual to employ a x1000 high voltage amplifier in combination with the function generator. Therefore, an amplitude setting of 1 Vpp will yield 1 kV peak-peak or ± 500 V at the specimen. Mis-typing this value can easily lead to sample breakdown !

The ‘offset’ value represents a DC bias voltage (in volts), while frequency and waveform shape should be self-explanatory. Various parameters can be used to control whether a continuous or burst-mode signal is applied, and the GPIB address of the function generator (on the IEEE-488 interface) is expressed as an integer value.

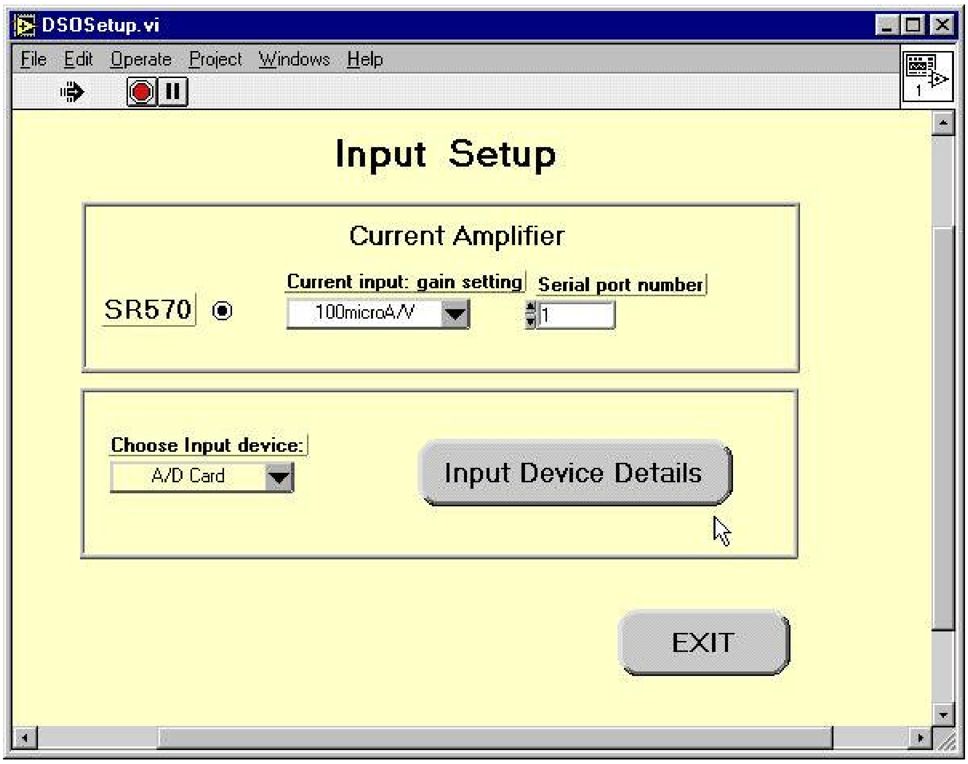


Function Generator Settings

amplitude	1.00
unit	Vpp
offset	0.00
frequency (Hz)	20.00
waveform shape	Sine
duty cycle	50
burst mode	triggered
burst rate (Hz)	10.00
burst phase	0
burst count	2
trigger	bus
GPIB address	GPIB::11

4.7.3 Setup Inputs**

The source of the input signals (i.e. voltage, current and displacement), as well as various other factors concerning channel gains etc can be configured using the *Setup Inputs* option:



SR570 ●

Current input: gain setting 100microA/V

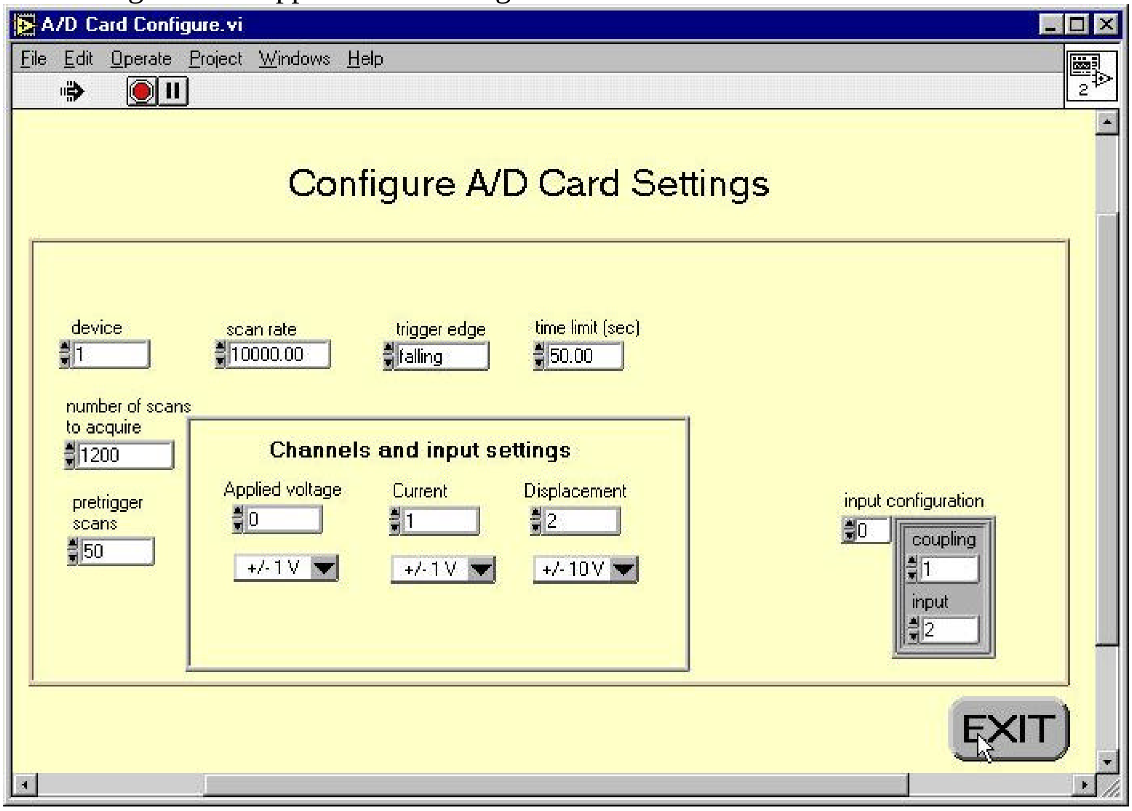
Serial port number 1

Choose Input device: A/D Card

Software setup routines are provided for the Stanford Research SR570 current amplifier (via a serial link), which then automatically update the current gain factor specified in the main *Data Acquisition* window. If a different type of current amplifier is being used, the information provided here has no function and it is necessary to set the current gain manually within the main *Data Acquisition* window.

Various types of input device can be used to interface between the measurement equipment and the PC. The active input device is selected here; the device can then be configured by pressing the *Input Device Details* button.

The following window appears when using an A/D card:



Configure A/D Card Settings

device: 1
scan rate: 10000.00
trigger edge: falling
time limit (sec): 50.00
number of scans to acquire: 1200
pretrigger scans: 50

Channels and input settings

Applied voltage: 0, +/- 1 V
Current: 1, +/- 1 V
Displacement: 2, +/- 10 V

input configuration: 0
coupling: 1
input: 2

The device number (as defined in the National Instruments Data Acquisition Utility or software provided by the board manufacturer), scan rate etc are all configured here; the meaning of these options should be fairly self-explanatory. The 'number of scans to acquire' and the 'scan rate' should be specified such that at least one or two complete cycles of data are acquired. The input limits on each channel (e.g. +/- 1 V) should be chosen with regard to the magnitude of the input signals, so that the maximum resolution possible can be achieved. It is also important to ensure that the maximum input limits of the A/D card are not exceeded by the signals to be measured.

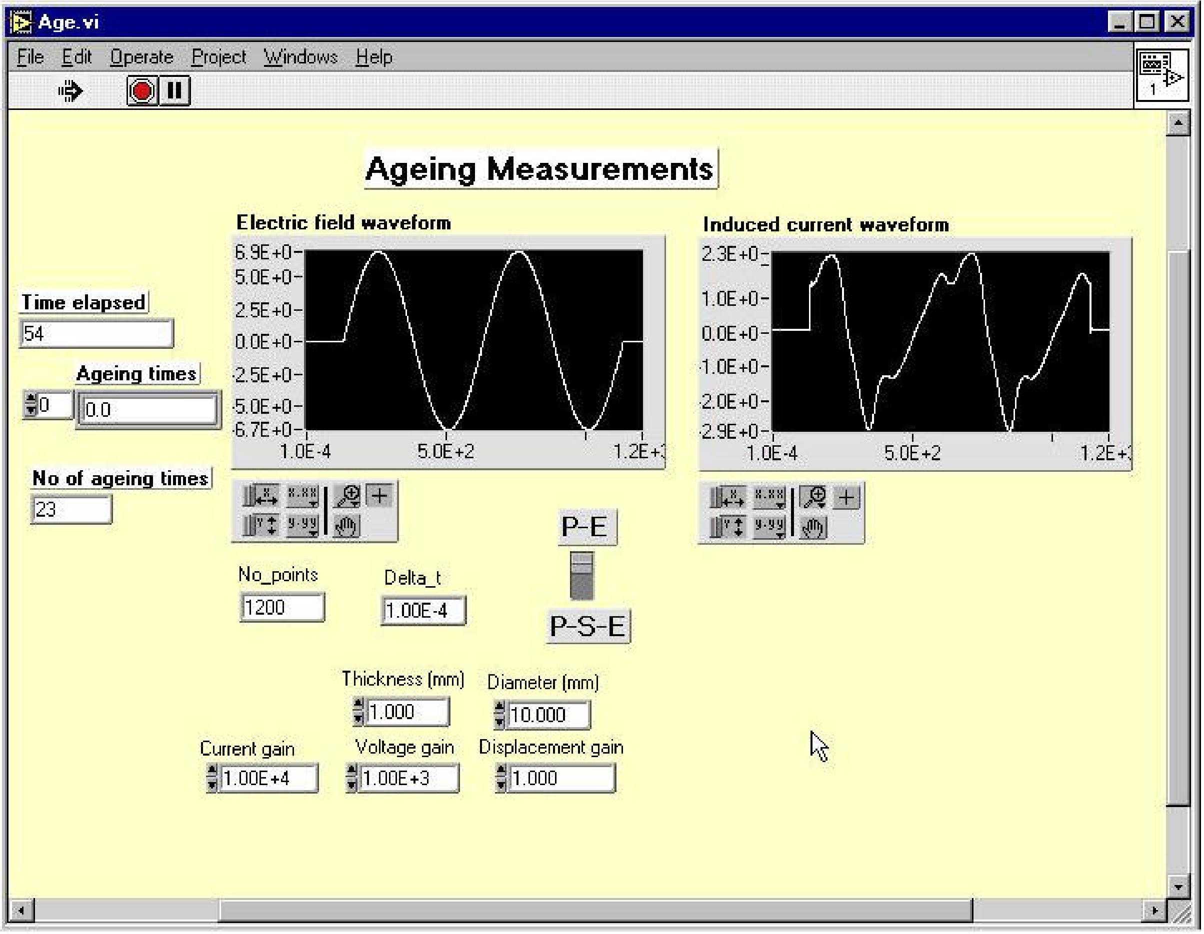
The type of trigger to be used for an A/D card is largely dependent on the particular hardware configuration being used. Often, the most reliable approach is to use a hardware trigger from the function generator, which should ensure that the acquisition of the data is synchronised with the signal source.

The 'input configuration' is an array of elements, each of which contains the configuration information for the channel specified (0,1,2). The meaning of the integer values selected is as follows:

coupling	**input type**
0: do not change coupling setting	0: do not change the input type setting
1: DC	2: differential
2: AC	2: referenced single ended
3: ground	3: non-referenced single ended
4: internal reference	

4.7.4 Ageing Measurements**

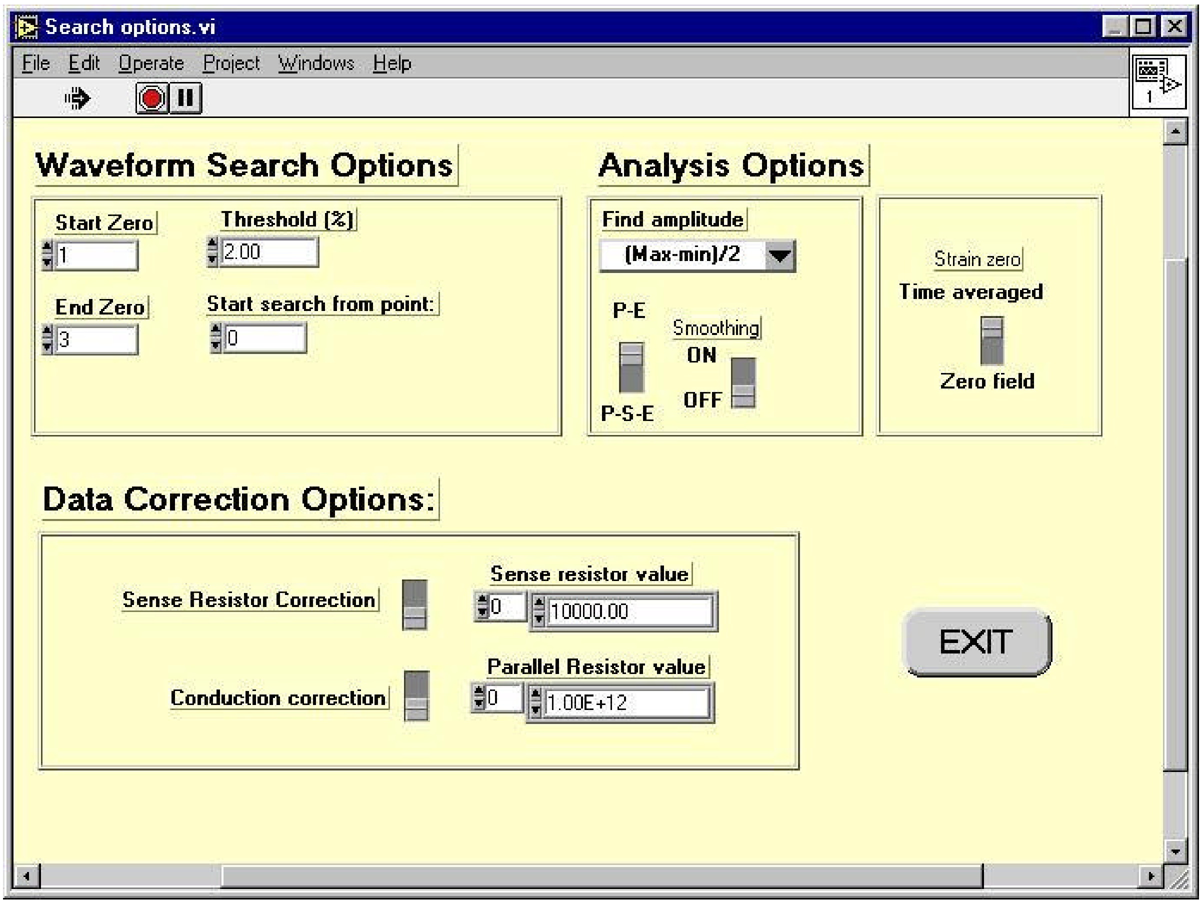
The data acquisition module incorporates a set of routines for automatic measurements over a specified period. This type of approach is often useful when the characteristics of a ferroelectric material are found to change significantly during ageing after poling or after application (or release) of mechanical stress. The measurement times to be used during the ageing schedule are specified within the program configuration file (e.g. PEconfig.txt); typically, these will range over a 24 hour period, with times being spaced out in a logarithmic fashion. On completion of this module, the program returns to the main Data Acquisition window where the data sets acquired can then be saved together in a single data file (the ageing times for each data set are also recorded).



Time elapsed: 54
Ageing times: 0 0.0
No of ageing times: 23
No_points: 1200
Delta_t: 1.00E-4
Thickness (mm): 1.000
Diameter (mm): 10.000
Current gain: 1.00E+4
Voltage gain: 1.00E+3
Displacement gain: 1.000

4.8 Analysis Options

Certain options used throughout the program for plotting and analysis of data can be set within this module, as illustrated below. The waveform search options specify which data points from the electric field waveform are used to construct the I-E, P-E and S-E loops (the same data points are then also used in the calculation of the effective dielectric and piezoelectric coefficients). Analysis options include the method of determining the amplitudes of the waveforms (as peak-peak or rms values), the inclusion of strain data, use of data filtering routines (smoothing) and the reference point for the strain waveform. In addition, correction routines are provided to subtract a parallel conduction current and to correct the applied voltage signal in the event that a series 'sense' resistor is used for measuring the induced current. The latter correction is not necessary when a 'virtual earth' current amplifier is employed (as used throughout the CAM 7 project), but has been used successfully for high frequency measurements using a sense resistor.



Search options.vi

Waveform Search Options

Start Zero: 1

End Zero: 3

Threshold (%): 2.00

Start search from point: 0

Analysis Options

Find amplitude: (Max-min)/2

Data Correction Options:

Sense resistor value: 0 10000.00

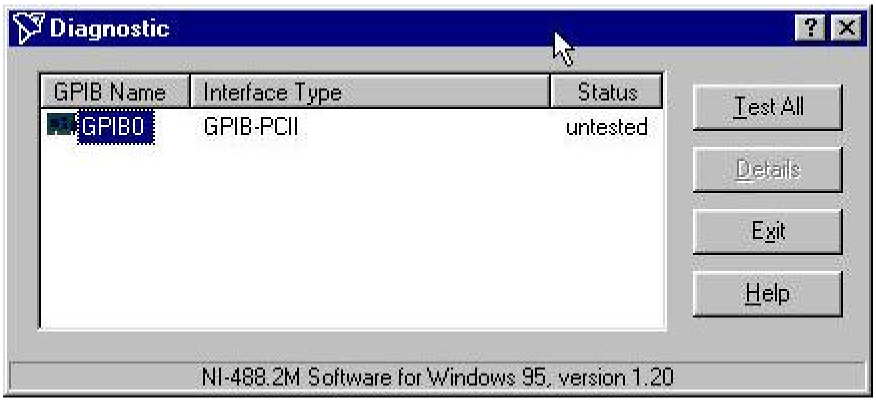
Parallel Resistor value: 0 1.00E+12

4.9 Recall / Save Setup

As a whole, the program incorporates a large number of options for data acquisition, plotting and analysis, most of which can be configured by the user within the various modules. Any given experimental setup will require customisation of many of these options. It would be highly undesirable if the program required the user to reset these values every time that it was run. Therefore, the majority of the options available to the user have been incorporated within a configuration file (default config.txt) which is loaded automatically each time that the program is re-started (as described above). A configuration file can be created with the existing settings simply be selecting the *Save Setup* action. Also, it is possible to edit a configuration file using any word processor, since it is formatted as standard ASCII text. Different program settings can be loaded at any time by choosing the *Load Setup* action from the front panel, which reads in any selected configuration file.

4.10 Hardware Support and Setup**

The hardware systems developed at NPL and the University of Manchester are both based around a Pentium-class PC with a National Instruments IEEE-488 interface card (e.g. GPIB-PCII). Both of these systems initially utilised a DSO (Digital Storage Oscilloscope). The software was later expanded to include an A/D card. The IEEE-488 controller cards supplied by National Instruments are provided with diagnostic software that can be used to check the function of the device:



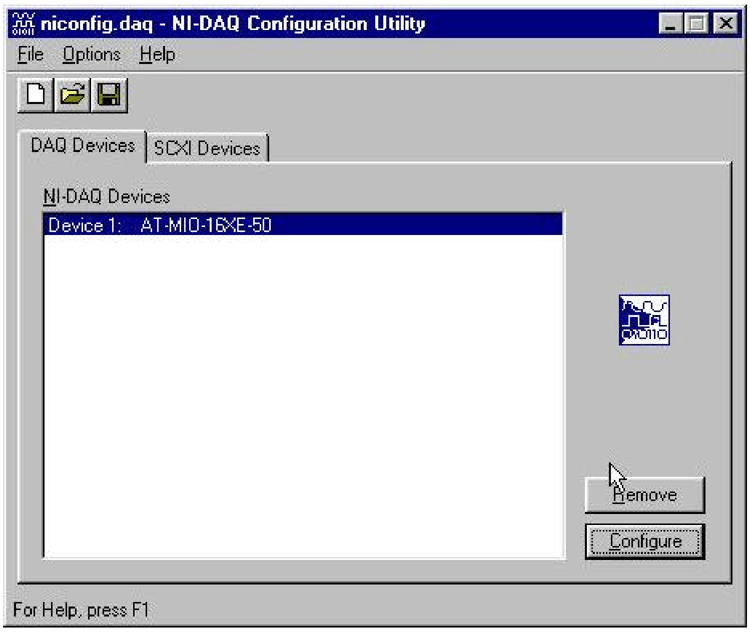
GPIB Name	Interface Type	Status
GPIB0	GPIB-PCII	untested

NI-488.2M Software for Windows 95, version 1.20

Such a controller card is necessary only if software control of the function generator and an external data capture device (i.e. DSO) is required. In the event that the drive signals are configured manually (e.g. for continuous AC cycling) and an A/D card is used for data capture, an IEEE-488 controller card should not be necessary.

Regarding the signal sources, almost any combination of instrumentation could be used to monitor the applied voltage, induced current, and induced displacement as long as a voltage is produced that is directly proportional to the measurand. The conversion factors should all be entered into the program within the *Data Acquisition* module.

When using an A/D card, it is necessary that the hardware configuration corresponds to the information used in the data capture routines. For example, the National Instruments DAQ Configuration Utility can be used to configure a given A/D card as ‘Device 1’:



This device number should then correspond to that selected in the Configure A/D Card Settings module (see section 4.7.3). The hardware connections to the A/D card should also correspond to the ‘Input Configuration’ defined in the same module.

4.11 Printing

There are no specific printing routines for the various subroutines in the software, however a printed copy of any panel in the software can be printed using the *File*, *Print* option available on the Windows menu bar of all panels. However this will print out the complete window. For more flexible output it is recommended that the data be exported, using the various *Export Data* options and loaded into a more versatile graphing package such as Excel.

5. References

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6. Appendix

6.1 Installing the software

6.1.1 Requirements

This software has been written and tested on systems running Microsoft Windows 95 and should be able to run on any PC running Windows 95, although a high specification machine is preferable. Most of the testing has been done on a 150 MHz Pentium PC and 32 MB of RAM, but it will run satisfactorily on a 100 MHz Pentium with 16 MB RAM. It will not work with Windows 3.1. It has not been fully tested with Windows 98 or Windows NT.

6.1.2 Installing the PEHys software

The software should run the main menu when the CD is placed in the drive, and there is an option on the main menu page to install the software. However should this fail to occur the software can be manually installed using the following procedure.

Use explorer to find the file \disks\setup.exe on the CD-ROM and double click on it, or alternatively use the Start, Run, (CD-ROM drive letter):\disks\setup.exe.
The setup program gives the option to install the software anywhere using browse, with the default location being C:\Program Files\PEHys. When the location has been chosen press Finish. The installer will also install the National Instruments Labview Run-Time engine. Should the installation fail before the LabVIEW run-time is installed this component can be separately installed by running the installation program (CD-ROM drive letter):\disks\RunTime\setup.exe.

6.1.3 Running PEHys software

The installation program will set up a program group called NPL PEHys, and the software can be run by using Start. Programs, PEHys, PEHys.exe.
When the program has been started it will display a licence agreement, followed by a request for a configuration file, Peconfig.txt. This file is located in the same folder as PEHys.exe. See the appendix for the contents of this file and how it affects the software.

6.1.4 Uninstalling the PEHys software

To uninstall the NPL PEHys software there are two components that need to be removed,

1) NPL PE loop software
   There is an uninstall program where the PEHys software is installed. The default installation occurs in \Program Files\PEHys, so the uninstall program will be \Program Files\PEHys\uninst.exe. Either use Start, Run C: \Program Files\PEHys\uninst.exe or go to the directory with explorer and double click on uninst.exe. Ignore any messages regarding erasing read only files and press yes.
2) Labview 5.1 Runtime Engine
   To remove this part run Start, Settings, Control Panel, Add/Remove programs and select NI LabVIEW Run-Time Engine 5.1. Click Add/Remove to remove this software. Removing this software may cause other Labview software not to run, if in any doubt leave this section installed.

6.2 Some Example files

6.2.1 File: Capb.txt

This file contains 3 PE loops taken at 10, 100 and 500 Hz of a low loss polypropylene capacitor in parallel with a high voltage resistor. This file can be used to explore the Parallel CR simulation section of the software.

1) Load the software and use “Read Data Files”, “Read New Files”, and choose the file “capb.txt” which should be in the Data directory.
2) There are 3 sets of data in the file (see field “No of data sets in file”), each taken at a different frequency. To select the second curve (100Hz) enter the number 2 in the field (Which data sets do you require from this file?). And then press OK. Be sure not to enter any other characters such as space or carriage return after the number or the program will crash. (see troubleshooting).
3) Return to the main menu by pressing “Exit” on the Read Data Files subroutine.
4) The Data can now be viewed using “Show Plots” or analysed in the “P-E Analysis” section. If the curves are not displayed see troubleshooting section.
5) To calculate simulated P-E loops select “Data Acquisition”.
6) Select “Capture”. On the Rayleigh Law or Parallel CR button select Parallel CR. The value of the capacitor can either be set by choosing Capacitance or Permittivity. Choose the Capacitance option and enter the following values, resistance 1.3e+7, capacitance 0.5, voltage 460, frequency 100Hz, and choose sine wave. Press OK to proceed.
7) The PE loop should be displayed, and the current-time waveform, however the field waveform will be a straight line. This is because the acquired waveforms are all on the same full scale and simulates the data seen on an oscilloscope screen. To expand the data experiment by changing the current gain from 1e+6 to 1e+3, and repeating the “Capture” process above. The field and current waveforms should now both be visible. The strain waveform will now be visible as a straight line. This is because there is no strain channel in the Parallel CR simulation. Switch the P-E P-S-E button to P-E, and repeat the capture process. There should now only be two waveforms present, field and current.
8) There should be one data set in memory (the experimental data loaded from capb.txt). Press “Add data to memory” to store the simulated data, and the no of data sets in memory should rise to 2.
9) Press “exit” to return to the main menu.
10) The Data can now be viewed using “Show Plots” or analysed in the “P-E Analysis”. The two curves, simulated (red) and experimental (blue) should be almost identical.
11) This process can now be repeated for the 10Hz case, either by adding onto the two PE loops stored in memory, or by clearing the memory and starting again.
12) To clear memory select, “Read Data Files”, “Clear Data”.
13) To examine the 10Hz data, load curve number 3 from capb.txt, and to create simulated data use the identical settings in step 6 except using a frequency of 10Hz.

6.2.2 File: PC5H_13.hyz

This file contains a series of 30 PE loops obtained experimentally on a PC 5H material all taken at 1Hz, with fields increasing from 0.05 to 3.5kV/mm. This file can be used to investigate the Rayleigh law simulation subroutine of the software and examine how the behaviour deviates from the Rayleigh law at high fields.

1) Load the software and use “Read Data Files”, “Read New Files”, and choose the file “pc5H_13.hyz” which should be in the Data directory.
2) There are 30 sets of data in the file (see field “No of data sets in file”), taken at increasing voltages. Select the ninth curve (400volts) enter the number 9 in the field (Which data sets do you require from this file?). And then press OK. Be sure not to enter any other characters such as space or carriage return after the number or the program will crash. (see troubleshooting).
3) Return to the main menu by pressing “Exit” on the Read Data Files subroutine.
4) The Data can now be viewed using “Show Plots” or analysed in the “P-E Analysis” section. If the curves are not displayed see troubleshooting section.
5) To calculate simulated P-E loops select “Data Acquisition”.
6) Select “Capture”. On the Rayleigh Law or Parallel CR button select Rayleigh Law. Enter the following values, relative permittivity 3030, alpha 7e-3, voltage 400, frequency 1Hz, and choose sine wave. We are not interested in the strain channel so leave the d_{33} at 600 and d_{33} alpha at 0. Press OK to proceed.
7) The PE loop should be displayed, the current-time waveform, however the field and strain waveform will be comparatively small. This is because the acquired waveforms are all on the same full scale and simulates the data seen on an oscilloscope screen. To expand the data experiment by changing the current gain from 1e+6 to 1e+5, and hide the strain data by switching the P-E P-S-E button to P-E. Then repeat the “Capture” process above. The field and current waveforms should now both be visible.
8) There should be one data set in memory (the experimental data loaded from pc5H_13.hyz). Press “Add data to memory” to store the simulated data, and the no of data sets in memory should rise to 2.
9) Press “exit” to return to the main menu.
10) The Data can now be viewed using “Show Plots” or analysed in the “P-E Analysis”. The two curves, simulated (red) and experimental (blue) should be almost identical. On close examination of the current time curves there is reasonable agreement on the positive voltage side, but there is a larger deviation on the negative going cycle. This is because the experimental data comes from a poled sample which has a directionality. The Rayleigh law will always predict symmetrical negative and positive behaviour.
11) This process can now be repeated for the lower and higher field curves, either by adding onto the two PE loops stored in memory, or by clearing the memory and starting again.
12) To clear memory select, “Read Data Files”, “Clear Data”.
13) To examine more data use “Read Data Files”, “Read New Data”.

6.2.3 File: Rayleigh.txt

This file contains some simulated PSE data obtained using the current PE loop software and saving the data as if it were experimental curves. The data simulated is at 100Hz on a 10mm diameter 1mm thick disc, with the Rayleigh law parameters permittivity=3000, aplha=5.0e-3, d_{33}=600 and d_{33} alpha=5.0e-4. There are 5 loops at voltages from 200 to 1000 volts. The file can be used to investigate the analysis routine in more detail, and the effect of d_{33} alpha on the piezoelectric coefficient and piezoelectric loss tangent.

1) Load the software and use “Read Data Files”, “Read New Files”, and choose the file “rayleigh.txt” which should be in the Data directory.
2) There are 5 sets of data in the file (see field “No of data sets in file”), taken at increasing voltages. Select all the curves, enter the number 1 2 3 4 5 in the field (Which data sets do you require from this file?). And then press OK. Be sure to separate each number with a space and not to enter any other characters such as space or carriage return after the last number or the program will crash. (see troubleshooting).
3) Return to the main menu by pressing “Exit” on the Read Data Files subroutine.
4) The Data can now be analysed in the “P-E Analysis” section.
5) If the curves are not displayed see troubleshooting section.
6) To view the results for the individual curves change the index number, either by pressing the up and down arrow, or by entering a number. All the parameters for the PE loop will be displayed. Careful that this index starts at zero, so PE loop 1 will have an index of 0, and for 5 curves the last index is 4. For a value of index greater than the number of PE loops all the parameter boxes will be ‘greyed out’.
7) The parameters for all five PE loops can be saved for retrieval into say a spreadsheet by selecting “Export Data” button. The data is in ASCII text format.
8) The effect of using RMS rather than peak to peak values can be investigating by selecting this option. In order for the changed option to come into effect the “Replot” button must be pressed after each change. If the data is exported for each case the differences can be quantified. Similarly the effect of data smoothing can be investigated by selecting “Plot Options” to change the data smoothing parameters.

6.3 File Formats

6.3.1 Configuration File : Peconfig.txt

The following file listing is the peconfig.txt file that comes with the PEHys software, should any changes be accidentally made to the file causing errors this version, found on the CD should return normal operation. The configuration file is broken down into several sections, some of which have little or no effect on the operation of the hardware control disabled version supplied with this report.

New versions of this file can be created by using the “Save Setup” command from the main menu, and loaded using “Recall Setup”. There is limited error checking on loading this file so errors in the file may not be immediately obvious until unexpected results occur in the output.

```
*** DATA ACQUISITION OPTIONS ***
```

All the items prior to *Serial port* in this section will affect the operation of the software. A common mistake is to load a file other than peconfig.txt which may lead to gains of zero, and number of points acquired zero. This will only affect the data acquisition section of the software and should not affect the loading previously saved of data files and subsequent plotting and analysis.

The Ageing measurement times is used to automatically capture P-S-E loops at a series of fixed times. This will not work in the hardware disabled version.

*** FUNCTION GENERATOR OPTIONS ***
This section deals with data capture using a function generator to generate the applied voltage signal and has no affect on operation of the hardware disabled version.

*** SMOOTHING/FILTERING OPTIONS ***
These section affects the values in the “Filter Options” sub section of “Plot Options” in either “P-E Analysis” or “Show Plots”. These will only effect the data if the smoothing option has been selected, either by switching the button or having the value TRUE in Waveform smoothing (boolean):.

*** PLOTTING/ANALYSIS OPTIONS
These values affect the way the zero crossover is found in order to identify a single hysteresis loop, and also switch on the correction factors for using a sense resistor to measure current. These options can be accessed either through “Analysis Options” on the main menu or the “Plot Options” sub menu of either “P-E Analysis” or “Show Plots.

****** DATA READ OPTIONS ***
The contents of this section can change the operation of the current version. Obviously the number of data sets and points should not be less than the data files that are being loaded or captured. These number affect the amount of memory needed for the program to store data, and can be reduced if the program reports memory errors, although obviously the amount of data allowed will be reduced.

*** A/D Card Options ***
This section deals with data capture using a National Instruments A/D card and has no effect on operation of the hardware disabled version.

PEHys Configuration File
NPL/DTI CAM7 Project
*** DATA ACQUISITION OPTIONS ***
Number of points required:
1200
Voltage divider:
1.000000E+3
Displacement gain (Volts/micron):
1.000000E+0
Current gain (Volts/amp):

1.000000E+6
Selected current gain (integer 0..27):
18
Specimen thickness (mm):
1.000000
Specimen diameter (mm):
10.000000
Serial port (integer):
1
SR570 current amplifier ? (boolean):
TRUE
Input device (integer 0..2):
2
GPIB address (DSO):
GPIB::4
Ageing measurement times (minutes):
0 0.5 1 2 3 5 7 10 15 20 30 40 *55 70 100 150 200 300 400 550 700 850* *1000*
*** FUNCTION GENERATOR OPTIONS ***
Unit (integer 0..2):
0
Duty cycle:
50
Offset:
0.000000
Frequency (Hz):
20.000000
Amplitude:
0.200000
Waveform shape (integer 0..15):
1
Burst mode (integer 0..2):
1
Burst rate (Hz):
10.000000
Burst count (integer):
2
Burst phase:
0
Trigger (integer 0..2):
2
GPIB address (generator):
GPIB::11

*** SMOOTHING/FILTERING OPTIONS ***
Waveform smoothing (boolean):
FALSE
Filter Rank (integer for averaging routine):
6
Select filter type (integer 0..1):
0
Windowed filter type (integer 0..3):
0
Window (integer 0..8):
1
Number of taps (integer):
50
Pass frequency (Hz):
200.000000
Stop frequency (Hz):
1000.000000
Sampling frequency (Hz):
1000.000000
*** PLOTTING/ANALYSIS OPTIONS ***
Threshold value (%):
1.000000
Start search (integer):
0
Sense resistor correction (boolean):
FALSE
Conduction correction (boolean):
FALSE
Plot type (integer 0..7):
0
Start zero (integer):
1
End zero (integer):
3
Find amplitude switch (integer 0..1):
0
PE/PSE switch (boolean):
FALSE
*** DATA READ OPTIONS ***
Maximum number of data sets (integer):
30
Maximum number of points (integer):
2500
Maximum number of zeros (integer):

30
Strain zero analysis option (boolean):
TRUE
*** A/D Card Options ***
Device number (integer):
1
Pretrigger Scans (integer):
0
Trigger edge (integer 0..2):
2
Time limit / s (real):
50.000000
Applied voltage channel (integer):
0
Voltage channel limits (integer 0..3):
3
Induced current channel (integer):
1
current channel limits (integer 0..3):
3
induced strain channel (integer):
2
strain channel limits (integer 0..3):
3
Input configuration definition Channel0 (Coupling, input):
1 2
Input configuration definition Channel1 (Coupling, input):
1 2
Input configuration definition Channel2 (Coupling, input):
1 2
Number of scans to acquire (integer):
1200
Scan rate (per second):
5000.000000

6.3.2 P-E and P-S-E Data Files

The format for the data files is ASCII text and the contents of each line are given below. The file names can have any extension name, but it is convenient to call them *.txt* so that they can be viewed easily with Notepad or WordPad in Windows95. P-E files are purely field and current data, whereas P-S-E files also include the strain channel.

P-E Data Files

Line	
1	Ferroelectric hysteresis data file (+version details)

2	NPL/DTI CAM7 project
3	Data Type: *P-E*
4	Specimen details / run information:
5	*Info line 1*
6	*Info line 2*
7	*Info line 3*
8	*Info line 4*
9	Specimen geometry (thickness and diameter / m):
10	*Thick Diam*
11	Generator details (frequency, wave, burst mode):
12	*frequency wave type burst/continuous*
13	Filter details:
14	*Low pass High pass*
15	Number of data sets and number of points per set:
16	*No_sets No_points*
17	Data:
18	*Set[1] Age_time[1] Current_gain[1] Volts_gain[1]*
19	*t[1,1] Volts_E[1,1] Volts_I[1,1]*
20	*t[1,2] Volts_E[1,2] Volts_I[1,2]*
21	.
22	.
.	*t[1,N] Volts_E[1,N] Volts_I[1,N]*
.	*Set[2] Age_time[2] Volts_gain[2] Current_gain[2]*
.	*t[2,1] Volts_E[2,1] Volts_I[2,1]*
.	*t[2,2] Volts_E[2,2] Volts_I[2,2]*
.	.

P-S-E Data Files

Line	
1	Ferroelectric hysteresis data file (+version details)
2	NPL/DTI CAM7 project
3	Data Type: *P-S-E*
4	Specimen details / run information:
5	*Info line 1*
6	*Info line 2*
7	*Info line 3*
8	*Info line 4*
9	Specimen geometry (thickness and diameter / m):
10	*Thick Diam*
11	Generator details (frequency, wave, burst mode):
12	*frequency wave type burst/continuous*
13	Filter details:
14	*Low pass High pass*
15	Number of data sets and number of points per set:
16	*No_sets No_points*
17	Data:
18	*Set[1] Age_time[1] Current_gain[1] Volts_gain[1] Strain_gain[1]*

19	*t[1,1] Volts_E[1,1] Volts_I[1,1] Volts_S[1,1]*
.	*t[1,2] Volts_E[1,2] Volts_I[1,2] Volts_S[1,2]*
.	.
.	.
.	*t[1,N] Volts_E[1,N] Volts_I[1,N] Volts_S[1,N]*
.	*Set[2] Age_time[2] Volts_gain[2] Current_gain[2] Strain_gain[2]*
.	*t[2,1] Volts_E[2,1] Volts_I[2,1] Volts_S[2,1]*
	t[2,2] Volts_E[2,2] Volts_I[2,2] Volts_S[2,2]
.	.
.	.

6.4 Troubleshooting

Unable to locate the LabVIEW runtime engine?
The Labview runtime engine has not been properly installed during the installation. This component can be separately installed by running the setup program in the disks\RunTime directory on the CD.

Program hangs when I close a window?
It is possible to exit individual windows using the normal windows exit modes such as clicking on the x in the right hand corner. However if this is done while the program is expecting input within this window then it is impossible to continue. To prevent this the user should exit each submenu using the required continuation button, usually *Exit*. To recover from this condition the user will need to exit the program, by clicking File, Exit, and then restart the program.

Program hangs when loading data from a file?
When loading files using the “Read New Files” subroutine be sure not to enter any other characters after the final number. A list of numbers should be entered in increasing numerical order separated by spaces, but characters such as space or carriage return after the final character will cause an endless loop. Decreasing numerical sequences will also cause the same endless loop. The Data set being read will keep increasing endlessly. The user will need to exit the program, by clicking File, Exit, and then restart the program.

Incorrect results for different sample sizes?
The data structure for the saved files is such that the sample dimensions are held at the beginning of the file and all the rest of the data in the file will implicitly be assigned the same dimensions. Therefor although it is possible to mix results from different samples in one file, this will lead to incorrect results if they are of different dimensions.

No curves or only partial curves on graph?
Sometimes the scaling on the graphs may not display the curve correctly. The simplest way to reset the scaling is to press the buttons marked X and Y underneath the graph in question. The graph can also be zoomed using the magnifying glass button, and moved by using the hand button.

No curves on graph?

A common mistake is to forget to click “Add data to memory” after data capture. The Data acquisition will always display the last data set captured, but this has to be added to memory for use in the rest of the program. The number of data sets in memory should increase by one when the “add data to memory button” is pressed.

Strange results when doing data capture/simulation?

The configuration file peconfig.txt is a text file containing information such as current gain, voltage gain etc, which is loaded at the beginning of the program. There is limited error checking on this file and it is possible to load any file at this point, and the software will use whatever settings it determines from this file. This is indicated by current gains of zero, and number of points required 0. To reload the correct configuration select “recall setup” on the main menu, and load the file Peconfig.txt. If this file has been corrupted by accidentally saving with “save setup”, then reload the original peconfig.txt data file from the data directory on the CD.

Memory Full Problems?

Try closing down any other applications that you may have running. Decrease the amount of data loaded by reducing the number of curves loaded simultaneously, and reduce the size of simulated data by reducing the number of points required.

6.5 Restrictions and Copyright

6.5.1 Version 1.9 CD release

This software was designed and developed by David Hall at the University of Manchester, and Mark Stewart at the National Physical Laboratory as part of the UK DTI funded project CAM7. In this version the hardware control subroutines have been disabled and replaced by simulated data. If you are interested in the version with hardware control please contact the authors at NPL.

6.5.2 Licence Agreement

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[**] The hardware control subroutines in this version have been disabled, so the following section may not function as described, however these notes have been left to summarise the full version.