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MEASUREMENT OF STRAIN AND POLARIZATION IN PIEZOELECTRIC AND ELECTROSTRICTIVE ACTUATORS

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ABSTRACT

This paper describes an economical measurement system that was developed to characterize piezoelectric and electrostrictive materials and actuators for smart structure systems. Strain measurement is performed using a linear variable differential transformer (LVDT). Absolute displacement is determined over a ±1.25 mm range with 16-bit resolution. The system's high-voltage amplifier has a peak voltage range of ± 4,000V, allowing measurements to be performed on devices with either thin or thick active layers. Polarization measurement is based on the Sawyer-Tower circuit. High-voltage protection devices prevent damage to major system components from unwanted breakdown events in the device under test (DUT). The system software offers high versatility in waveform generation and test sequencing. Test results are presented for both hard and soft piezoelectric ceramics over a broad range of test conditions below and above the coercive field limit of the active materials.

INTRODUCTION

In order to make effective use of piezoelectric or electrostrictive actuators in smart structure systems it is necessary to accurately measure the actuator strain vs. field characteristics. These characteristics generally display non-linearities, especially in the case of electrostrictive materials, and also exhibit hysteresis, temperature and frequency variation and aging effects. Accurate characterization is needed both for quality control in actuator manufacturing and for design and optimization of the actuator control system. Polarization vs. field studies yield additional information about the material properties and, in particular, provide the designer with information on losses, charge storage and the impedance characteristics needed for designing the driving electronics.

Laboratory strain measurements are often performed using optical techniques involving interference effects [1,2] or optical levering [3]. While such techniques can provide sub-nanometer resolution they also require special sample preparation to affix a mirrored surface. In addition, the overall measurement procedure can be too tedious for high volume testing. On the other hand, by using a linear variable differential transformer (LVDT) as the displacement sensor, it is possible to design a simple and robust measurement system that uses as-manufactured samples not requiring a surface mirror or other special features. The SS50 strain measurement system uses a LVDT displacement sensor and has a spatial resolution of several tens of nanometers. While the resolution is not as fine as that obtainable with an optical system, it is nevertheless adequate for the characterization of typical high-strain piezoelectric or electrostrictive materials and of complete actuation devices such as multi-layer or bending-mode actuators. A simple sample holder can provide for easy loading and unloading of a wide variety of samples and can be used for simultaneous or sequential strain and polarization measurements.

In this paper the SS50 strain measurement system is described, and measured data is presented. The SS05 polarization measurement system is also described and, measured polarization data is presented for SensorTech BM400 piezoelectric material.

STRAIN MEASUREMENT SYSTEM

The SS50 strain measurement system uses a LVDT with movable nickel-iron core that is suspended in a non-contacting (ie. frictionless) manner in the LVDT main body. The core is mounted on a non-magnetic threaded rod that is attached, on the top side, to a miniature linear bearing slide to ensure vertical-only motion and, on the bottom side, to a probe that rests on the DUT. The ± 6 mm movement range of the linear bearing slide also prevents the probe from sliding completely through the LVDT main body when not resting on a sample. All of the above are mounted on a vertical movement stage that can be locked at a range of heights to accommodate a variety of actuator sizes and sample mounting arrangements. The overall measurement unit rests on sorbothane bumper mounts to reduce vibrational noise.

The measurement unit of the strain measurement system is shown in Fig. 1. The figure shows a particular sample mounting arrangement in which power is delivered through a probe that is attached to the lower end of the LVDT moving rod and rests on top of the sample. The sample is placed in an open metallic dish that is electrically grounded and is resting on a heated stage. The dish may be filled with high resistivity oil for arc suppression. The high voltage probe is electrically insulated from the LVDT moving rod and magnetic core. The heated stage is removable and alternative arrangements for sample mounting or power delivery may be used as required.

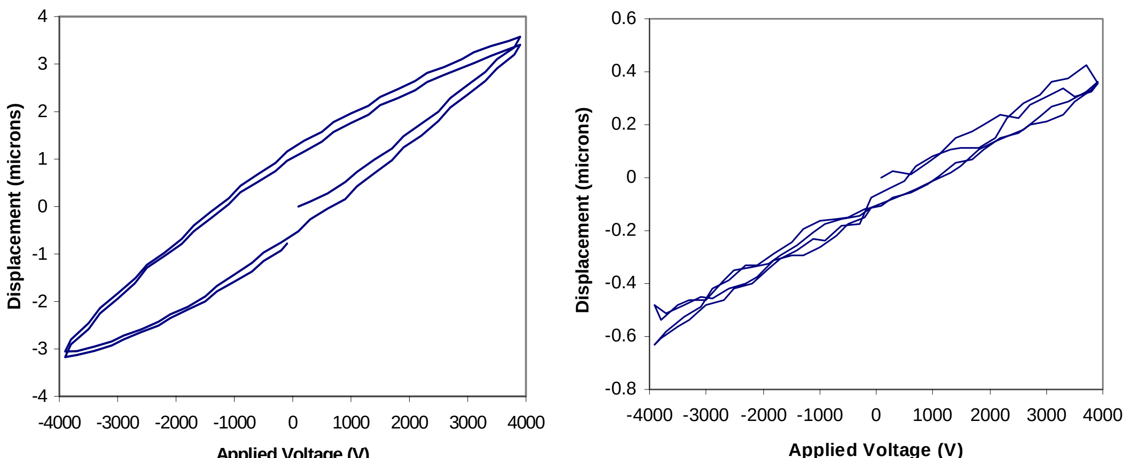
Figure 1. SS50 strain measurement unit.

The LVDT consists of a central primary coil and two co-axial secondary coils placed in close proximity on either side. The movable magnetic core provides a path for magnetic flux to link the coils. The primary coil is energized with an external 3kHz source and the secondary coils are connected in series with each other so that the two induced voltages are of reverse polarity. Zero voltage is produced when the movable core is precisely centered in the LVDT main body. However when the core is displaced, the voltage increases in the secondary coil toward which the core has moved. The differential voltage varies linearly with core position over a broad range.

The LVDT in the SS50 strain measurement system is connected to a signal conditioner that generates the 3kHz primary signal and uses synchronous demodulation and filtering to convert the rms value of the secondary output to a DC displacement signal. The output signal has a nominal 250 Hz (-3dB) frequency response and a nominal range of ± 1.25 mm, over which the non-linearity of the response is less than 0.25%.

The voltage signal that is delivered to the sample is generated by a 12-bit D/A converter associated with the data acquisition card (DAC) that is supplied with the system. The same DAC also has 16-bit A/D converters for receiving the LVDT output signal with a maximum I/O sampling rate of 20 ks/s. The drive signal is amplified by a Trek 609E high-voltage amplifier having a maximum voltage range of ± 4,000 V. The drive signal is currently configured as a staircase waveform that approximates a triangle wave. The staircase waveform allows for substantial signal averaging for noise reduction at each voltage step. When integrated with a polarization measurement system, the option will be available to use a continuous sine wave drive signal. Further study is needed to compare the noise response of the strain measurement system using the latter approach.

The software for the SS50 strain measurement system stores both the voltage and displacement values as well as field and strain values obtained using the known sample thickness. Fig. 2 shows displacement vs. voltage hysteresis loops measured with the SS50 for a voltage range of -4,000 to + 4,000 V. Results are shown for both a high-strain “soft” PZT ceramic element and a low-strain “hard” PZT ceramic element. In the first case the sample was a disk with 4 mm thickness, so that the maximum field was 1MV/m. In the second case the sample was a rectangular bar with 12 mm length, so that the maximum field was 0.33 MV/m. The sweep period in both cases was 30 s and two consecutive sweeps were performed. Wide hysteresis loops and a maximum displacement in excess of 3 :m were observed with the high-strain sample. For the low-strain sample, the maximum displacement was about 0.5 :m and the system noise is more evident in relation to the displacement signal. Hysteresis is noticeably reduced. If a linear fit is made to a single sweep from -4,000 to +4,000 V (Fig. 2b), the random deviations from the fit have an rms value of approximately 20 nm. This is near the digital quantization limit but may also involve contributions from vibrational or electronic noise.



a) b)

Figure 2. Displacement vs. voltage curves measured at room temperature using the SS50 strain measurement system, a) result for high-strain “soft” PZT ceramic, b) result for low-strain “hard” PZT. The voltage sweeps begin at 0V and initially increase in the positive direction.

POLARIZATION MEASUREMENT SYSTEM

The SS05 polarization measurement system uses a modified Sawyer-Tower circuit [4]. The system has been tested in breadboard form and the final printed circuit board and housing design are currently in progress. A block diagram of the overall system is shown in Fig. 3. The DUT is mounted in an external sample holder and is connected in series with a sampling capacitor C_S. The latter is housed in a small plug-in module that can be easily changed according to the capacitance of the sample. C_S must be chosen so that the sampling voltage is less than 10

V when the maximum voltage is applied to the DUT. In the case when a maximum voltage of 4,000 V is used, C_S should be at least 400 times larger than C_{DUT}.

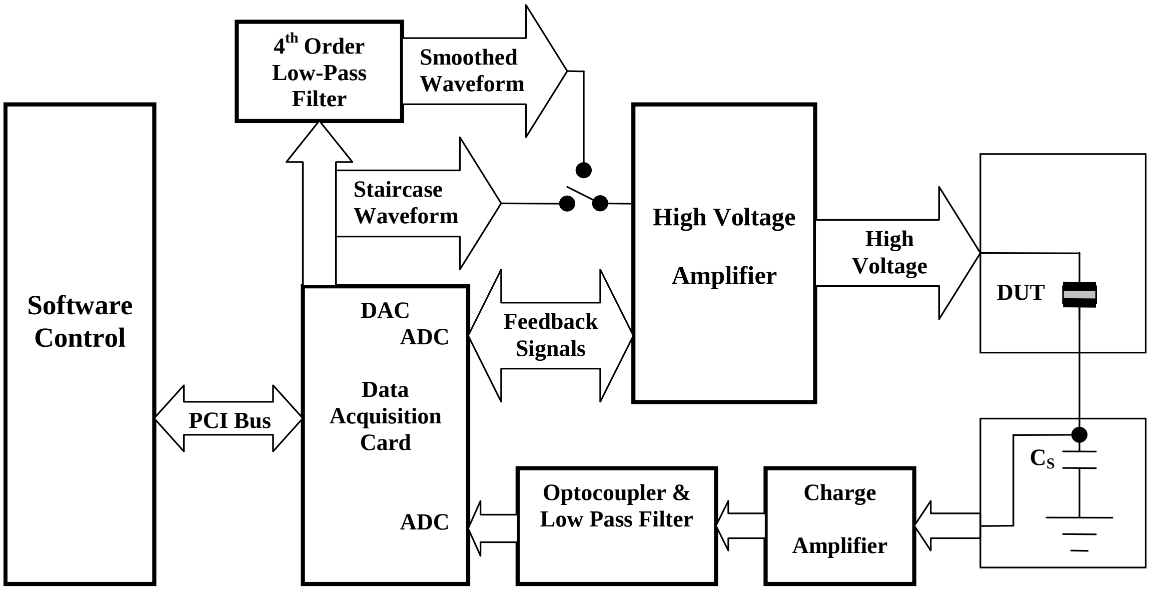


Figure 3. Block diagram of SS05 polarization measurement system.

The system employs optocouplers in order to protect the data acquisition card and control PC from high voltage spikes that might occur with a breakdown event in a defective DUT. The PC board uses plug-in sockets for any front-end components that may need replacement due to such events. The high voltage amplifier is a Trek 609E which has an analogue low-voltage output for monitoring the high-voltage signal. The monitor output signal is sampled by the system DAC.

The polarization system generates an analogue sine wave signal by generating a staircase sine wave approximation in the data acquisition card and passing it through a 4th order low-pass filter. The filtered signal then proceeds to the input of the high-voltage amplifier. This approach provides maximum versatility in controlling the drive signal and in designing sequential tests under software control. The strain and polarization measurement systems are configured to function as stand-alone units or as components in a combined strain/polarization measurement system, as shown in Fig. 4.

The polarization measurement system has recently been used to characterize hard PZT ceramics that are suitable for high-power sonar transducers. For this application it is necessary to determine the maximum field amplitude that may be used without depolarization-induced losses. This may be readily deduced from the area of electrical displacement vs. field (D vs. E) hysteresis loops [5]. For the case of typical piezoelectric ceramics, the dielectric constant is high enough that the electrical displacement is approximately equal to the polarization and P vs. E loops can be used for the same purpose. Disk samples of 0.38 mm thick SensorTech BM400 PZT ceramic were characterized by measuring P vs. E loops and determining the energy loss from the area in the loop. This was first performed with low electric field amplitude and was then repeated with progressively higher field amplitude. The measurements used a sweep frequency of 0.01 Hz and a sampling rate of 40 samples per second. Fig. 5 shows the energy loss per unit volume as a function of field amplitude. The inserts show the shape of the P vs. E loops at selected points in the characteristics. For low electric field amplitude the loops have a relatively simple and approximately symmetric shape. As the electric field increases beyond about 1.5 MV/m, the loops begin to bulge in the reverse polarity region due to the onset of depolarization. The energy loss then begins to increase more rapidly and very wide loops with high losses are observed in the high-field region.

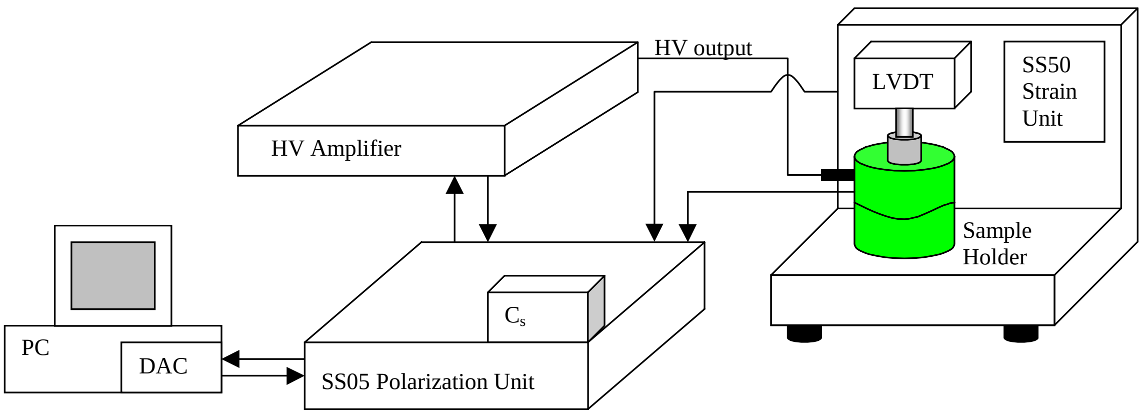


Figure 4. Combined strain and polarization measurement system.

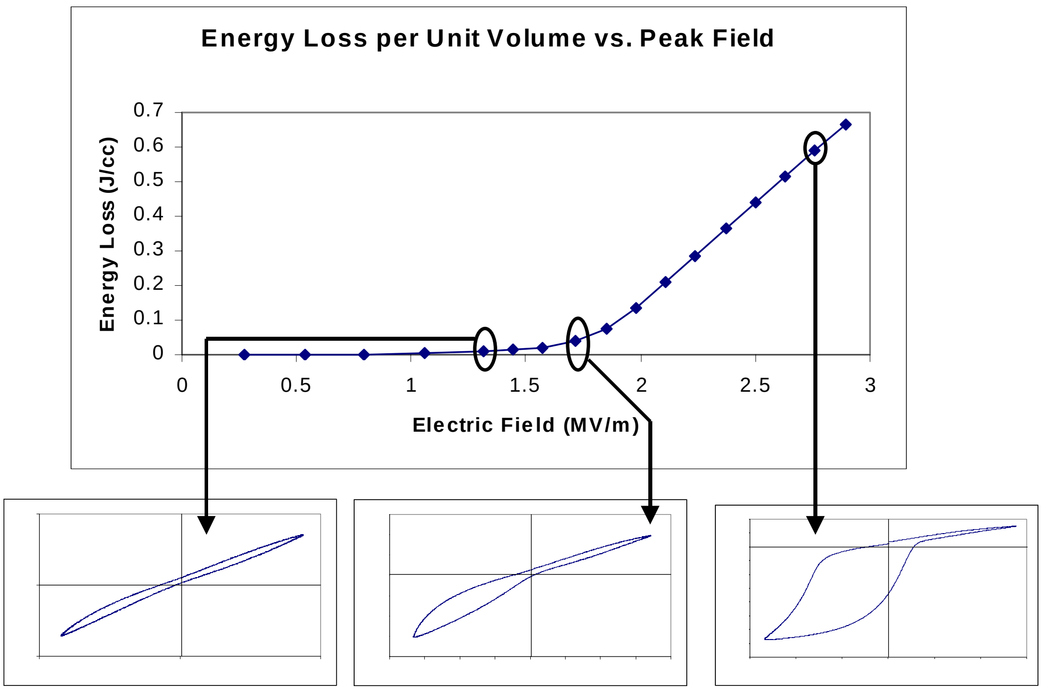


Figure 5. Energy loss per unit volume as a function of electric field amplitude for BM400 PZT ceramic. The inserts show the shapes of the P vs. E hysteresis loops at different points of the characteristic.

CONCLUSIONS

Systems have been developed to measure strain and polarization in piezoelectric or electrostrictive materials and actuators. The systems can be used for a wide variety of sample configurations without the need for special sample preparation. The systems can be configured for strain only, polarization only, or combined strain/polarization measurement.

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