Quantitative Measurement of Tribo-electric Charging Phenomena of Dielectric Materials

S. T. Beardsmore-Rust, P.Watson, R. J. Prance, C.J.Harland, H.Prance

***Abstract*—In this paper we discuss a new electrostatic charge imaging instrument, based around a 16 element array of novel, ultra high impedance electric field sensors, developed and patented at the University of Sussex. We report measurements taken on samples of Mylar®, Kapton® and PTFE sheet and demonstrate the imaging of the spatial charge distribution on these sheets which occurs as a result of tribo-charging, by an earthed lead and by a human finger. These measurements are compared with several published tribo-electric series, and by comparing our measurements taken on various samples and thicknesses of material, we show that it is possible to make quantitative measurements of tribo-electric charge density and therefore to establish a quantitative tribo-electric series in this way.**

***Index Terms*—Electrostatic measurements, Tribo-electric, Dielectric materials, Electrets, Electric field measurement**

I. Introduction

THE process by which charge can be built up on insulating materials as a result of rubbing or contact is known as tribo-charging. Through this process it is possible for very large voltages to be built up on these materials. This tribo-charging appears to be a combination of an effect due to movement, as well as an equilibrium effect[1]. Tribo-charging, as a phenomenon, is not well understood. One possible explanation often given is that a temperature gradient is formed between the rubbing and rubbed surfaces and that this gives rise to the movement based component of the charging effect[1]. Opinions are more widely divided on the cause of the contact electrification component of the charging, a comprehensive review of the field is given by Fuhrmann[2]

Industrial processes involving electrostatics are typically based around the controlled charging of particles and/or surfaces. There is often a requirement, therefore, to measure the charge on particles, or collections of particles, and a measurement involving a Faraday cup or Faraday pail is often used[3]. The charge density on an electret, or surface of an insulating material, can be measured using a dissectible capacitor[4] and is discussed and described recently by Sessler[5]. However, when a measurement of the spatial distribution of charge on a surface is required, a different technique is often employed. This typically involves bringing a low impedance field meter close to a charged surface, such that it represents the closest earthed object coupling to the surface charge. As a result, field lines will terminate on the electrode of the meter and a measurement will be made[6]. By moving this electrode, or applying some kind of aperture, it is possible to obtain a crude measurement of the spatial distribution of the charge. This technique, however, has limitations if more than one sensing electrode is to be used simultaneously. In this case, field lines will terminate on both electrodes, and the presence of a second electrode will compromise the measurement being taken by the other electrode, thereby making large arrays of this type of sensor an unattractive proposition.

We have previously published details of an ultra high impedance electric potential sensor (EPS)[7]. These sensors use a combination of established high impedance techniques such as bootstrap and guarding, as well as a means of supplying the DC bias current required by the amplifier to remain stable. As a result of these techniques, they achieve input impedance in the range of 10^{13} Ω and input capacitance in the range of 10^{-16} F. As a result of these characteristics they are capable of passively measuring very small changes and disturbances in electric field, without significantly affecting the field lines and distribution in electric potential. Details of the application of these sensors to a broad range of fields have previously been published, including electrophysiology[8], measurement of a human heart beat from distances of up to 40cm from the body [9], novel nuclear magnetic resonance NMR probes[10], non destructive testing of composite materials[11] as well as in a range of other fields [12-14]

Although a low impedance measurement is most often made to measure the spatial distribution of charge, other examples of high impedance measurements of this type do exist. Hughes and Secker published details of a two dimensional charge scanning instrument based on a high impedance measurement technique[15] and a comprehensive review of electrostatic measurement equipment and

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techniques, including some high impedance techniques, was published by Secker and Chubb[16]. We propose an extension of these techniques, using our EPS sensors, to create a spatial charge distribution imaging instrument. We show that using this design, it would be possible to extend the performance of the instrument to very high resolutions, simply by increasing the density of sensors in the linear array.

Here we report measurements taken on samples of Mylar®, Kapton® and PTFE sheet and demonstrate the imaging of the spatial charge distribution on these sheets which occurs as a result of tribo-charging, by an earthed lead and by a human finger. These measurements are compared with several published tribo-electric series[17], and by comparing measurements taken on various samples and thicknesses of material, we show that it is possible to make fully quantitative measurements of the tribo-electrically generated charge density and therefore to establish a quantitative tribo-electric series. This opens up the possibility of absolute, rather than simply relative, positioning of materials within a tribo-electric series using a repeatable and calibrated measurement technique.

We show that this charge distribution can be imaged, and that complex distributions of tribo-electrically generated charge 'drawn' on these materials with an earthed lead can be clearly identified. The nature of the sensors involved allows measurement at resolutions limited only by the density of the sensor array that it is possible to fabricate. Furthermore, if a CMOS process was employed, sensor arrays at arbitrarily high densities, and therefore arbitrarily high resolutions, become plausible. Since the measurement is totally non invasive, it is possible to measure and observe the decay of tribo-electrically generated charge, across time periods which vary between samples but are often in the order of many days.

II. METHODOLOGY

A conventional A4 flatbed scanner was disassembled and the control electronics removed, leaving only the mechanical components and stepper motor. Redesigned control electronics were added to allow Labview[18] control over the stepper motor. A National Instruments USB Data Acquisition card[18] was integrated into the system to allow easy data acquisition, and simple signal and data processing in Labview was used to control the instrument, obtain data, visualize it in real time and save data files for post processing using Matlab.

Two PCBs, each containing eight ultra high impedance EPS sensors were constructed, and attached to a PCB containing a l6 element linear array of electrodes. The electrodes each measured 6.5mm by 4.5mm and the exact layout and orientation is presented in figure 1. Details of the design and performance of these EPS sensors is discussed briefly in the previous section and has been published previously [7-14]. The electrode array measured 175mm across, and allowing space for the control electronics at each end of the scanner meant the distance travelled by the scanning head when triggered was 230mm, giving a total scanning area of 175mm by 230mm.

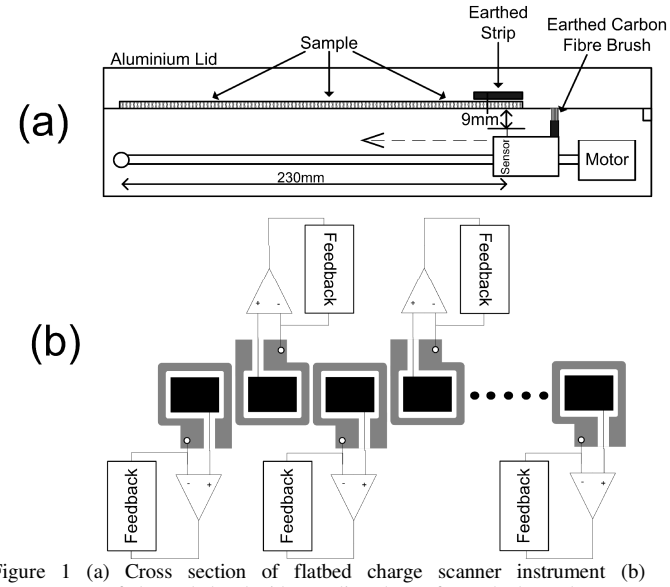

Figure 1 (a) Cross section of flatbed charge scanner instrument (b) Arrangement of electrode head with guarding shown for each electrode

A multiplexer was used to allow all 8 sensors to be quickly sampled by the 8 channel analog to digital converter within the National Instruments USB data acquisition module[18] which was integrated into the scanner control electronics. Guarding techniques were used to prevent cross channel leakage, provide some level of screening against noise from the surrounding electronics and improve the directionality of the sensors.

Control software was developed in Labview to create a virtual instrument, which moved the scanner head in fixed step increments, sampled all sixteen channels and then waited for a period of time long enough that the sensors could settle to their zero point. By repeating this process until the entire surface had been scanned, an image could be built up of the derivative of the charge distribution on the surface of the material. In this case, the image was made up by a 16 by 92 element array of data, however this resolution is restricted only by the step size and density in which it is possible to construct the sensors. The measurement system is illustrated in Figure 2.

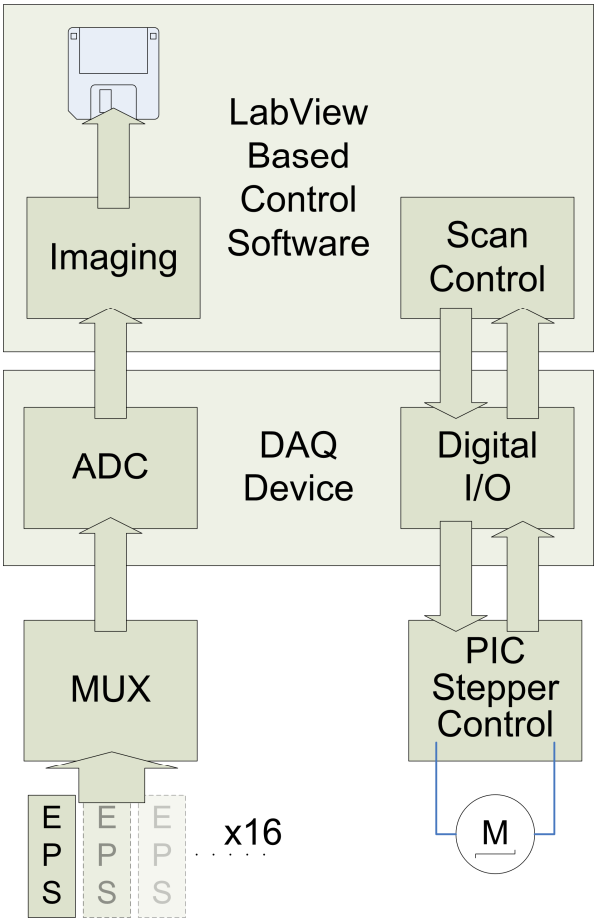

Figure 2. The charge imaging scanner system

Once data was collected, the nature of the measurement was such that the results represented the derivative of the charge on the surface, with each value giving the difference in charge between one point and the next. Therefore in order to obtain the spatial distribution of the charge, these values must be integrated, in one dimension, across the surface. This was achieved both using Matlab, as well as in real time in Labview, in order to visualize the charge distribution for each measurement. Equation 1, given here, describes the technique.

$$Q_x = \sum_{s=0}^{s=x} \Delta Q(s) = \int_0^x \frac{dQ}{dx} \qquad (1)$$

Very little screening was needed to achieve these measurements. An aluminium lid was added to screen against electrical noise and to ensure, where possible, that air movements within the laboratory did not affect the presence of charge. In practice this was not necessary other than during extended runs over 8 days where discharge of some materials was being measured.

No attempt was made to control temperature or humidity, which did not seem to have a major effect on shorter measurements (i.e. those taking less than 8 hours to complete). The scanner was operated in a busy laboratory environment in the presence of other equipment, movement and temperature changes.

A set of material samples were obtained, consisting of well specified sheets of Mylar®, Kapton® and PTFE. Several thicknesses of Mylar® were also obtained. Material dimensions are shown in Table 1. These samples were mounted in cardboard frames to ensure they remained rigid during measurement and to avoid handling.

Table 1 – Sample materials and dimensions

Material	Dimensions
PTFE	230mm x 175mm x 0.050mm
Kapton®	230mm x 175mm x 0.050mm
Mylar®	230mm x 175mm x 0.050mm
Mylar®	230mm x 175mm x 0.023mm
Mylar®	230mm x 175mm x 0.125mm
PVC	230mm x 175mm x 0.100mm
Acetate	230mm x 175mm x 0.070mm

A commercial charge measuring electrometer was connected such that the reference was common (ground), and the input of the electrometer was connected to a standard 3.5mm plug. The sample was mounted in the scanner and the lead was positioned within a short reach, before being zeroed. The lead was then drawn across the sheet, and as charge was deposited or removed from the surface of the sample, this was indicated on the electrometer. The sample was then scanned and the total amount of charge indicated by the electrometer used as a calibration factor to allow the measurements made by the scanner to be given in absolute terms (i.e. total charge in nanocoulombs). This value was found to be stable over time, and consistent between materials.

A carbon fibre brush was attached to the arm of the scanner in such a way that it would brush over a sample of material as the scanner made a measurement. Labview control software was then written which scanned each sample twice. Samples were first discharged, by placing them in front of an ionizing blower for several minutes. The scanner then passed the sensors across the sample, as described above, measuring the discharged state. In the process of this, the brush passed behind the scanner head, performing a repeatable tribo-charging process on the sample. The scanner then scanned a second time, this time measuring the quantity of charge added to the sample by the brush. This process was repeated several times to establish the repeatability of the charging process.

III. RESULTS

By measuring the discharged state of each sample, then taking a measurement of the charge deposited using the carbon-fibre brush charging method it was possible to obtain a very reliable and repeatable quantity of tribo-electric charging. Once these charged samples are scanned, the section charged

by the brush is clearly visible, and the image resulting from one such scan is shown in Figure 3.

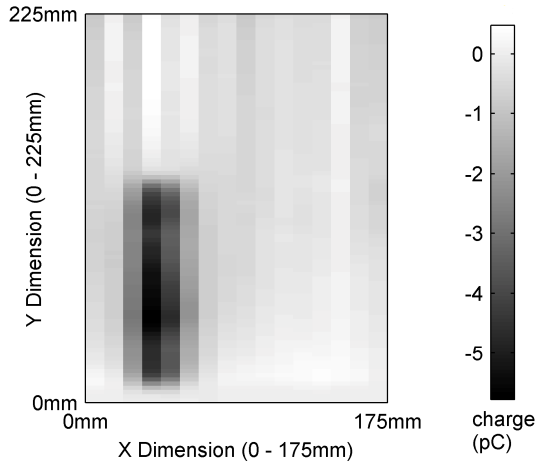

Figure 3. A Mylar sample imaged after being charged by the carbon fibre brush within the scanner

The charge was then summed over the full area of the sheet to give an indication of the total charge on the sheet. These values, as well as an error percentage calculated by dividing the standard deviation of the values by the mean are given in Table 2.

Table 2. Results of standardized tribo-charging process

Material	Thickness	Charge	$\sigma / \bar{x}$
PTFE	50µm	-20.0 nC	
	50µm	-18.9 nC	
	50µm	-18.3 nC	**+/- 4.5%**
Kapton®	50µm	-13.3 nC	
	50µm	-11.46 nC	
	50µm	-12.0 nC	**+/- 7.2%**
Mylar®	50µm	-1.44 nC	
	50µm	-1.317 nC	
	50µm	-1.36 nC	**+/- 4.5%**
Mylar®	23µm	-0.70 nC	
	23µm	-0.77 nC	
	23µm	-0.82 nC	**+/- 7.9%**
Mylar®	125µm	-1.09 nC	
	125µm	-0.9 nC	
	125µm	-1.08 nC	**+/- 10.45%**
PVC	100µm	-9.6 nC	
	100µm	-8.6 nC	
	100µm	-8.9 nC	**+/- 5.68%**
Acetate	70µm	+14.99 nC	
	70µm	+12.86 nC	
	70µm	+13.22 nC	**+/- 8.33%**

Having measured the amount of charge typically deposited using a repeatable standard measure of tribo-generated charge, the samples were then compared to several previously published tribo-electric series[17] in an attempt to compare our quantitative measurement of susceptibility to tribo-electric charging processes with previous results.

Table 3. Materials in order they appear on other tribo-electric series (Positive to Negative charging) and charge as measured by the charge imaging scanner.

Material	Mean charge after tribocharging
Acetate	+13.69 nC
Polyethylene terephthalate / Mylar®	-1.37 nC
Polyvinylidine Chloride / PVC	-9.03 nC
Kapton® (not present on published series)	-12.25 nC
PTFE/Teflon®	-19.06 nC

The results presented here mirror the relative positions of these materials on published series, but clearly also we are able to give a quantitative indication of charging and position within the series.

A second experiment was then carried out. In this case, a sheet of Mylar was first discharged, by placing it in front of an ionizing air blower. It was then mounted in the scanner and a letter 'Q' was drawn with an earthed cable. This was then imaged, the data integrated in Matlab and the result shown here in Figure 4, with figure 4a showing the raw integrated data and figure 4b showing data visualized after a piecewise bilinear interpolation has been applied in Matlab. The Q, drawn originally on the surface of the material, is clearly visible.

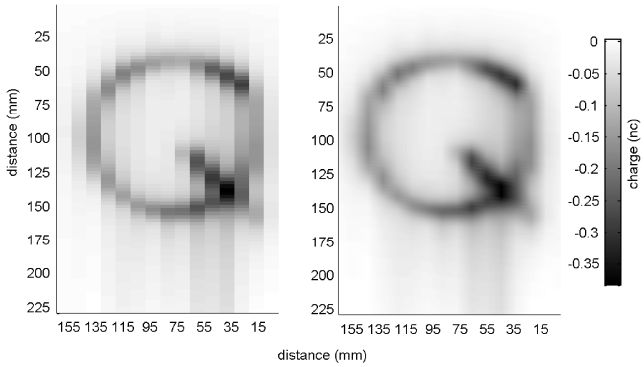

Figure 4 – charge deposited in the shape of a letter 'Q' using tribo-charging. (a) shows raw data after integration, (b) shows data smoothed using a bilinear interpolation is applied in Matlab to achieve smoothing

The ultra high impedance nature of this measurement meant it was possible to observe the discharging of these materials over long periods of time. Data was collected from a charged Mylar sheet, with scans taken continuously over an 8 day period, with each scan taking 3 minutes to complete and a new scan being initiated immediately after the previous one had finished. This allowed the comparison of the discharge time against a set of data collected only at sporadic points in time, with measurements made at daily intervals across a similar period of time. In this way we demonstrated that the measurement technique had no measureable effect on the

discharging of the samples.

As such, it was then possible to observe the discharging of materials. These values of time varied between materials, but ranged from several hours for Acetate, to several days for many of the other materials. The discharge of a letter Q on a sheet of Acetate over 8 hours is shown pictorially in Figure 5.

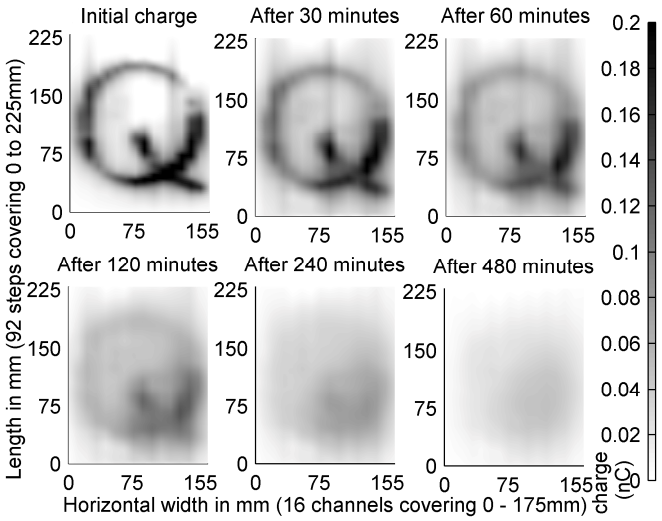

Figure 5. Discharge of a sheet of Acetate over 8 hours

The noise on the instrument was measured as being approximately +/-0.1pC peak to peak across a scan.

IV. Conclusions

In this paper we demonstrate an ability to perform a quantitative measurement of the ability of materials to become charged through contact electrification. If further safeguards were taken to ensure reliable results, notably ensuring temperature and humidity were strictly controlled, and possibly making use of a vacuum in which to carry out the charging and measurements, these techniques could allow for a fully quantitative tribo electric series to be developed. In comparison to previous studies, which often require multiple charging events in the order of 400 contacts to establish a reliable and measurable quantity of charge, we have shown repeatable and measurable results can be obtained using only a single charging event.

It appears that variation on charging of different thicknesses of Mylar® might be explained by the somewhat unknown nature of the tribo-charging technique. Since, in this experiment, thicker materials result in a larger force being applied vertically downwards counter to the brush as it moves across the surface, very thin materials such as the 23µm Mylar® tend to be significantly displaced by the brush and therefore charge less. A better arrangement might involve the samples being mounted against a rigid insulating material to ensure they were not displaced by the brush, which would hopefully ensure charging was more consistent across various thicknesses of material.

We have also presented the ability to measure the charge present on an insulating material as a result of contact electrification. Furthermore, we have shown that the spatial distribution of this charge can be imaged using the techniques outlined in this paper. The resolution of this image is dictated only by the density of sensors and electrodes which can be fabricated. With CMOS process based circuit integration this resolution could reach very high values.

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