Non-contact measurement of local conductivity variations in carbon fibre based composite materials

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Abstract. An ultra high input impedance sensor is used to monitor the electric field above a sample of carbon composite. The working distance, spatial resolution and diameter of the sense electrode are all of the order of 50 \( \mu \text{m} \). The sample is excited with an a.c. current over a range of frequencies up to 11 MHz. The resultant potential gradient gives rise to the electric field near the surface of the sample. Results are presented for different excitation frequencies showing the internal structure of the composite material. A gradient subtraction technique is used to enhance the variations in local conductivity.

1. Introduction

Electric Potential Sensor (EPS) technology has been developed at Sussex over a number of years for a wide variety of applications. These span the fields of body electrophysiology [1], security [2], nuclear magnetic resonance [3], forensics and materials testing [4]. EPS technology may be most easily understood by assuming that it behaves as a perfect voltmeter, with infinite input impedance, requiring no external bias current for stable operation. Previous publications on the microscopic imaging applications of EPS have focused on either using an a.c. potential drop method on stainless steel samples [5] or on low frequency low spatial resolution measurements on carbon fibre [6].

Other non-destructive testing methods such as acoustic [7], eddy current [8] X-ray and contact surface resistance [9] are of importance, but all suffer from problems when applied to carbon based composites. The most commonly used methods in fault detection are acoustic and eddy current probes. For acoustic measurements the sample generally has to be immersed in a liquid to enhance the coupling between the sensor and the sample. As for the eddy current method, this is best suited to highly conducting materials and so far from ideal for carbon composite. In general x-ray techniques are extremely inconvenient and in many cases will require the section to be tested to be removed from the structure. In addition, for carbon based materials the image contrast is generally poor.

2. Method

The principles of operation of the EPS have been described previously by the authors in detail in the literature [10]. A combination of positive feedback techniques such as guarding and bootstrap are applied together with a mechanism for providing a stable d.c. bias current. The significant development of the technology reported here is a dramatic increase in the operational bandwidth. Previous versions of the EPS, used for microscopic imaging applications, have been restricted to audio
frequency (<100 kHz). The sensor used for the results reported in this paper has an upper frequency -3 dB point of >30 MHz. This has been achieved, without compromising the input impedance, by the use of phase compensation networks in the feedback circuitry to ensure that the positive feedback (guard) signal remains precisely in phase at all frequencies.

The sensor electronics is attached to a coaxial electrode structure with an inner sense electrode diameter of 50 μm. The complete sensor assembly is then placed on the movable carriage of a stepper motor driven XYZ stage. This system allows the position of the sensor to be controlled in three dimensions and raster scans to be performed at a fixed height above a sample with a minimum step size of 6 μm. For the initial laboratory tests reported in this paper the carbon composite sample consisted of a 19 mm wide strip 3 mm thick and was directly connected to an a.c. signal source via metal end electrodes. It was driven by a current (I) of 146 mA, as shown in figure 1, corresponding to a current density of 2.6 mA/mm². For a practical implementation of this system it is envisaged that an induction excitation coil, similar to that used for eddy current testing, would be employed. The electric field above the surface of the sample corresponding to the potential drop created by the current flow is detected, as a function of position, by the sensor during a raster scan. The gradient of the potential should be linear for a sample of homogeneous conductivity. In order to visualize the small variations in conductivity within the material this constant linear background is subtracted from the data.

Figure 1. Schematic of the experimental setup.

3. Results
The broadband nature of the EPS used for these measurements is demonstrated by the frequency response shown in figure 2. This was acquired using a calibrated and guarded coupling capacitor of 500 fF, somewhat higher in value than the coupling capacitance usually encountered during a scan. A deliberate decision was made to restrict the low frequency response of the sensor to a few kHz, at the design stage, in order to reduce the settling time required when conducting a raster scan. The data of figure 3a shows the raw output from the sensor when used to raster scan a 12.6 mm x 12.6 mm section of the sample. An excitation frequency of 100 kHz was used in this case. The potential gradient from left to right, the direction of current flow, may be clearly seen in the raw data of figure 3a. In figure 3b a linear background has been subtracted from the data enabling the local conductivity variations to be visualised easily over the whole of the scan area. The rhomboid shaped features are coincident with the weave of the carbon fibre mat within the sample. It is possible that the speckling seen at the top left is indicative of imperfections in the epoxy bonding to the fibre, but we are unable to confirm this at this stage. It should be noted at this point that the composite was fabricated by hand at Sussex in order to produce a sample containing significant imperfections. It is to be expected from simple skin...
depth arguments that as the signal frequency increases the image will be dominated by surface effects. However, simple skin depth calculations can be misleading for multilayered composites of finite sample size [11]. Initial results obtained at a range of signal frequencies show similar results for this sample, with apparent defects in the top left corner section of the scan area. This may be seen in the results shown in figure 4a at a frequency of 10 kHz and figure 4b at a frequency of 1 MHz.

![Figure 2. Frequency response of sensor measured using a 500 fF coupling capacitor.](image)

(a)     (b)

**Figure 3.** EPS raster scan of composite sample at 100 kHz, (a) raw data and (b) processed data with potential gradient subtracted.

(a)     (b)

**Figure 4.** EPS raster scan of composite sample at, (a) 10 kHz and (b) 1 MHz.
Comparing these initial results taken over a large range of frequencies seems to indicate that the apparent defects are not a surface feature. It would be expected that surface or near surface features would dominate the response with higher signal frequencies. This is not the case with the data presented here. Indeed, if we scan the sample at the highest frequency at which we can currently operate (11 MHz), due to instrumental limitations, we see not dissimilar results occurring. A smaller scan area corresponding to the left hand side of the other scans is shown in figure 5 for comparison purposes. Potential gradient subtraction has been applied to all of the data shown in figures 4 and 5.

Figure 5. EPS raster scan of composite sample at a frequency of 11 MHz.

4. Conclusions
A broadband version of the electric potential sensor has been applied to the measurement of local conductivity variations in a carbon based composite material over a range of frequencies from 10 kHz to 11 MHz. The sensor was used as a non-contact detection system with high spatial resolution, of the order of 50 μm. The well known a.c. potential drop method was employed, but the potential gradient induced by the current was monitored via the electric field it generated close to the surface of the sample, instead of the usual contact probe. Initial results were presented which indicate that local variations in conductivity due to the structure of the composite may be imaged by this technique. In addition, there is some indication that defects within the material may also be imaged. These are seen to be present at the same physical location in each case and at all signal frequencies used. This opens up the possibility of a new technique, similar to eddy current testing, but suitable for lossy poor conductors. In practice such a system would require a complementary non-contact inductive excitation coil. As such, it would also be capable of monitoring local conductivity variations through insulating surface layers.

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References
[1] Harland C J, Clark T D and Prance R J 2002 Electric potential probes—new directions in the remote sensing of the human body. *Meas. Sci. Technol.* 13 163–169.
[2] Beardsmore-Rust S T, Watson P, Stiffell P B, Prance R J, Harland C J, Prance H 2009 Detecting electric field disturbances for passive through-wall movement and proximity sensing. Proceedings of SPIE ‘Smart biomedical and physiological sensor technology VT’ 16-17 April 2009, Orlando USA’ 7313, 7313OP, ISBN 9780819475794
[3] Prance R J, Aydin A 2007 Acquisition of a nuclear magnetic resonance signal using an electric field detection technique. *Appl Phys Letters* 91 DOI: 10.1063/1.2762276
[4] Beardsmore-Rust S T, Watson P, Prance R J, Harland C J, Prance H 2009 Imaging of charge spatial density on insulating materials Meas. Sci. Technol. 20 095711 doi:10.1088/0957-0233/20/9/095711

[5] Prance R J, Gebrial W, Antrobus C 2008 Depth profiling of defects in stainless steel using electric potential sensors and a non contact a.c. potential drop method. Insight 50(2) 95-98.

[6] Gebrial G, Prance R J, Harland C J, Stiffell P B, Prance H 2006 Non-contact imaging of carbon composite structures using electric potential (displacement current) sensors Meas Sci & Technol 17(6) 1470-1476.

[7] Chen A S, Almond D P and Harris B 2001 Acoustography as a means of monitoring damage in composites during static or fatigue loading. Meas. Sci. Technol. 12 151–156.

[8] Tavrin Y, Krause H J, Wolf W, Glyantsev V, Schubert J, Zander W and Bousack H 1996 Eddy current technique with high temperature SQUID for non-destructive evaluation of nonmagnetic metallic structure. Cryogenics 36 83–86.

[9] Irving P E and Thiagarajan C 1998 Fatigue damage characterization in carbon fibre composite materials using an electrical potential technique. Smart Mater. Struct. 7 456–66.

[10] Prance R J, Debray A, Clark T D, Prance H, Nock M and Harland C J 2000 An ultra low noise electric potential probe for human body scanning. Meas. Sci. Technol. 11 291–297.

[11] Stiffell P, Prance R J, Gebrial W, Harland C J, Prance H 2008 Defect detection using a non-contact electric potential drop method for multilayer carbon composite materials Emerging Technologies in NDT eds. G Busse et al, Taylor and Francis, London, 251-255.