# Characterisation and location of faults in composite materials using a novel electric potential sensor

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## ABSTRACT

We describe the preliminary results of a blind trial conducted on commercial samples of carbon composite using a new non-contact electric potential sensor. The sensor has been developed at the University of Sussex and in this application operates by measuring the spatial potential above the surface of the sample due to a small applied a.c. current(~1A). The sensor is capacitively coupled to the sample over a range of signal frequencies from <1Hz to >10kHz. Over this range the sensor exhibits a flat frequency response. It is capable of monitoring, via the displacement current, changes in potential due to currents flowing within the material even through an insulating surface layer. This makes it ideally suited to composite materials, such as the examples studied here, where the carbon mat is embedded in an insulating matrix. The system has proved capable of yielding local conductivity information for a range of materials which are less well suited to eddy current techniques due to their poor electrical conductivity.

One extremely useful feature of the sensor technology is that it is truly scalable. The spatial resolution required may be chosen by selecting the correct combination of electrode size and working distance. In other applications the sensors have been used to achieve <1µm resolution, for the imaging of the microscopic behaviour of integrated circuits, and >10cm resolution in the remote detection of the human electrocardiogram. For the results presented in this paper we have chosen to operate at a spatial resolution of ~1mm, although we could choose to image defects at a much higher resolution.

As such we believe that this method will provide a complementary technique to thermography and acoustic methods which are being developed for use with composites. Damage resulting from impact or excessive loading will typically lead to delamination in these materials with a resulting reduction in the conductivity in the damaged regions. We describe the measurement system consisting of a single sensor, a three axis computer controlled scanning system, signal processing hardware and data acquisition. The results of an early blind trial conducted on both unloaded and preloaded samples provided by Engenuity Ltd [1] are presented. We conclude that the technique is able to differentiate between the damaged and undamaged sample and to provide spatial information about the location of the damage.

In addition the system is capable of operating in a second mode where the sample is raised to a constant potential, but no current flows. In this case, when the sample is scanned, the system records a potential with respect to a reference ground. This potential reflects the surface topography of the local source within the material. Thus, the topography of the top conducting mat in the composite may be independently determined. This information may be combined with the local conductivity information

obtained from the current scan so that changes in the effective working distance of the sensor from the conducting mat may be compensated for.

## 1. INTRODUCTION

The electric potential sensor (EPS) is a new technology which, in this paper is applied to the location and characterisation of faults in conducting composites based on carbon. Measurement of the local electrical conductivity via a non-contact capacitive coupling to the sample is demonstrated. It is worth noting that an important feature of this new technique is that it performs best when the electrical conductivity of the sample is low, unlike conventional methods such as eddy current testing. A comparison with earlier results for poorly conducting metals, such as stainless steel [2] is given and new results are presented from a number of carbon fibre laminate materials. The local electrical conductivity is monitored by measuring the potential drop as a function of position over the material. The sample is excited by an a.c. current, chosen to be low enough in frequency such that the current will penetrate the thickness of the sample. This criterion is set by the skin depth for the sample material. Preliminary results are presented from a blind trial conducted on two samples of carbon fibre laminate. One of these had been preloaded by compression almost to the point of failure, the other was an undamaged control sample. Initial indications are that internal damage to the material, such as delamination, may be seen even when the load has been removed.

It is apparent from the results presented in this paper that this local conductivity method may be used to monitor the electrical characteristics of conducting materials and that in many cases this relates well to the physical properties of the sample. However we have also demonstrated in previous work [3] that we can image the dielectric behaviour of non-conducting (electrically insulating) materials. This can be achieved using the EPS to monitor the amplitude and phase of an a.c. displacement current in an insulating material. Using this technique we have been able to infer the dielectric constant of the material and find good agreement with published data. It is suggested that this method may be extended to the characterisation of non-conducting composite materials via their local dielectric properties. Clearly voids, impurities and inhomogeneities will cause this to vary through the sample.

Magnetic methods such as eddy current testing are in use for the detection of faults and work well with good conductors such as metals [4] but are less effective for materials with lower electrical conductivity. Ultrasonics use a pulse echo technique to monitor reflected signals [5]. This normally requires a liquid coupling medium between the sensor and the sample. Radiological methods can give good information, but are hazardous and may suffer from a lack of contrast [6]. Surface inspection techniques include infra-red thermography which monitors the local temperature of the surface [7]. This is useful, but restricted to near surface fault detection. By comparison, the technique of non-contact electric field sensing described here is new in the context of non-destructive testing. The lack of an appropriate sensor is the main reason why this method is relatively unknown. A sensor has been developed at Sussex which is now being applied to a wide range of areas [8]. The signal is capacitively coupled to the sensor via the displacement current. As a result, relatively poor conductors such as carbon fibre composites and insulators (e.g. ceramics) may be imaged [9].

## 2. METHOD

The electric potential sensor (EPS) is a patented technology developed at the University of Sussex. The aim of the sensor is to approach the ideal voltmeter approximation as closely as possible. This means that it should exhibit an infinite input impedance (R), zero input capacitance (C) and require no d.c. input current. This is of course impossible to achieve, but we have come very close. The EPS is capable of measuring the spatial electric field or potential arising from a source via weak capacitive coupling using only the displacement current. Typically, R~$10^{18}\Omega$, C~$10^{-17}$F, Voltage noise <30nV/$\sqrt{Hz}$ and a bandwidth d.c.~100MHz may be achieved. These remarkable characteristics result from using a novel input bias scheme and a combination of feedback techniques, shown schematically in figure 1 and described in considerable detail in reference [8]. The sensors are stable in operation and are both electrically and mechanically robust. To measure the local conductivity of a sample we apply an a.c. current of a low enough frequency such that the skin depth is sufficient to allow the current to penetrate the sample [10]. The sensor is then scanned in a raster pattern across the surface to measure the potential as a function of position, as shown in figure 2. The scanning system is chosen depending on the scan area and resolution required. A large 1m table with 0.75mm resolution allows us to examine large components, while a microscopic XYZ system with 1µm resolution is suited to the study of small samples. Both use an IEEE interface and LabView virtual instrumentation software for control of the positioning and data acquisition.

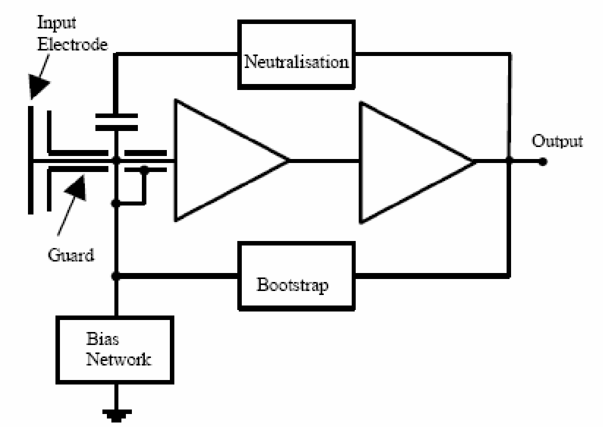

Fig 1. Block diagram of the electric potential sensor showing feedback mechanisms used to enhance the input impedance of the device.

Two modes of operation are possible and both are desirable, since thay yield different information. The local conductivity measurement outlined above uses an alternating current to generate an a.c. potential difference signal (here termed a current scan) which varies with position and is analogous to the familiar contact a.c.p.d. method used in NDT of metals. However, we are using a non-contact sensor to make the measurements which gives rise to a possible source of error due to variations in the working (stand off) distance of the sensor. Using a dielectric spacer to define the working distance eliminates this error for simple samples such as metals, but for carbon composites where the conducting sheets may undulate this is still a problem. Thus, although the working distance from the surface of the sample is kept constant the actual distance between the sensor and the conducting sheet will vary with position. This will lead to a variation in the spatial potential measured by the sensor and will be convoluted with that due to the local conductivity variation. The second mode of operation addresses this issue. It involves the application of an alternating voltage to the sample with respect to a reference (ground), without a flow of current through the sample. This creates an equipotential surface on the conducting sheet with the result that any undulations will give rise to a varying potential which reflects this topographical information. Thus, we may obtain topographical information by performing a voltage scan and combined local conductivity and topographical information from a current scan. Both signals may be acquired from a single physical scan by switching the current on and off. This procedure should allow us to deconvolute the local conductivity information and obtain quantitative data in the near future.

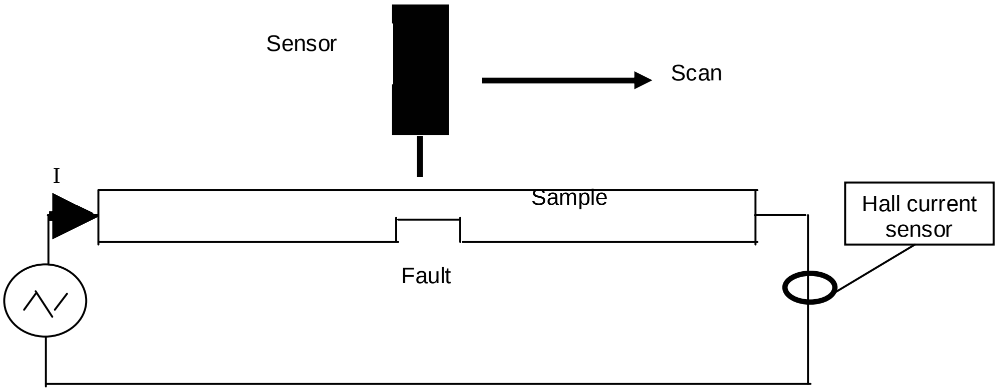

Fig 2. Laboratory setup for measuring variations in the local electrical conductivity of a sample

The nature of the signal expected from a current scan in the ideal case of a homogeneous sample is shown in figure 3. Here the top picture shows a constant slope background corresponding to a constant resistance in the bulk of the material in the case where the signal frequency is too high to penetrate the region of the fault. The lower picture shows the expected response when a lower signal frequency is used namely an increased slope (higher resistance) in the region of the fault. For the results presented in this paper we have chosen to excite the samples with a sufficiently low frequency, such that a reasonably uniform current distribution exists throughout the thickness of the sample. This is determined in the usual way [10] from the skin depth relation,

$$\delta = \sqrt{\frac{2}{\mu\mu_0\sigma\omega}} \qquad \text{Eq. 1}$$

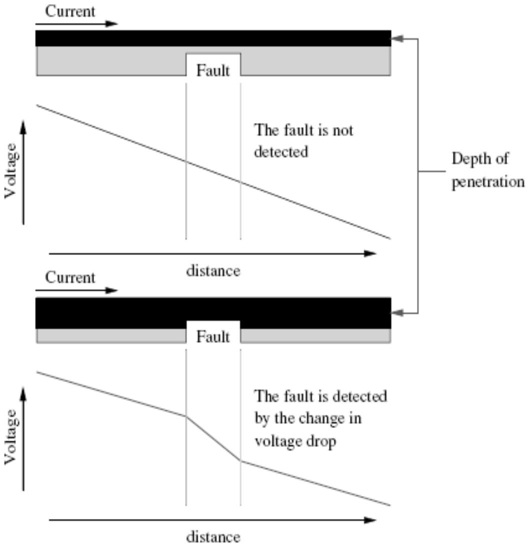

Fig 3. Ideal voltage response where signal frequency is too high to penetrate fault region (top), and lower signal frequency where a change in local sample resistance is seen in the region of the fault (bottom)

where $\mu$ is the magnetic permeability, $\sigma$ is the conductivity and $\omega$ is the angular frequency.

## 3. RESULTS

Fiqure 4 shows an example of a voltage scan conducted on a sample of carbon fibre mat. The false colour image clearly reproduces the pattern of the weave in the mat and correlates well with the distance of the sensor from the mat. It is this topographical information which we intend to use in conjunction with the results of a current scan to enable us to deconvolute the local conductivity information in the future.

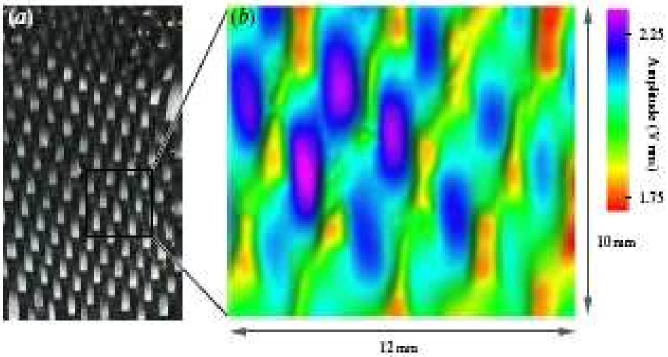

Fig 4. (a) Photograph of a woven carbon fibre mat. (b) Voltage scan of a section of the carbon fibre mat showing the variation in voltage due to topographical changes as a false colour image

Figure 5a shows the result of a simple line current scan across of 2mm thick carbon fibre reinforced plastic (CFRP) sample with a 1mm deep machined fault on the reverse side. Here a 1.5Hz signal with an amplitude of 1.06A has been used. The presence of both a local conductivity variation and an undulation due to the mat weave may be seen. This is even more apparent in figure 5b where the ohmic background due to the bulk conductivity has been subtracted off. It is now clear that we have a large conductivity anomaly due to the fault superimposed on a smaller conductivity modulation caused by the weave of the mat.

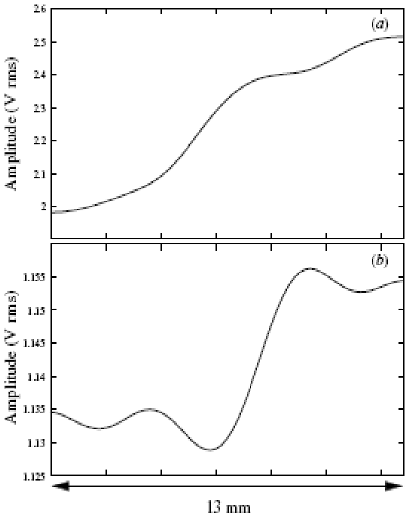

Fig 5. (*a*) EPS ac current scan (1.5 Hz and 1.06 A rms) across a 2 mm deep machined fault buried 1 mm below the surface of the sample.
(*b*) ac current scan with the same sample, for a fault buried 2 mm below the surface (1.3 Hz and 1.41 A rms), background conductivity subtracted.

A more significant result is showed in figure 6. A blind trial was conducted on two test samples of CFRP. One was a control, sample ‘A’, the other, sample ‘B’, had been previously subjected to a high load. No damage was visible and measurements were carried out with no applied load. From the data observed we concluded that the much larger variation in conductivity observed in sample ‘B’ was associated with internal damage, >2V compared with <0.5V for sample ‘A’, i.e. 4x larger variation in conductivity for sample B. This subsequently proved to be correct. In both cases the background bulk conductivity has been subtracted to enable the variation in conductivity to be seen easily. It should be emphasised again here that these measurements were a blind trial and that we have successfully identified the changes in local conductivity associated with this delamination, caused by the preloading, after the loading has been removed.

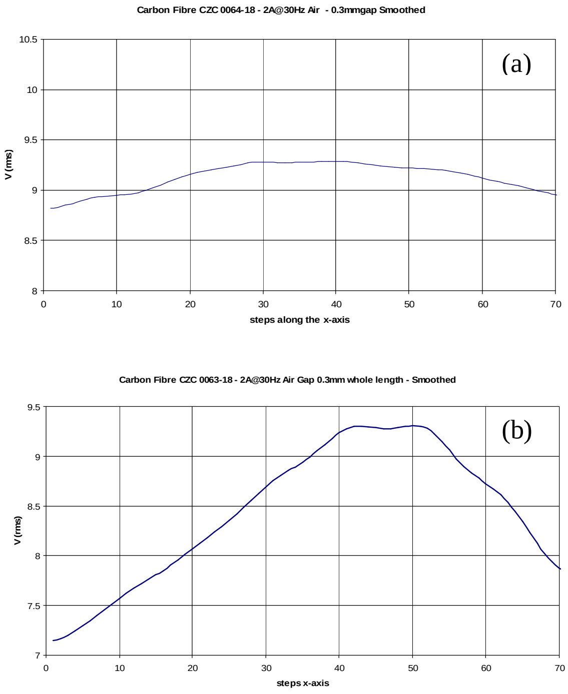

Fig 6. (a) Single line current scan of sample A showing <0.5V variation in the measured voltage. (b) Single line current scan of sample B showing >2V variation in the measured voltage

## 4. CONCLUSION

We have demonstrated that the non-contact potential difference method using the electric potential sensor presented in this paper provides an alternative technique for the NDT of poor electrical conductors. The results of a blind trial on a preloaded sample of CFRP indicate that we are able to detect internal damage such as delamination even when the load is removed, via the increased variation in the local electrical conductivity. This would indicate that more work should be done towards producing quantitative local conductivity data and using the topographical voltage scan information to deconvolute this from the results obtained by current scanning Useful additional information may be gained by extending the method to include a range of frequencies up to radio frequency, well within the capability of the sensors. It has already been established in other applications [11] that the sensors are ideal for integration into array formats either 1 or 2 dimensional. This is an exciting possibility which would allow for the real time imaging of faults in 2 dimensions, which could be extended to a third dimension with the addition of multi-frequency excitation signals [9].

It should also be noted that we are not restricted to using the a.c.p.d. method as used on conducting materials. Earlier work by the authors [3] demonstrated that by exciting a displacement current in a sample, via capacitive electrodes, we could quantify the real and imaginary parts of the dielectric constant of insulating materials. We see this local measurement of dielectric constant as particularly important as a new technique for characterising both insulating composites such as glass fibre reinforced plastic (GRP) and ceramic materials.

## 5. ACKNOWLEDGEMENTS

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