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Abstract: Dielectric materials are becoming widely used because of their versatility and low-cost. Examples include carbon fibre, glass reinforced plastic, polymers and ceramics. These materials are increasingly used for aircraft structures and other important areas, such as transportation in gas pipelines, whose materials require regular inspection. There is a need for a new technology for rapid inspection of dielectric materials. This paper is focusing in one of the most challenging material inspection problems using an electrical capacitance tomography (ECT) system. We show that volume cracks could be detected using ECT data using state of the art shape reconstruction algorithm. The reconstruction of cracks is not possible using conventional image based approach that is used in the industrial process tomography application of ECT.

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CRACK DETECTION IN DIELECTRIC OBJECTS USING ELECTRICAL CAPACITANCE TOMOGRAPHY

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ABSTRACT- *Dielectric materials are becoming widely used because of their versatility and low-cost. Examples include carbon fibre, glass reinforced plastic, polymers and ceramics. These materials are increasingly used for aircraft structures and other important areas, such as transportation in gas pipelines, whose materials require regular inspection. There is a need for a new technology for rapid inspection of dielectric materials. This paper is focusing in one of the most challenging material inspection problems using an electrical capacitance tomography (ECT) system. We show that volume cracks could be detected using ECT data using state of the art shape reconstruction algorithm. The reconstruction of cracks is not possible using conventional image based approach that is used in the industrial process tomography application of ECT.*

1 INTRODUCTION

Electrical Capacitance Tomography (ECT) is a technique which uses external capacitance measurements to obtain the dielectric permittivity distribution within an object. The uses of this emerging technology are numerous, but it has particular use in the monitoring of industrial processes, such as finding out the concentration of one fluid in another such as water in oil in oil wells (Yang, Stott et al. 1996), monitoring the flow of fluids within pipes or even the distribution of solids within fluids. The systems have also been shown to work particularly well when imaging combustion, due to the free electrons and ions effecting the permittivity. In this paper we propose the use of ECT for non-destructive evaluation (NDE) of dielectric materials (Banasiak *et al* 2008). ECT has critical advantages over existing ultrasound and X-ray methods, particularly in NDE applied to dielectric materials. A very challenging ECT application in NDE is detection of cracks. This paper presents a preliminary simulated study of the potential application of ECT in identifying cracks in dielectric materials.

2 ECT SYSTEM

ECT is a new and emerging Tomographic imaging technique. The main advantage of this technique is of course, that it is non-invasive and non-destructive. However it is also reasonably inexpensive and fast. Figure 1 shows a complete system consists of the sensor, a data acquisition system and a computer.

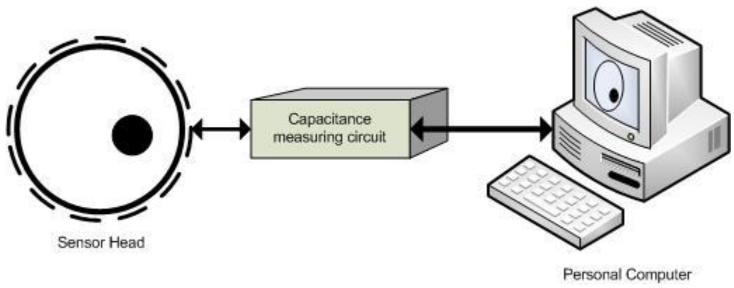


Figure 1: An ECT system

An ECT sensor basically consists of a non-conducting pipe, on which an array of electrodes is mounted externally, with an earthed screen around it. This earthed screen protects the data readings from being affected by external electrical field changes. The earthed screen may have radial earthed screens in an attempt to improve the quality of the image by preventing flux density between adjacent electrodes. The design and effect of these radial screens are discussed in (Alme and Mylvaganam 2006). If we are using a metal vessel, then the electrodes are mounted internally, and the vessel itself acts as the earthed electrical screen (Soleimani and Lionheart 2005).

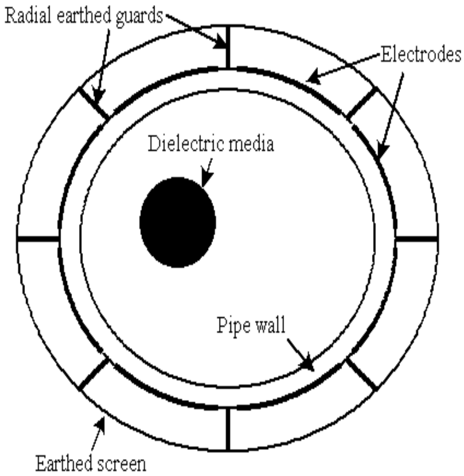


Figure 2: A diagram of an ECT sensor with eight electrodes

To obtain an image of the region under investigation we solve the problem in two phases. The first stage involves solving the forward problem, which is: given an estimate for permittivity distribution ε_0 and the electric potential at the boundary, find the electrical response $\underline{u}$, if

$$\nabla \cdot \ (\underline{\varepsilon}_0 \ \ \nabla \underline{u}) \ = \ 0 \text{ on } \Omega \tag{1}$$

$$\underline{u} \ = \ c \text{ on } \partial\Omega$$

We then solve the inverse problem using the electrical response $\underline{u}$ found in the forward problem. The inverse problem is find a new approximation for the permittivity distribution ε, if

$$J(\varepsilon o)\underline{x}=\underline{y} \tag{2}$$

Where ε_0 is the permittivity estimate used in the forward problem, J is the sensitivity matrix which is the Jacobian of the capacitance with respect to pixels evaluated at ε_0, $\underline{x} = \varepsilon - \varepsilon o$ is the difference between the permittivity distribution solution and the previous estimate of the permittivity distribution, and $\underline{y}$ = f(ε)-f(εo) where f is the capacitance, calculated using $\underline{u}$ and the equation

$$f(\varepsilon) = \frac{1}{Area \quad of \quad electrode} \int \varepsilon \frac{\partial u}{\partial n} \tag{3}$$

The new ε can then be fed back into the forward problem and the cycle can be repeated to improve your permittivity approximation (Soleimani and Lionheart 2005).

3 LEVEL SET METHOD

Level set method is a popular technique in image processing. It enables the user to easily follow shapes changing topology and thus track the evolution of an interface. We are able to perform numerical computations involving surface and curves on a Cartesian grid, without needing to parameterise the objects (Osher and Sethian 1988, Soleimani et al 2006). This is known as the Eulerian approach.

The main advantage of the method is that it is much easier to work with the level set function of a shape than the shape directly, since we can then avoid having to find new models when the shape deforms.

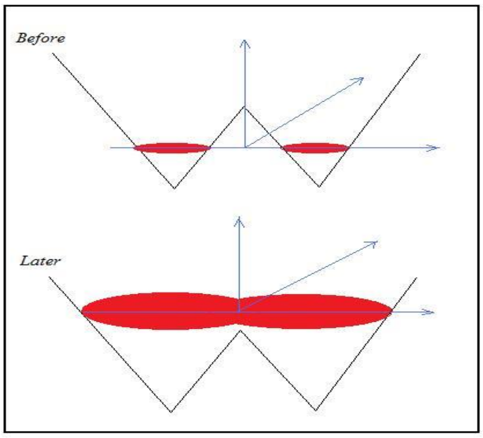


Figure 3: The level set method naturally handling changes in topology through evolution

In the basic level set method, we use what is known as the “full matrix approach”, which involves updating all level sets as opposed to only the zero level set which corresponds to the front. We do this by solving the initial value partial differential equation for our level set function over the entire domain. Although on occasions we are required to carry out computations over the whole domain, we can reduce the computation time by taking what is known as the narrow band approach, which involves working only in a specific region neighbouring the zero level set, corresponding to the front (Sethian 1999).

The choice of narrow band width is very important. In order to reduce the computational time required by the basic method, we must strike a balance between having a narrow band which is small enough to reduce the computations required by the full matrix approach, whilst being large enough so that we are not losing time by re-initialising too frequently. (Sethian 1999) states that experience has shown that an appropriate band width is 6 points either side of the front. If used effectively this method can be ten times faster than the full matrix approach on a 160 by 160 grid (Sethian 1999).

In this paper, we examine the use of the narrow band level-set method for detecting cracks. We begin by choosing a level set function as an initial guess for the interface between the two materials and from this we obtain an initial estimate for the permittivity distribution:

$$\underline{\varepsilon}_0 = \begin{cases} \varepsilon_i & for \quad interior \\ \varepsilon_e & for \quad exterior \end{cases} \tag{4}$$

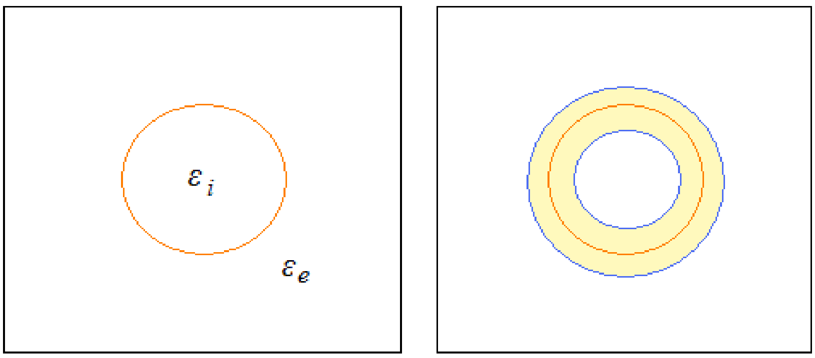


Figure 4: Initial interface and narrowband

The method can then be summarised as follows:

1. Solve the forward problem over the whole domain as usual using $\underline{\varepsilon}_0$ in order to obtain an estimate for the potential u.

2. Calculate the derivative of this potential with respect to the normal to the curve. This will be used in solving the inverse problem to obtain a new approximation for the permittivity, $\underline{\varepsilon}$.

3. Solve the inverse problem over the narrow band. From this you obtain the new level set function. The Jacobian in the inverse problem is the change in capacitance with respect to the motion of the interface, evaluated at the previous permittivity estimate. It directs the evolution of the interface towards the actual solution. The difference between the measured capacitance C and $f(\underline{\varepsilon}_0)$ gives the distance the solution should move.

4. If the residual $C - f(\varepsilon_0)$ is satisfactorily small then stop, otherwise continue on to step

5. Create a band for the new interface by again selecting neighbouring points.

6. Return to step 1 where the new $\underline{\varepsilon}$ is fed back into the forward model as $\underline{\varepsilon}_0$, and repeat the process.

4 RESULTS & DISCUSSIONS

Figure 5 shows the target image of a crack in a two phase material, which we will attempt to reconstruct using the method described above. It also includes a comparison of the reconstruction achieved using this narrow band level set method with the reconstruction achieved by using the standard Gauss-Newton approach with Tikhonov regularisation. Firstly it is clear that the level set method produces a much improved reconstruction. There is some notable discontinuity in this reconstruction but this may be improved using a finer mesh, which will be demonstrated later. Figure 6 shows the evolution of our levels set function from an initial poor guess of a circle in the centre to a good reconstruction of the crack.

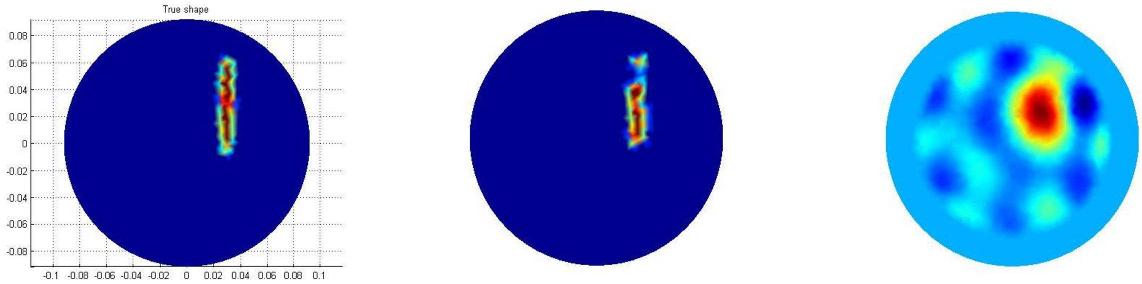
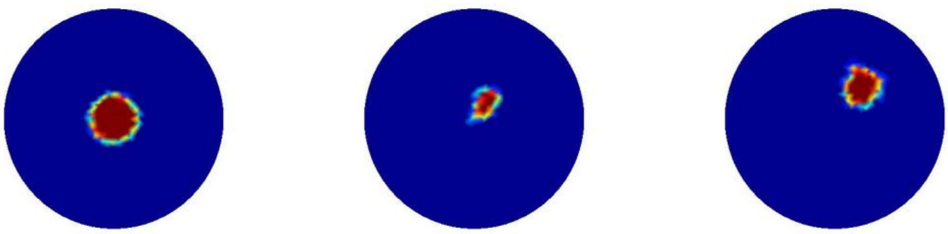


Figure 5: True image, image reconstructed via narrow band level-set approach, image reconstructed via Gauss-Newton approach.



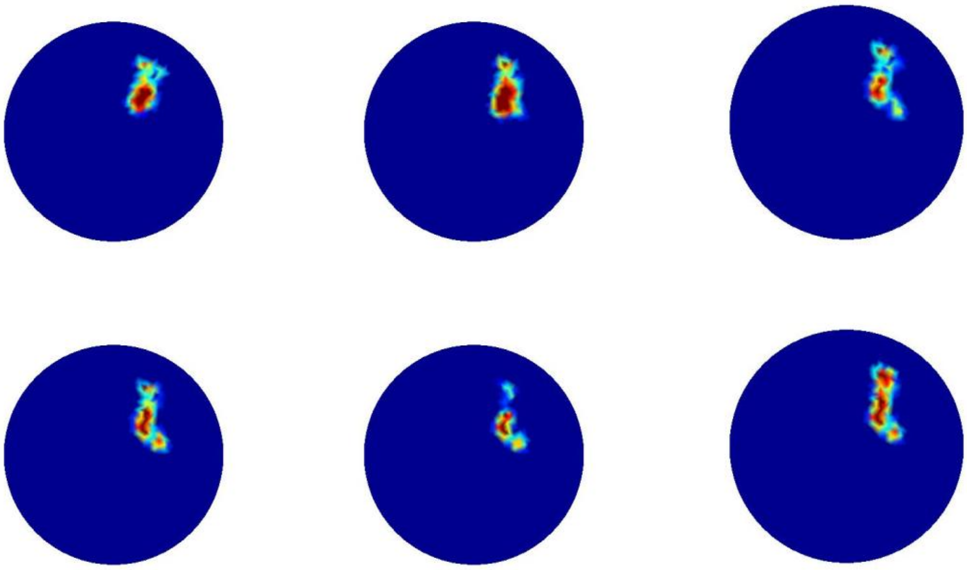


Figure 6: Evolution of image reconstruction for crack problem

We can further improve the image by using a higher density mesh. In Figure 7 we have a similar target crack to test our approach and the improved image reconstruction using a denser mesh. This finer mesh has removed many of the inaccuracies such as discontinuities and extra pixels that were present in the narrow band level set reconstruction when using the more sparse mesh.

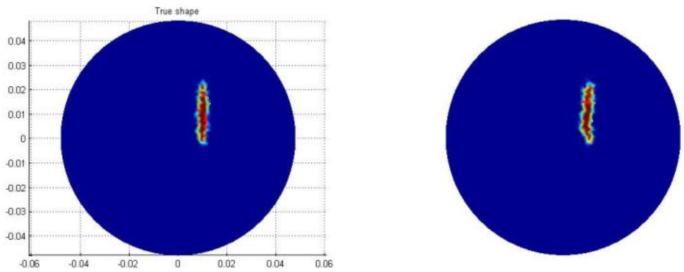


Figure 7: True image and reconstructed image using narrow band level set approach and a finer mesh

The narrow band level set approach also produces reasonable reconstructions for more complicated shapes such as the one seen in Figure 8. When compared with the reconstruction via the Gauss Newton approach, the improvement is dramatic.

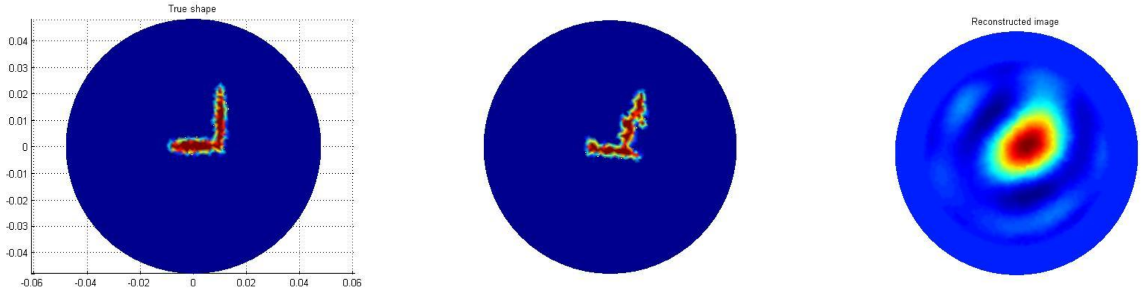


Figure 8: True image with increased complexity, reconstructed image using narrow band level set approach and a finer mesh, reconstruction used Gauss-Newton pixel based method.

Figure 9 shows that the method is capable of handling thin cracks. Figure 10 shows the convergence of the level set algorithm where the norm differences between measured and estimated capacitance data has been presented. Figure 11 shows that it is possible to reconstruct multiple cracks using this method. However it is quite clear that the addition of separate cracks does reduce the quality of the reconstruction, but the reconstruction is still a lot better than that of the pixel based method.

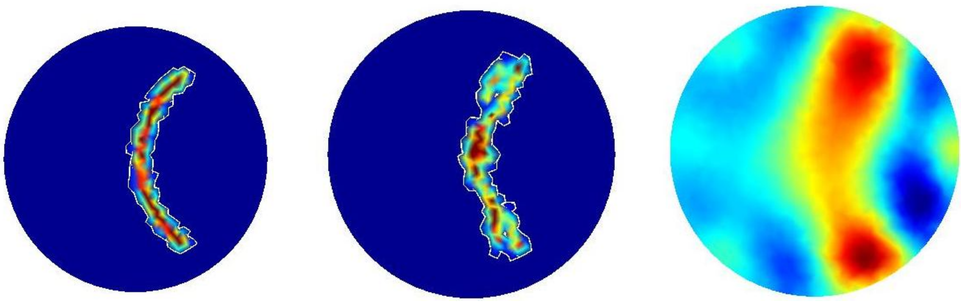


Figure 9: Complex slim crack, true image and reconstruction via narrow band level set and traditional image reconstruction

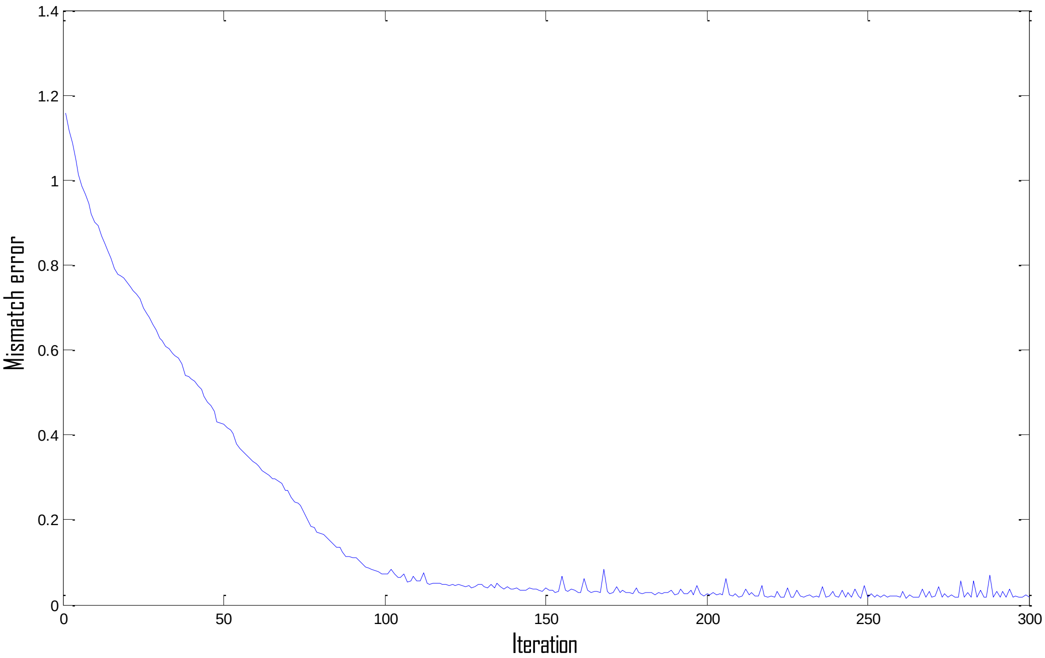


Figure 10: True double crack image, image reconstruction using narrow band level set approach, image reconstruction using traditional pixel based approach

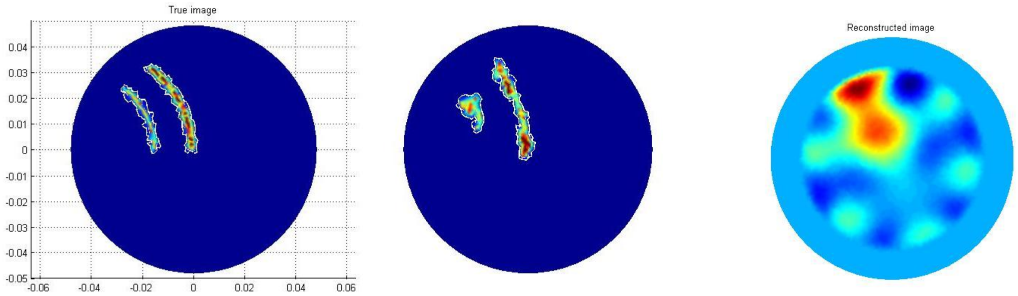


Figure 11: True double crack image, image reconstruction using narrow band level set approach, image reconstruction using traditional pixel based approach

5 CONCLUSION

These results suggest there is potential for this narrow band level-set approach to be used in the field of crack detection. Difficulties may arise for narrower cracks; however the results suggest that some improvement can be gained by creating a finer mesh. The cracks detected here are still volume cracks and we will further investigate the reconstruction of smaller cracks using specific methods developed for crack reconstruction (Alvarez et al 2006). We will further investigate the results of this work using experimental data.

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