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With the funding provided by AFOSR, the PI was able to take his sabbatical leave for the period of 1 Sep 91 - 31 Aug 92 at Rutgers University. At Rutgers, the PI collaborated with Prof. Michael Vogelius on several problems. The research resulted in several reports, some of which have already been accepted for publication. The main research proposed was to investigate various aspects of the problem of electrical impedance tomography. In electrical impedance tomography, the problem is to image the interior of an object from static electrical measurements conducted on the boundary. The techniques of electrical impedance tomography may be applied to nondestructive evaluation of structures. The grant was directly responsible for two major accomplishments - (1) Inversion from real data and (2) Sensitivity of electrical impedance tomography.

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Final Report of Grant AFOSR-91-0360
Project title:
Inverse Problems in Nondestructive Evaluations

Funding Period: September 1, 1991 to August 31, 1992
Fadil Santosa, Principal Investigator

December 1992

Summary

With the funding provided by AFOSR, the investigator was able to take his sabbatical leave for the period August 1991 to August 1992 at Rutgers University. At Rutgers, the PI collaborated with Prof. Michael Vogelius on several problems. The research resulted in several reports, some of which have already been accepted for publication.

The main research proposed was to investigate various aspects of the problem of electrical impedance tomography. In electrical impedance tomography, the problem is to image the interior of an object from static electrical measurements conducted on the boundary. The techniques of electrical impedance tomography may be applied to nondestructive evaluation of structures.

The grant has been directly responsible for two major accomplishments.

1. **Inversion from real data** In collaboration with Prof. Valdis Liepa of the Radiation Laboratory at the University of Michigan, we constructed an electrical impedance imaging device in the laboratory. Data collected by the device were inverted using algorithms that Prof. Vogelius and I have developed over the past few years. The results show that electrical impedance tomography is a viable alternative to well-established nondestructive evaluations methods such as eddy current and ultrasonics.

2. **Sensitivity of electrical impedance tomography** With Prof. David Dobson of the School of Mathematics at University of Minnesota, we developed a method for analyzing the sensitivity and the resolution power of various electrical impedance imaging devices. The results further leads to an understanding of how to obtain higher resolution images in electrical impedance tomography.

While at Rutgers, the PI also worked with Prof. Vogelius on a problem arising in the study of vibrations of composite materials. We developed an asymptotic theory to predict the long-time vibration of composite with a periodic microstructure. Our results show that the long-time behavior of the vibration depends very strongly on the interaction of the periodic structure with the boundary of the medium. Rigorous treatment of the boundary layer effects on the vibration was carried out. The work resulted in two reports, a third is being written for the proceedings of a conference on control of distributed parameter systems which was held at the Institute for Mathematics and its Applications at the University of Minnesota.

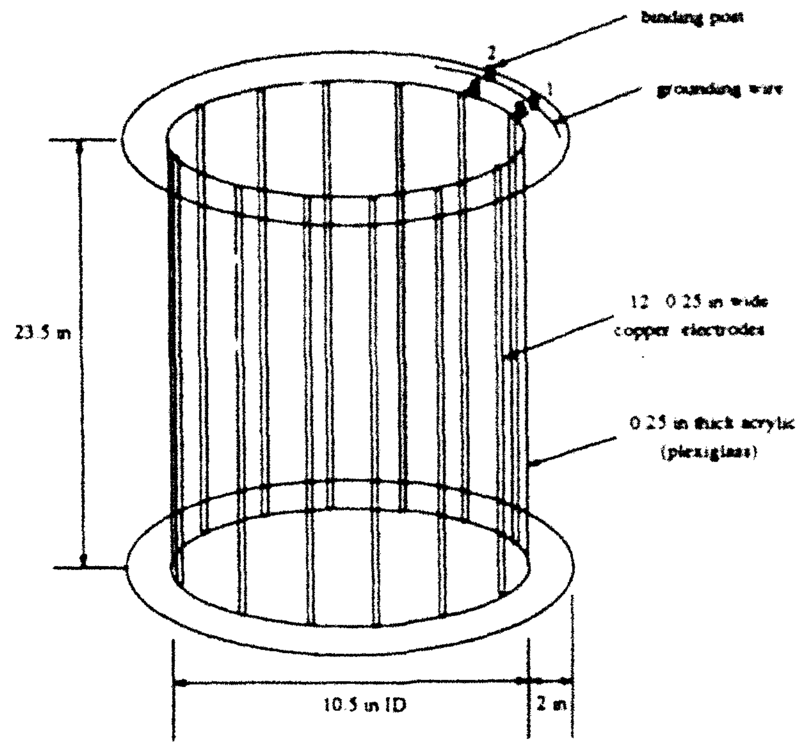

Figure 1: The design of the tank.

Application of electrical impedance tomography to crack detection

We set out with the goal of showing that the method of electrical impedance tomography is a viable alternative to the problem of the detection (and determination) of cracks in structures. To this end, we constructed a cylindrical tank, to which 12 electrodes are attached. Please consult Figure 1. The tank is filled with an electrolyte solution. The presence of a crack is simulated by immersing a metal strip vertically in the tank.

To generate the data, a low frequency AC source is used. A single measurement consists of passing current through an adjacent pair of electrodes and recording the resulting voltage drops in all adjacent pairs of electrodes. A total of 12 measurements is carried out, cycling the applied current through all possible pairs of adjacent electrodes.

All the equipment we used — current source, digital voltmeter, IEEE buses, etc; are of the the "off-the-shelf" variety. The data collected were then processed to conform with the data needed for the two algorithms tested.

The two algorithms used were designed for different purposes. The first one, a back-projection algorithm, was first proposed by Barber and Brown. The method provides an approximate image of the conductivity distribution in the interior of the tank. It gives only a blurry image of the crack; it can be used for crack detection and for providing a rough estimate of the crack size and location.

The second algorithm has been specifically designed to look for a straightline crack. Given

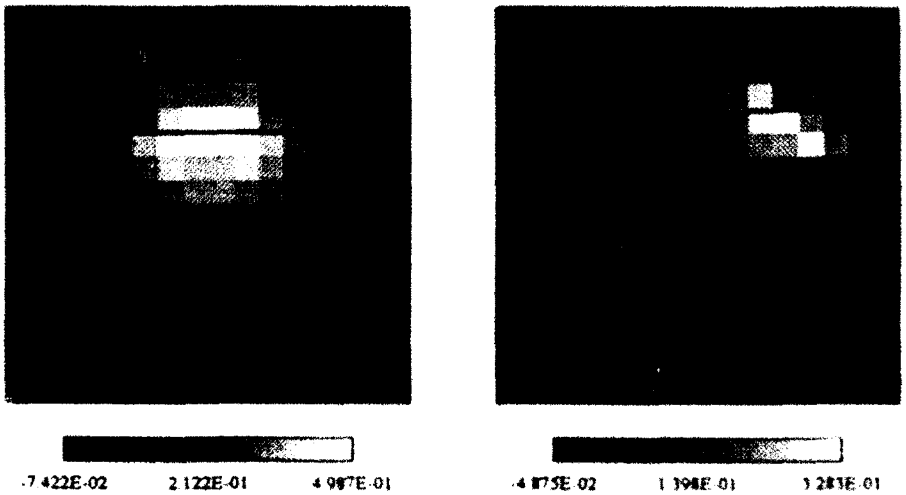

Figure 2: The images obtained by applying the backprojection algorithm on the measured data. The exact locations of the cracks are shown for reference.

exact data, it can find the actual location of the crack iteratively beginning with an initial guess.

The results of the application of the backprojection algorithm are displayed in Figures 2a and 2b for two experiment. In the first experiment, the actual crack is a line segment whose endpoints are

$$(-0.38, 0.38) \quad \text{and} \quad (0.38, 0.38),$$

(in units of the cross section radius). The second experiment involve a 2-inch metal strip simulating a crack with endpoints at

$$(0.24, 0.50) \quad \text{and} \quad (0.62, 0.50).$$

In each figure, we superposed the actual locations of the crack for reference. In viewing these results, we must keep in mind that there is a substantial amount of noise in the data in the form of measurement errors, as well as some modeling errors. These results do however indicate that the data are sufficiently accurate for the backprojection algorithm to reconstruct a rough image of the cracks. However, the images are too blurry to give good estimates, for instance of the crack sizes. In general, even with perfect data, this is probably the best we can hope for with the backprojection algortihm.

The result of application of the crack finding algorithm on the experimental data is given next. In applying it to the first data set, we took the initial guess to be a crack whose endpoints are (-0.5, 0) and (0.5,0). The algorithm converged in 4 iterations. The result of this calculation is shown in Figure 3, which gives a comparison of the actual crack (shown in dashes) with the crack found by the algorithm. The reconstruction yielded a crack whose endpoints are (-0.3402, 0.3173) and (0.3885, 0.3341).

An initial guess in the form of a crack with endpoints at (0,0) and (0.5,0) was used when applying the algorithm to the second data set. Convergence is achieved after 5 iterations. A

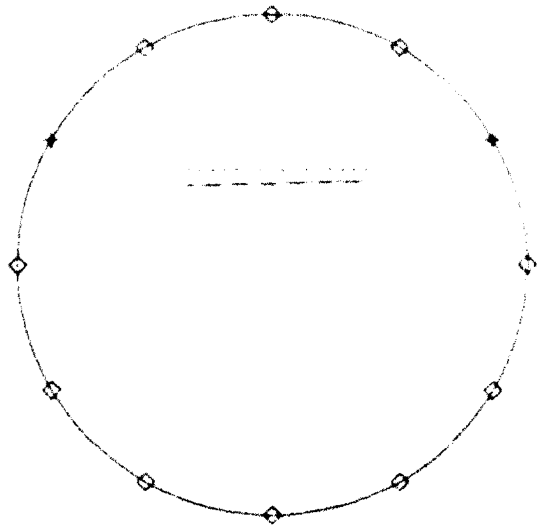

Figure 3: A comparsion of the actual crack with the crack reonstructed by our algorithm. The algorithm took 4 iterations to reconstruct the crack shown in solid line. The actual crack is shown in dashes.

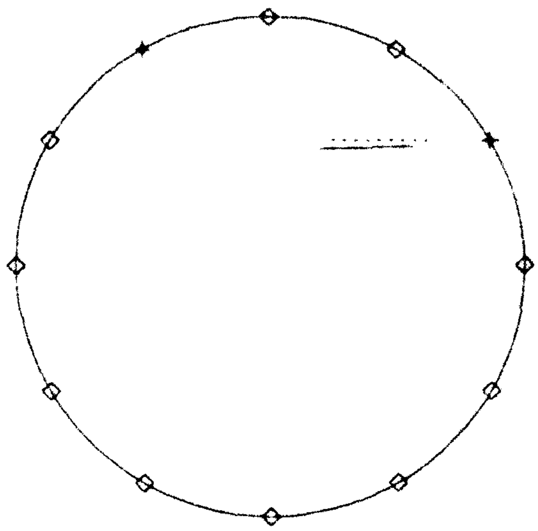

Figure 4: A comparison of the actual crack with the crack reconstructed by the algorithm. The algorithm took 5 iterations to reconstruct the crack shown in solid line. The actual crack is shown in dashes.

comparison of the actual location of the crack with the reconstructed crack is made in Figure 4. The reconstruction yielded a crack whose end points are (0.1964, 0.4666) and (0.5703, 0.4773).

Based on these results, we propose an inspection strategy which consists of first using the backprojection algorithm to detect the presence of a crack. If a crack is detected, we use the result from the backprojection algorithm to obtain an initial guess for the crack finding algorithm. These initial findings seem to indicate that Electrical Impedance Tomography may prove to be a promising nondestructive evaluation technique for certain applications. The results of our investigation is reported in publication 3 of the next section, which has been submitted for publication in Journal of Nondestructive Evaluations.

Sensitivity analysis of electrical impedance imaging devices

The object of this work was to determine that a certain set of current pattern has an advantage over another set in electrical impedance tomography. A current pattern is the distribution of the applied current on the electrodes. Barber and Brown favor the "dipole" pattern, and Isaacson and his co-workers favor the "trigonometric" pattern. Besides settling the controversy of dipole versus trigonometric patterns, we also wanted to know how the current pattern is responsible for an increase in stability and resolution in an electrical impedance imaging device.

What is novel in our work is that we do not discretize the problem. Rather, we work with a concept of a pseudo-inverse, which allow us to conclude properties about an imaging device without discretization. In this way, we were able to conclude convincingly if a certain current pattern does have an advantage over another. The quality we try to quantify is the stability property and the resolution power of the imaging device.

We are lead to the conclusion that in realistic applications, the trigonometric current pattern is better than the dipole pattern. The work lead to a direction for further research: **Current patterns that focus**. If we are interested only in imaging the conductivity of a part of a domain, then our work shows that it is possible to generate a set of current patterns that gives the best "illumination" of that part of the domain. This is a subject of our current research. The work described here has appeared as an IMA (Institute for Mathematics and its Applications) report, and has been submitted to SIAM Journal of Applied Mathematics for publication.

Publications acknowledging support of AFOSR 91-0360

1. First order corrections to the homogenized eigenvalues of a periodic composite medium (with M. Vogelius), to appear in *SIAM J. Appl. Math.*

2. A note concerning bounday effects and long time vibration of layered media (with M. Vogelius), *University of Delaware Center for the Mathematics of Waves Report, 92-9.*

3. Crack determination from boundary measurements — reconstruction from experimental data (with V. Liepa and M. Vogelius), submitted to *Journal of NDE.*

4. **Resolution and stability analysis of an inverse problem in electrical impedance imaging — dependence on the input current patterns** (with D. Dobson), submitted to *SIAM J Appl. Math.* also IMA Report number 1038.