Feasibility Study of Capacitive Tomography

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Abstract - *In this paper, a feasibility study was conducted to test whether capacitive sensors could be used to detect water and produce a graph with the minimal amount of equipment and materials. A lab was setup to conduct experiments and retrieve raw data. The data is then processed using a back projection algorithm in an attempt to produce an image of the water from within a non-metallic pipe. The images are compared to theoretical models to determine whether the test results are comprehensive and reliable enough to be used as a testing procedure.*

Keywords: capacitance, tomography, back-projection, electrical tomography, electrical capacitance tomography

1. Introduction

Many studies and research have been introduced to explain the different aspects of capacitance tomography. They could range from electrode design to algorithm coding. These studies are usually based on theoretical data produced to create certain results and outcomes. But how effective are the results? How do the results compare to actual measured data? Is it even feasible to create a model, with limited resources, to take measured data? This paper will attempt to answer those questions and make a comparison between measured data and theoretical data.

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2. Capacitive Sensors

English physicist Michael Faraday (1791-1867) discovered that electric charge could be stored in a device now called a capacitor which later led to the development of Maxwell's Equations [2]. Capacitance is influenced by the surface area of the conductive plates, the distance between them, and the dielectric strength of the material between the plates [2]. Water has a very high dielectric constant with a value of about 80 and air has a low dielectric constant of about 1. Most of the other materials will fall somewhere between the dielectric values of 1 and 80 [2].

With the basic principles of a capacitor, a system could be developed to measure the capacitance between its own electrode and the targeted object. From the capacitance, the system would be able to determine whether or not the output would detect the object or ignore it. There are several features of the system that will be addressed in order for the system to work.

As illustrated in Figure 1, a dielectric plate is needed to use as the system's sensing surface. It creates an electrostatic field. As an object enters that field, it changes the capacitance in an oscillator circuit. As a result, the oscillator begins to oscillate. The trigger circuit reads the oscillator's amplitude and when it reaches a specific level the output state of the sensor changes. As the object moves away from the sensor the oscillator's amplitude decreases, switching the sensor output back to its original state.

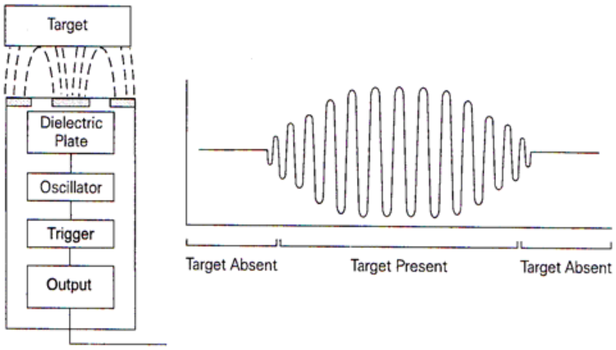

Figure 1: Capacitive sensor theory of operation [1].

The capacitance of the sensor system is determined by the target's size, dielectric constant and distance from the sensing electrode. The larger the size and dielectric constant of a target, the more it increases the capacitance. The shorter the distance between the target and sensor, the more the target increases the capacitance.

Capacitance is calculated by

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

where ε_0 is the permittivity of free space, ε_r = dielectric constant, A is the area of each electrode, and d is the distance between the electrodes.

Table 1: Common dielectrics

Material	Dielectric Constant
Air	1
Oil	2.2
Paraffin Wax	2.2
Wood	2.7
Alcohol	25.8
Water	80

3. Capacitance Tomography

Electrical Tomography (ET) or Electrical Capacitance Tomography (ECT) is an attempt to image the permittivity distribution of an object by measuring the electrical capacitances between a set of electrodes placed around the object [3]. Capacitance tomography has been used to image several processes, such as liquid/gas pipe flow, oil/water gravity separation, pneumatic conveying, fluidized beds and flame combustion [4].

The system model for a capacitance tomography system is explained in Isaksen's 1996 paper, A review of reconstruction techniques for capacitance tomography [4]. In his paper the system model for a capacitance tomography system is based on Poisson's equation given by

$$\nabla \bullet \left(\varepsilon(\chi)\nabla\Phi\right) = -\rho(\chi) \qquad (1)$$

where $\varepsilon(\chi)$ is the dielectric constant distribution, Φ is the potential ρ and is the charge distribution. The electric field is given by

$$\mathrm{E} = -\nabla\Phi \,. \qquad (2)$$

By applying Gauss's law, the induced charge at electrode *j* when electrode *i* is the source electrode can be calculated by the following expression:

$$Q_{ij} = \oint_{\Gamma_j} \varepsilon(\chi)\mathrm{E} \bullet \hat{n} dl \qquad (3)$$

where Γ_j is a closed curve enclosing the detector electrode and is the unit normal vector to Γ_j. Given the charge Q_{ij}, the capacitance between electrodes *i* and *j*, C_{ij}, can be calculated by

$$C_{ij} = Q_{ij} / U_{ij} \qquad (4)$$

where U_{ij} is the voltage between the source electrode *i* and the detector electrode *j*.

Equations (1) – (4) relate the dielectric constant distribution, $\varepsilon(\chi)$, to the measured capacitances, C_{ij}. That is, for a given medium distribution, $\varepsilon(\chi)$ and the Dirichlet boundary conditions, the capacitances can be calculated by using the equations above.

Figure 2 shows a model of a CT sensor. A capacitance tomography sensor consists of a number of electrodes mounted around the process to be imaged. The data-acquisition unit measures all the capacitances. The reconstruction unit converts the capacitance measurements to the dielectric distribution inside the pipe by using a suitable reconstruction algorithm.

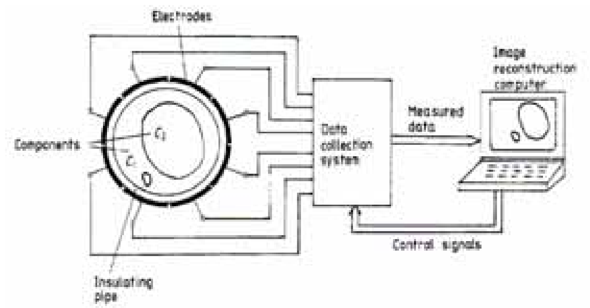

Figure 2: CT sensor model [7].

4. Back-Projection Algorithm

An algorithm is needed to reconstruct the image. The algorithm is well understood and is commonly known as the back-project algorithm. In this project, a basic back-projection algorithm was used and performed in Matlab to reconstruct an image of the water in the pipe. As described in the well regarded text by A.C. Kak and Malcolm Slaney [5]:

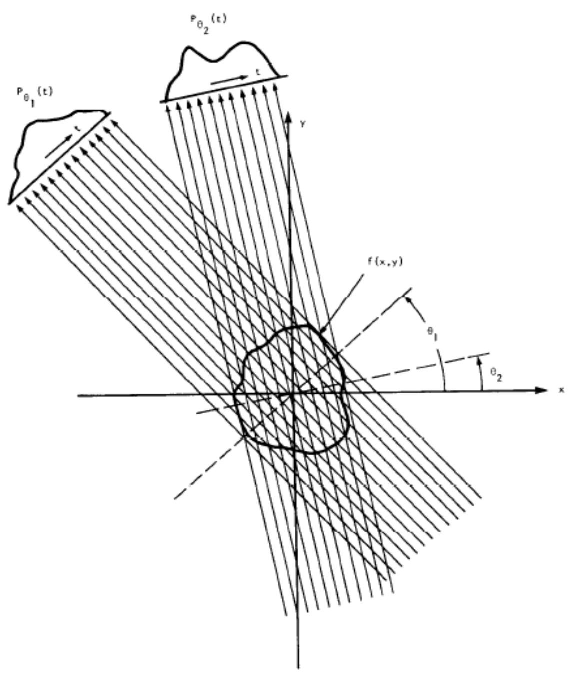

Figure 3: Parallel projections are taken by measuring a set of parallel rays for a number of different angles [5].

A projection is formed by combining a set of line integrals. The simplest projection is a collection of parallel ray integrals as given by $P_\theta(t)$ for a constant θ. This is known as a parallel projection and is shown in Figure 3. It can easily be measured, for example by moving an x-ray source and detector along parallel lines on opposite sides of an object.

5. Theoretical Image Results

Through an exhaustive literature search about capacitive tomography and back projection algorithms, it was found that many articles and research papers used a sensitivity map, as illustrated in [6]. Having a sensor with *N* electrodes, the charge (*q*) on each electrode equals *CV*, in matrix form

$$\begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ \vdots \\ q_n \end{bmatrix} = \begin{bmatrix} C_{1,1} & -C_{1,2} & -C_{1,3} & \cdots & -C_{1,N} \\ -C_{2,1} & C_{2,2} & -C_{2,3} & \cdots & -C_{2,N} \\ -C_{3,1} & -C_{3,2} & C_{3,3} & \cdots & -C_{3,N} \\ \vdots & & & & \vdots \\ -C_{N,1} & -C_{N,2} & -C_{N,3} & \cdots & C_{N,N} \end{bmatrix} \times \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ \vdots \\ V_N \end{bmatrix} \quad (5)$$

where q_i is the charge stored on the *i*th electrode, V_j the voltage applied to the jth electrode, and Cij the capacitance between electrode pair i-j (i≠j).

Keeping voltage the same for all electrodes, a conventional 12 sensor model was used to show six basic sensitivity maps of the sensor.

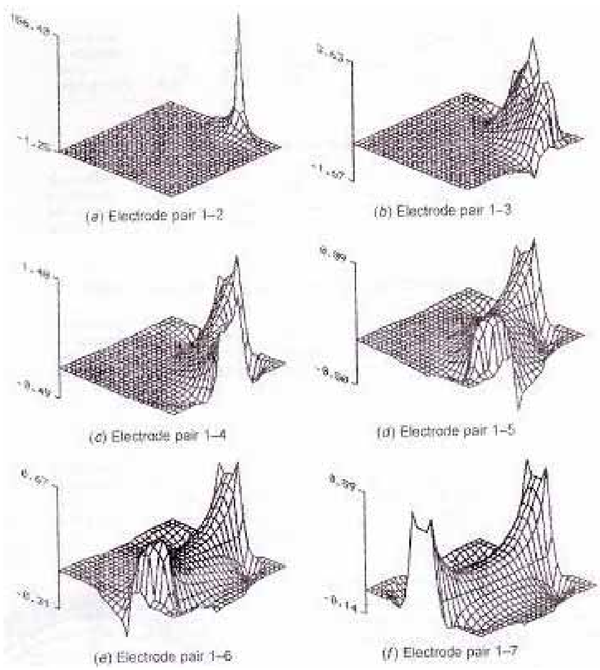

Figure 4: Six basic sensitivity maps of the conventional sensor [6].

6. Experiment Overview

The purpose of this experiment is to be able to measure raw data and create a matrix that can be used with our back-projection algorithm in a timely manner.

6.1 Setup

The experimental apparatus consisted of two linear electrode arrays etched on a copper plated printed circuit board (PCB). Each electrode was 5mm by 10mm. The electrodes were placed parallel to each other with a 2mm gap in between. Each array had 8 electrodes. Figure 5 illustrates this arrangement. Holes were drilled in the middle of the electrode so wire could be soldered from the other side. The wire served as test points so the data could be recorded. Two PCBs were created to act as electrode pairs labeled 1 through 8.

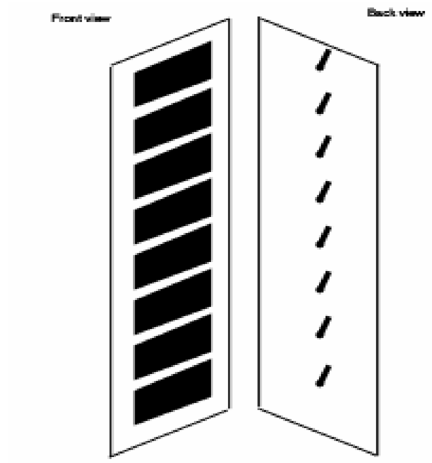

Figure 5: Front and back view of electrode array.

A test fixture was created to hold the electrodes around the pipe. This device was made so it could tilt 180 degrees. This allowed us to take measurements from different angles around the pipe. The device was marked so 8 different angles could be used. The angles used were 0°, 13°, 26°, 39°, 52°, 65°, 78°, and 90°. Two sets of measurements were taken from 0° to 90° and then again from 0° to -90°. This was done so we could measure all 360°. The material of the fixture was chosen based on the low dielectric of wood.

A clear PVC water bottle with a diameter of about 4 inches was used to simulate a pipe. It was half filled with tap water. The pipe would lay perpendicular to the electrodes. Supports were used to hold the bottle steady while measurements were taken.

For the measuring device, the Agilent4263B LCR meter was used. Since this project is a feasibility study, developing the data collection system would be to costly and time consuming. The LCR meter allowed us to take extremely accurate capacitance measurements in a timely manner. Figure 6 illustrates the experimental setup

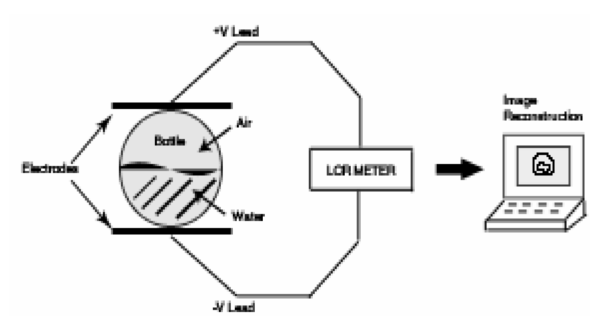

Figure 6: Experimental sensor model

6.2 Experiment Results

First, measurements were taken when the bottle was empty. As can be seen from Table 2 and Table 3, electrode pairs 1 and 8 had the highest readings because they were measuring along the wall of the pipe. The lowest readings were in the middle of the bottle. These tables follow the matrix tables explained in [6].

Table 2: List of measured capacitances (pF) without the water in the pipe. The set of data was measured from 0° to 90°.

		Degrees							
		0	13	26	39	52	65	78	90
Electrodes	1	0.25	0.25	0.24	0.22	0.22	0.23	0.23	0.22
	2	0.24	0.23	0.23	0.21	0.21	0.22	0.22	0.22
	3	0.23	0.23	0.23	0.21	0.21	0.22	0.21	0.22
	4	0.23	0.23	0.24	0.21	0.21	0.22	0.22	0.23
	5	0.23	0.24	0.24	0.22	0.22	0.22	0.22	0.23
	6	0.24	0.24	0.25	0.22	0.22	0.22	0.22	0.23
	7	0.25	0.25	0.25	0.23	0.23	0.23	0.23	0.24
	8	0.26	0.27	0.27	0.24	0.25	0.23	0.24	0.25

Table 3: List of measured capacitances (pF) without the water in the pipe. The set of data was measured from 0° to -90°.

		Negative Degrees							
		0	13	26	39	52	65	78	90
Electrodes	1	0.25	0.26	0.26	0.25	0.26	0.25	0.25	0.25
	2	0.24	0.24	0.24	0.24	0.25	0.24	0.23	0.23
	3	0.23	0.24	0.24	0.24	0.24	0.24	0.23	0.23
	4	0.24	0.23	0.23	0.23	0.24	0.23	0.22	0.22
	5	0.24	0.23	0.23	0.23	0.23	0.23	0.22	0.21
	6	0.25	0.23	0.23	0.23	0.23	0.23	0.21	0.21
	7	0.25	0.23	0.23	0.23	0.23	0.24	0.22	0.21
	8	0.26	0.24	0.24	0.24	0.24	0.24	0.22	0.21

Plots were created using the measured data. Figure 7 indicates a cylindrical object is present, but no change of capacitance in the middle of the cylinder. Figure 8 shows the mesh plot created the expected volcano shaped graph that was discussed in the sensitivity map [6].

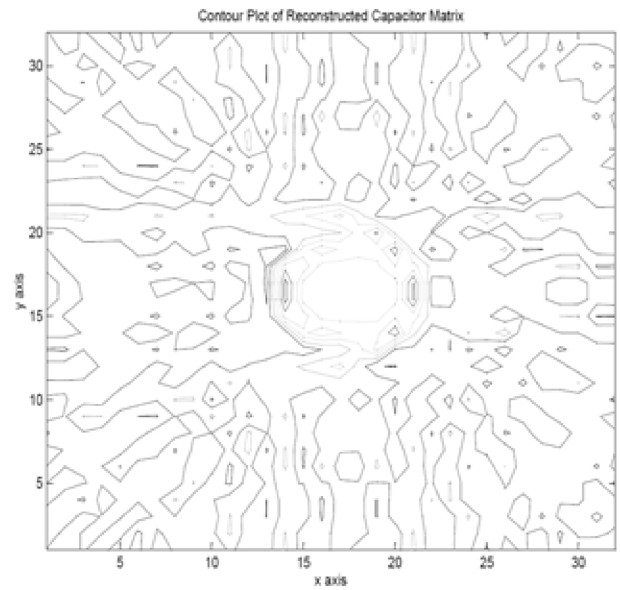

Figure 7: Contour plot of pipe without water.

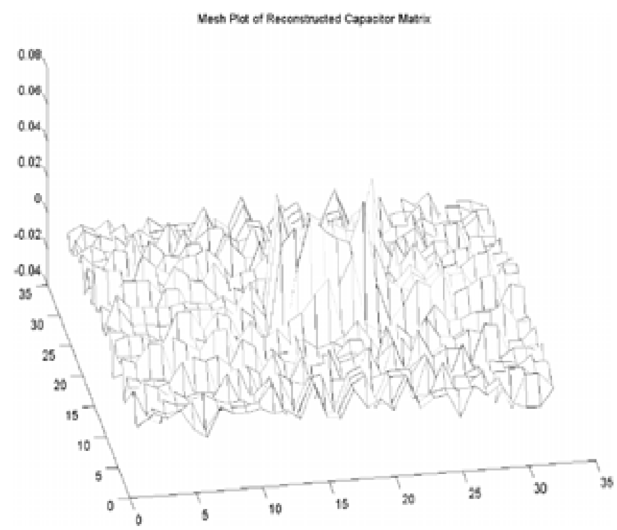

Figure 8: Mesh plot of pipe without water.

The next measurements consisted of filling the bottle half way with tap water and repeating the same procedure of collecting data. The results are given in Table 4 and Table 5:

Table 4: List of measured capacitances (pF) with the water in the pipe. The set of data was measured from 0° to 90°.

		Degrees							
		0	13	26	39	52	65	78	90
Electrodes	1	0.28	0.27	0.27	0.29	0.35	0.37	0.42	0.39
	2	0.34	0.31	0.3	0.32	0.38	0.41	0.5	0.5
	3	0.35	0.34	0.33	0.35	0.43	0.46	0.57	0.65
	4	0.38	0.33	0.35	0.35	0.46	0.5	0.55	0.66
	5	0.33	0.31	0.34	0.33	0.41	0.45	0.44	0.45
	6	0.27	0.28	0.32	0.3	0.33	0.35	0.33	0.32
	7	0.25	0.25	0.27	0.26	0.29	0.3	0.28	0.28
	8	0.25	0.25	0.25	0.25	0.27	0.27	0.27	0.27

Table 5: List of measured capacitances (pF) with the water in the pipe. The set of data was measured from 0° to -90°.

		Negative Degrees							
		0	13	26	39	52	65	78	90
Electrodes	1	0.25	0.22	0.24	0.25	0.24	0.29	0.29	0.28
	2	0.25	0.24	0.26	0.27	0.25	0.29	0.31	0.3
	3	0.28	0.26	0.29	0.28	0.26	0.3	0.35	0.38
	4	0.33	0.28	34	0.32	0.3	0.35	0.45	0.51
	5	0.38	0.3	0.34	0.34	0.32	0.38	0.52	0.67
	6	0.33	0.28	0.32	0.33	0.3	0.41	0.48	0.57
	7	0.3	0.29	0.3	0.32	0.3	4	0.43	0.5
	8	0.27	0.28	0.31	0.3	0.28	0.37	0.39	0.41

From the test result we could definitely see that the water was being detected. Electrode pairs 3-6 had much greater capacitances than the measurements without water. This is due to the high dielectric value of water. The same capacitance matrix was created from the measurements and a contour plot and mesh plot were graphed from our algorithm.

Looking at Figure 9, we can now see the water in the bottom half of the pipe. Figure 10 still shows the volcano shaped plot. This indicates that the edges are still the most sensitive, but the middle should be higher than before. Due to the view of the graph, the middle section is not clearly seen in the mesh plot.

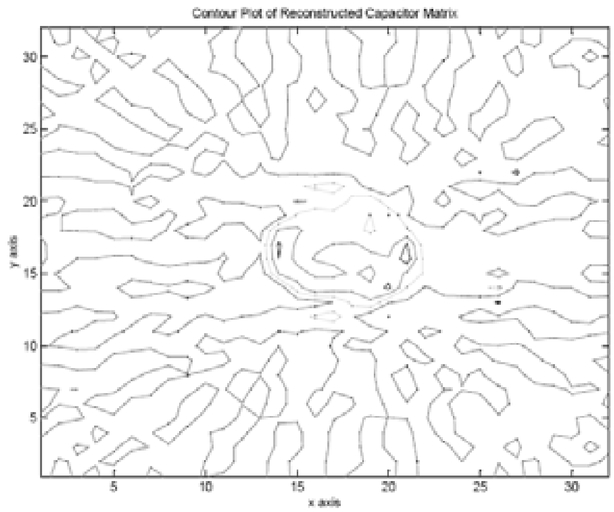

Figure 9: Contour plot of pipe with water.

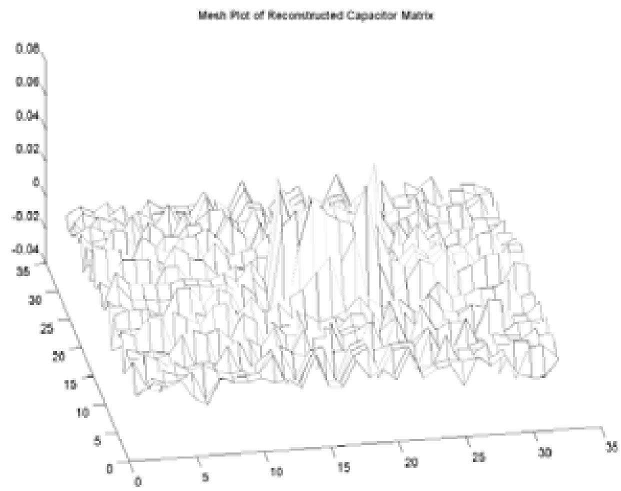

Figure 10: Mesh plot of pipe with water.

7. Conclusion

When comparing the mesh plots to the sensitivity maps, if we were to rotate graph (f) from Figure 2 180°, a resemblance of the mesh plot would be created. This indicated that our sensor system was working in accordance to the description in Sensitivity distributions of capacitance tomography sensors with parallel field excitation [6] about sensitivity maps.

After comparing the contour plots, the plot with no water in the bottle Figure 7 shows an empty space in the center of the bottle. The plot with the bottle half filled with water Figure 9 clearly indicates the bottom half of the bottle has a higher dielectric than the top half of the bottle; therefore, we were able to image the water in the bottle.

Keep in mind that the modeled data in Figure 2 was created from a twelve electrode system and the experimental system only had eight electrodes. This could dramatically change the sensitivity of the electrodes and resolution of the images. The electrode configuration was also different. The formation of the twelve electrodes was cylindrical and thereby non-linear. The experimental electrodes were parallel and linearly measured.

By constructing this simple setup, someone seeking an approach to creating images using capacitive sensors should be able to do so and with improvements to the system would be able to produce a better quality image.

8. Acknowledgements

Thanks to Mononita Ghoshal of Agilent Technologies for assistance with measurement equipment.

9. References

[1] www.enm.com/training/siemenscourses/snrs_3.pdf

[2] www.everything2.com/index.pl?node_id=1739225

[3] Soleimani Manuchehr and Lionheart W R B 2005 Nonlinear image reconstruction for electrical capacitance tomography using experimental data *Meas. Sci. Technol.* **16** 1987-1996

[4] Isaksen Q 1996 A review of reconstruction techniques for capacitance tomography *Meas. Sci. Technol.* **7** 325-337

[5] A.C. Kak and Malcolm Slaney*, "Principles of Computerized Tomographic Imaging", IEEE Press, 1988",* also available online at http://www.slaney.org/pct/

[6] Yang W Q, Spink D M, Gamio J C and Beck M S 1997 Sensitivity distributions of capacitance tomography sensors with parallel field excitation *Meas. Sci. Technol.* **8** 563-569

[7] Huang S M, Plaskowski A B, Xie C G and Beck M S 1988 Tomographic imaging of two-component flow using capacitance sensors J, Phys, E: Sci, Instrum. **22** 173

[8] Warren Tony 2006 "*Feasibility Study of Capacitive Tomography*", Master's Thesis, Southern Polytechnic State University