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Sensitivity Mapping for Electrical Tomography Using Finite Element Method

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Abstract: This paper presents the construction of sensitivity map (SM) using finite element method for electrical tomography systems that has the soft-field characteristic such as electrical capacitance tomography (ECT). The SM is generated based on a sixteen-channel ECT system on a 110 mm diameter pipe circumference by using COMSOL Multiphysic. Sensitivity mapping is the pivotal element for tomography imaging in solving the forward problem. The obtained sensitivity map for 120 projections forming a sensitivity matrices are presented in this paper.

Keywords: Sensitivity map, tomography, electrical capacitance

1. Introduction

Electrical Capacitance Tomography (ECT) is a technique for cross-sectional visualization of the distributed dielectric materials within the sensing region. It is based on measuring the changes of inter-electrode capacitance of the distributed field. Commonly, is it applied in a multiphase flow formed by elements of different permittivity [1]. From the measured data, a reconstructed image of the permittivity distribution inside the vessel can be obtained via an image reconstruction algorithm such as linear back projection or tikhonov regularization method. A typical tomography system can be describe as in figure 1[2].

2. The basic principle of ECT

The basic principle of ECT system is to detect the capacitance changes within an electric potential distributed field. A simple and most effective applications of such system is to measure the capacitances changes on a parallel plate electrode configuration [3] as in figure.1.

The basic buildup of an ECT system will consist of a sensory system, signal processing circuitry and software interfacing where image reconstruction work take place. The process flow of ECT is depicted in figure 2 follows [2, 5].

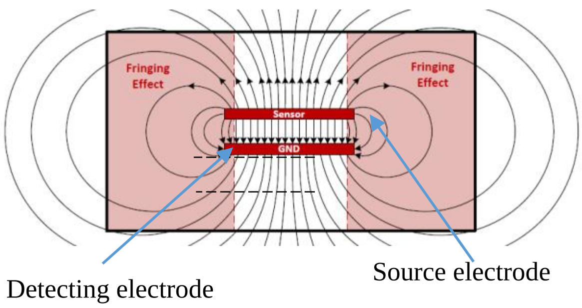

Fig. 1. Electric fields of a parallel plate electrodes

The energized capacitive plate will have a uniform electric field between the electrodes far from their edges but these field lines form fringes at the edge of these plates known as fringe effect which can be removed by encircling the sensing electrodes with a guard electrode [4]. By applying Gauss' law, the charge measurement of the inter-electrode capacitances can be determined from equation (1). Further understanding of ECT modelling is explained in [5].

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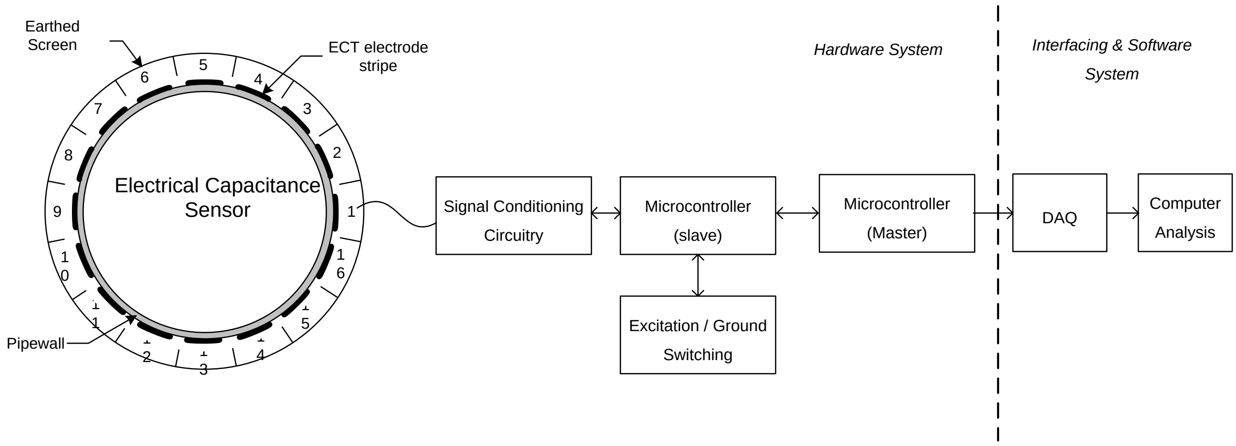


Fig. 2. Electrical capacitance tomography system

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d_p} \quad (1)$$

Where ε_0 is the permittivity of vacuum space, ε_r is the permittivity of the dielectric material between the measurement electrodes, d_p is the distance between the electrodes, A is the area of the sensing plate.

Referring to figure 3, unlike hard-field system, the soft-field system has electric potential field line propagates from a source electrode (e1) in a curved line and further curves away between the two different dielectric materials (liquid ε_2 and air ε_2).

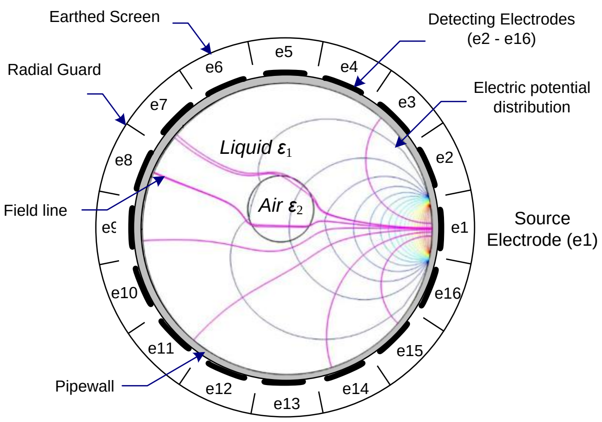


Fig. 3: Soft-field effect with two different dielectric materials

The presents of different dielectric materials in this inhomogeneous condition changes the space distribution thus causes capacitance changes between the electrodes. The capacitance between electrodes are measured between each source and detector electrode sequentially with a sum of 120 independent measurements obtained with equation (2) [6-8].

$$N = \frac{n(n-1)}{2} \quad (2)$$

where N is the total number of electrodes. The increasing number of electrodes generally could improve the resolution of image result but in practice, higher number of sensor will trade-off in decreasing the sensing size of the sensor to fit on a pipe circumference thus reduces the sensitivity to capture the inter-electrode capacitance.

3. Forward Problem

The forward problem is addressed to determine the theoretical sensor data by discretizing an image plane into a grid of 128 × 128 pixels for each sensor projections (e1 to e16) [79].

Therefore, the 100 mm diameter pipe is discretized into an image plane which consist of 16384 element array of which 13076 effective pixels within the boundary circle or within the region of interest while 3308 pixels are ineffective as in figure 4.

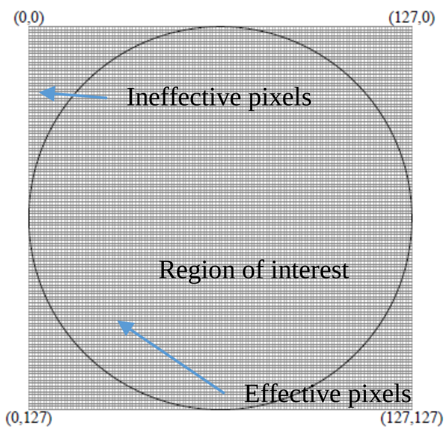


Fig. 4. 2D discretized image plane of 128 × 128 pixels

The discretized image plane in pixels will be used to display the sensitivity distribution of the normalized composite permittivity (ECT) of each pixel to construct images. Therefore, the forward problem can be solved by modelling the ECT sensor projections to its corresponding sensitivity map matrices [9, 10].

4. FEM Modelling

The basis of the finite element method was developed as a way of decomposing complex problems into simple well known parts. COMSOL Multiphysics software is able to carry out FEM to solve physical systems of immense complexity through approximated simulation of the system geometry. The FEM setup includes following steps to generate the sensitivity maps for 120 projections [11].

- Sensor geometry modelling
- Material selection and assignment
- Meshing process
- Pre-processing work

The electrostatic multiphysics (ES) is selected for the whole FEM analysis. By using COMSOL, an ECT geometry model is created to virtualize the sensor projections in two dimensional view with its actual size and dimension as in figure 5.

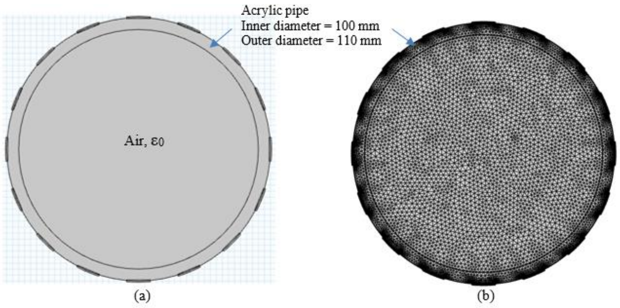


Fig. 5. 16-channel ECT configuration (a) Geometry model (b) Meshed geometry

To obtain a smooth projection map, extra fine meshing with maximum element size of 0.222 mm and minimum 44e^{-3} mm under meshing physics controlled setting is chosen since denser meshing would provide better image reconstruction. The relationship between the capacitance and the permittivity distribution is governed by Poisson equation as follows [12].

$$\nabla \cdot [\,\varepsilon(r)\nabla\,\varphi(r)] = 0 \qquad (3)$$

Where $\varepsilon(r)$ = spatial permittivity distribution and $\varphi(r)$ = potential distribution. The boundary conditions imposed on the model has an electric potential $\varphi(r) = \Delta V_{ij}$ where ΔV_{ij} is the potential difference between the excitation electrode *i* and detection electrode *j*. Meanwhile, the remaining electrodes are virtually set as ground where $\varphi(r) = 0$. The electrical charge Q_{ij} on the detecting electrodes can be calculated using Gauss surface integral law as in equation (4) thus the inter-electrode capacitance is as equation (5) [14].

$$Q_{ij} = \oint_s \varepsilon(r) \cdot \nabla\varphi(r) ds \qquad (4)$$

$$C_{ij} = \frac{1}{\Delta V_{ij}} \oint_s \varepsilon(r) \cdot \nabla\varphi(r) ds \qquad (5)$$

where *s* = electrode surface. Electrostatic interface model will simulate and solve these complex numerical problems. This process will be repeated for each electrode until all 120 projections are measured. As a result, the electric field distribution of the projection beam from one sensor to another will be intensified as in figure 6. It shows the generated sensitivity map for the permittivity distribution for electrode e1 to e5.

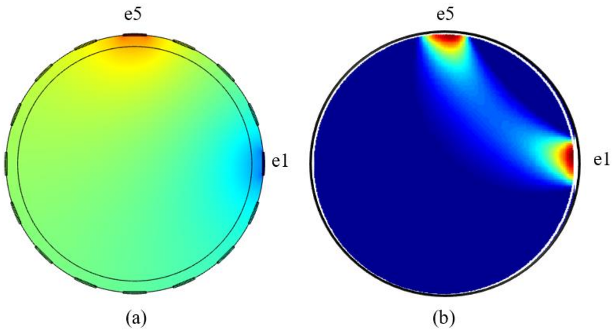
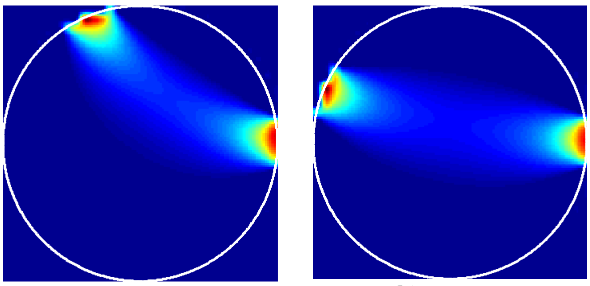


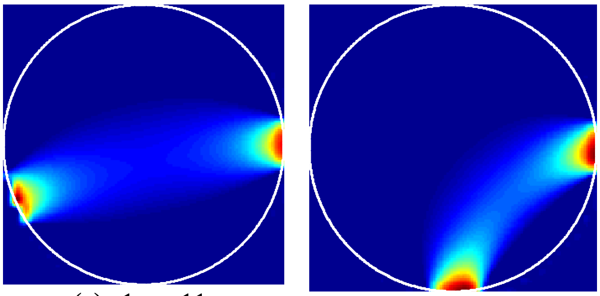
Fig. 6. Sensitivity map projection e1 to e5 (a) projection in COMSOL (b) refined projection using Matlab

5. Results and Discussion

The other projections from an excitation electrode e_i to the detectors e_j are depicted in figure 7 follows. Since the circular electrode positions are symmetrical, only 120 independent projections are required.



(a) e1 to e7 (b) e1 to e9



(c) e1 to e11 (d) e1 to e13

Fig.7. Sensitivity distribution projections for ECT

From figure 7, it is observed that the sensitivity field is non-uniformly distributed over the medium of interest. The sensitivity is higher within the area closer to the excitation and detection electrode pair. On the other hand, its sensitivity is much lower in the center region. Therefore, the drawback of this soft-field effect will affect the measurements on the center region.

6. Conclusion

This paper presented a method to generate sensitivity distribution of an electrical capacitance tomography system using COMSOL multiphysic software; a finite element analysis software. The complex forward problem can be solved using COMSOL by visualizing the cross-sectional image on a discretized image plane of 128 × 128 pixel for high spatial resolution image. All 120 sensitivity maps formed up a sensitivity matrices which will be used for image reconstruction work. The generated sensitivity map will be useful for image reconstruction task by using a specific algorithm such as linear back projection.

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