

## 3D MODELLING OF ELECTRICAL CAPACITANCE AND ULTRASONIC SENSOR INTEGRATION USING FINITE ELEMENT METHOD

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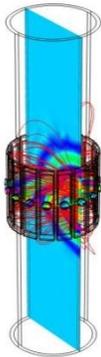
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### Graphical abstract



### Abstract

This paper presents a three dimensional (3D) modelling of a dual modality sensor composite which emerges electrical capacitance sensor (ES) and ultrasonic transducer (UT) for process tomography applications. The dual-modality tomography (DMT) setup has employed a customized ES electrodes along with UT on a single-plane. A finite element method is used to analyze the feasibility and the behavior of the DMT setup in 3D environment using COMSOL Multiphysics software. This simulation is performed both in a homogeneous and inhomogeneous conditions to investigate the wave distribution and its pattern thus the simulation results are presented in this paper.

**Keywords:** Tomography, electrical capacitance, comsol, finite element analysis, sensor guard

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## 1.0 INTRODUCTION

Electrical Capacitance Tomography (ECT) and Ultrasonic tomography (UT) has been extensively employed in the field of process tomography (PT) for flow monitoring applications such as oil and gas industries and others.

However, most tomography systems employ a single measurement techniques which often suffers from insufficient data to produce better results [1-4]. This problem is seen to be more critical in multiphase flow conditions whereby a mixture of oil, water and

gas components needs to be visualize. Due to the limitation of these sensors, a multisensory technique is necessarily needed to obtain complimentary data where a single-sensory approach could not achieve.

Multi-modal tomography system was developed as a part of the Technology Foresight Challenge (TFC) research project which began in United Kingdom (UK) in 1996 [4].

In this paper, a non-invasive approach of a combined ECT and UT sensor array to form a dual modality tomography (DMT) system. A basic block diagram of such system is illustrated in Figure 1.

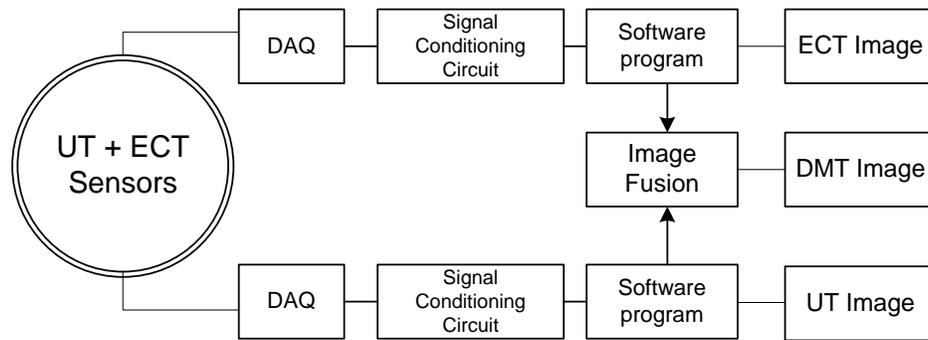


Figure 1 Electrical capacitance tomography system

## 2.0 DMT FUNDAMENTAL

Basically, the DMT system incorporates the emergence of ECT and UT system composite which essentially bind to its respective sensing principle. Both ECT and UT is sensitive to different parameters and properties. Its sensing behavior depends on the soft-field and hard-field characteristic respectively.

### 2.1 ECT Principle

The principle of ECT sensor is to measure the capacitance changes within the cross sectional distributed field with different dielectric materials. This can be determined by equation 1 [3, 5, 6].

$$C = \frac{\epsilon_0 \epsilon_r A}{d_p} \quad (1)$$

Where  $C$  is the capacitance value,  $\epsilon_0$  is the permittivity value in free space,  $\epsilon_r$  is the permittivity value of the dielectric material,  $A$  is the sensing zone and  $d_p$  is the distance between electrode sensors.

### 2.2 UT Principle

Unlike ECT whereby its detection principle is based on capacitance distribution within a particular area, UT relies upon detectable interactions between bulk mediums. Due to the difference in acoustic properties between these bulks, partial reflection and transmission of the acoustic pressure at the boundary interface will occur. This interaction can be estimated by determining the acoustic impedance as in equation 2 [7, 8].

$$\pm Z_0 = \pm \rho_0 V_0 \quad (2)$$

Where  $Z_0$  is the acoustic impedance ( $\text{kg/m}^2\text{s}$ ),  $\rho_0$  is the density of the medium ( $\text{kg/m}^3$ ) and  $V_0$  is the sound velocity in the medium ( $\text{m/s}$ ).  $Z_0$  carries a positive and negative sign indicating a forward or backward propagation of ultrasonic wave.

## 3.0 PREPARATION OF FINITE ELEMENT ANALYSIS

A simulated experiment is carried out using electrostatic solver (ES) and pressure acoustic solver (PA) to evaluate the ECT and UT system respectively.

Since both types of sensor are configured on the same plane, the multiphysic solvers needs to be performed simultaneously to reflect to the real-time condition of the DMT system. Several steps of FEM are taken as follows:

- Sensor geometry modelling
- Material selection
- Boundary settings
- Meshing process

### 3.1 Sensor Geometry Modelling

The COMSOL Multiphysics software is used to establish the 3D modelling of the DMT system. The constructed 3D geometry model of the DMT system has the actual dimension of a real physical system as shown in Figure 2.

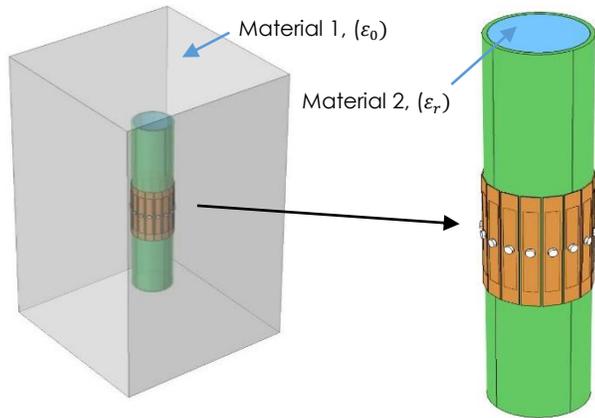


Figure 2 3D geometry model of DMT hardware for finite element analysis

A total of 16 units of customized FR4 copper ECT sensor is employed as explained in [9] along with 16 units of UT sensors on a 110 mm acrylic pipe. The customized ECT sensor has the flexibility to easily curve or bend to attach firmly on a curved pipe surface [9]. A 10 mm diameter is allocated in the middle of the sensing zone to allow UT sensor to be installed. Figure 3 further illustrate the sensor design.

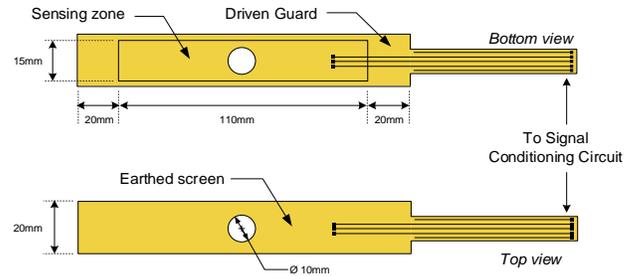


Figure 3 Customized ECT sensor from FR4 copper material

### 3.2 Material Selection

A variety of material selection is available in the material browser inside COMSOL software. The FR4 copper material were applied on the ECT sensor whilst air (gas) material were applied to the surrounding area of the sensor to create a virtual empty air (gas) environment (see Figure 2). Following Table 1 provides the materials involved for the simulated experiment and its properties.

Table 1 Materials and properties of DMT model for FEM analysis

Properties / materials	Acoustic Impedance x10 <sup>6</sup> [kg/m <sup>2</sup> s]	Relative Permittivity ε(r)
Copper	44.6	6.0
Water	1.5	80.4
Acrylic	3.25	1.9
Air	0.43	1.0
Crude oil	1.3	3.0

### 3.3 Boundary Setting

Since the geometry model settings involve several types of materials, the boundary conditions and interfaces between two or more of these materials need to be set accordingly. The boundary conditions for ECT setup is to solve the sensor electric potential φ(r) according to Poisson equation as follows [6].

$$\nabla \cdot [\epsilon(r)\nabla \phi(r)] = 0 \tag{1}$$

Where ε(r) is the spatial permittivity distribution and φ(r) is the potential distribution.

As for UT, The acoustic wave propagation will have to travel through several sound soft boundaries which creates a boundary condition at the domain interfaces of the acrylic wall and the inhomogeneous materials. The impedance boundary condition is specified according to the material properties which is governed by follows.

$$-n \left[ \left( \frac{-1}{\rho} (\nabla p_t - q) \right)_1 - \left( \frac{-1}{\rho} (\nabla p_t - q) \right)_2 \right] = 0 \tag{3}$$

Where ρ is the density, p<sub>t</sub> is the total acoustic pressure.

### 3.4 Meshing Process

Finite element meshing technique is used for dividing a complex problem into small elements by breaking down the geometry model into nodes and then connecting these nodes to form triangle elements. The 3D geometry model is discretized and meshed at an extremely-fine quality ranging from a maximum and minimum size of 0.8 mm and 0.0016 mm respectively as in Figure 4.

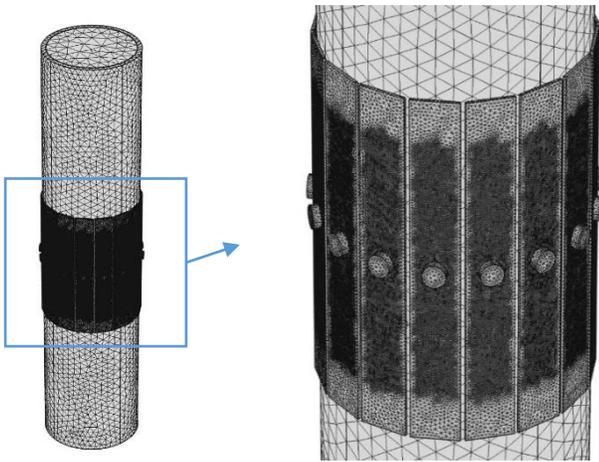


Figure 4 Finite element 3D mesh model

After meshing process, the meshed model is solved using stationary domain solver over each meshed elements.

#### 4.0 RESULTS AND DISCUSSION

The computed simulation results are visualized in a 3D environment which could easily viewed in multiple angles for further analysis. Following Figure 5 shows the FEM result at time ( $t$ ) = 65  $\mu$  second.

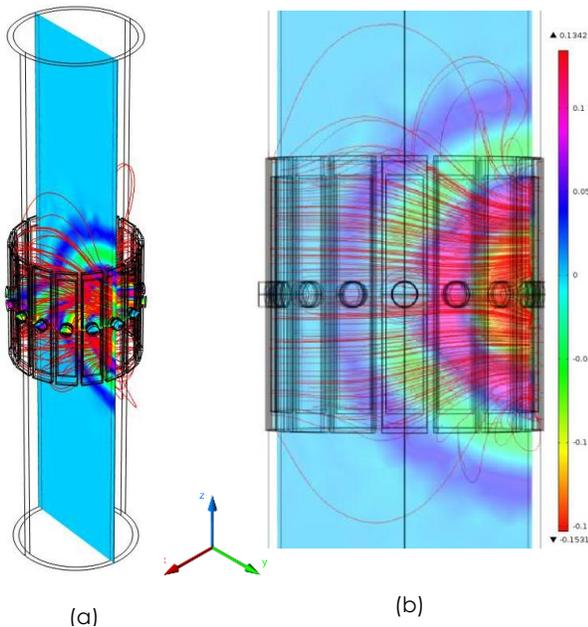


Figure 5 FEM result for DMT system (a) 3D view (b) zy-plane view

Figure 5 shows that both the ECT and UT sensors are able to incorporate with each other on a single-

plane. The streamline of electric field for a single excitation is in curved shape. Due to the soft-field effect, this curved shape lines dispersed over the 10 mm diameter hole in the middle of the ECT sensing zone as in Figure 5(b). This way, the electric field gap at the hole area is reconciled.

In the meantime, ultrasonic sensors mounted through these holes will anticipate any disclosed object such as air bubble. To further investigate the 3D results, the model is sliced into xy-plane in 2D view as in Figure 6.

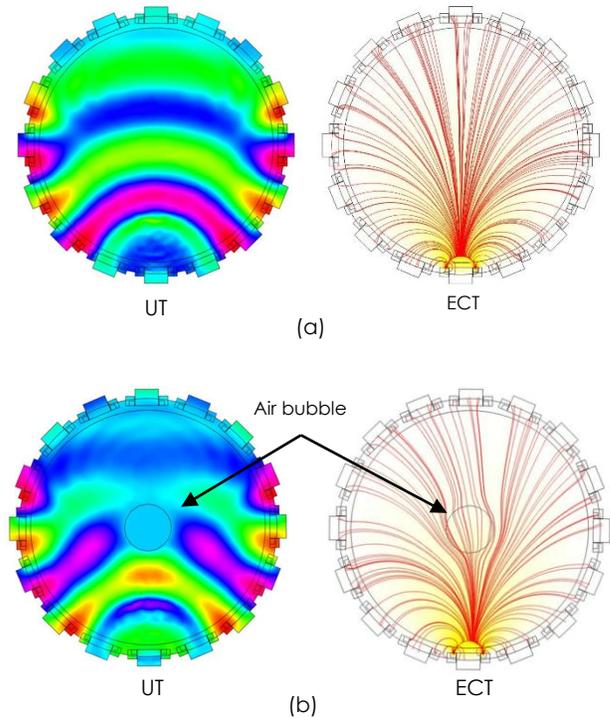


Figure 6 Acoustic pressure field and streamline electric field on xy-plane view at  $t = 65 \mu s$  (a) homogeneous condition (b) inhomogeneous condition

The acoustic pressure field and the streamline electric field for ECT and UT respectively is seen to propagate evenly across the transmitting sensor towards the detecting sensors in homogeneous condition (Figure 6(a)).

While the electric field lines curves and sway away between two different dielectric materials in an inhomogeneous condition, the acoustic wave responded by reflecting or deflecting at interface boundaries between bulk mediums with different acoustic impedance. Therefore, a drop of sound pressure and potential distribution is anticipated on the neighboring detecting sensors [10].

The response of both ECT and UT on a single-plane has shown that the model is feasible for dual-modality sensor integration. Thus, the DMT system could provide complimentary sensor data for multiphase flow applications measuring oil, water and gas components on a single-plane.

## 5.0 CONCLUSION

DMT system is basically the emergence of two single-modality system using ECT and UT technique. To further investigate the feasibility of such system, a 3D model of this DMT system is carried out using FEM with a 3D geometry model. The geometry model employs dimensions of the actual physical system which is constructed in COMSOL software. With this model, the pressure acoustic solver and electrostatic solver is used to solve the complex forward problem of the system.

The simulated result of the electric field distribution and wave propagation is successfully visualized by streamlines and surface view for ECT and UT respectively. Thus, the sensor response in both homogeneous and inhomogeneous condition satisfied the soft-field and hard-field characteristic. This further indicates that the customized ECT sensor incorporates well with the ultrasonic sensors on a single-plane simultaneous measurement.

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