Modelling, Calibration and Fabrication of Electrical Capacitance Tomography Sensor for Bone Imaging

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Abstract. Electrical capacitance tomography is a technique to measure internal permittivity distribution based on external capacitance measurements which in turn generate a cross-sectional image representing the permittivity distribution thereby the material distribution. It possesses the advantages of non-radioactive, non-intrusive, non-invasive, high imaging speed and low cost over the conventional medical imaging techniques. Inter-electrode measurements are done by placing electrodes around the non-conductive dielectric medium cylinder inside which, the medium to be imaged is placed. This paper emphasizes on modelling and fabricating an electrical capacitance tomography sensor using ANSYS APDL for bone for which the sensor is calibrated using air and water. ECT sensor is modelled and fabricated by mounting 12 identical rectangular copper electrodes were placed symmetrically outside the Poly-vinyl chloride (PVC) cylindrical tube. The output from sensors can be converted to digital voltage values used for image reconstruction in MATLAB.

1. Introduction

Electrical Capacitance Tomography (ECT) is a process of recovery of the image depending on the capacitance change technique which possesses the qualities required for medical imaging. An ECT sensor gives electrical output which can be measured across multiple electrodes which surround the dielectric medium. Capacitive electrodes are mounted around the measured object, to find the distribution of dielectric capacitance between the electrodes measured which are given for further processing to generate an output image representing the material to be imaged.

An ECT sensor has been modelled, calibrated and implemented for normal and cracked bone using ANSYS [1]. A numerical modelling of crack in femur shaft bone using ANSYS has been done [2]. Designing, modelling and analysis of a three phase induction motor drive [3], a three phase squirrel cage induction motor [11] have been done using ANSYS. An AC (Alternating Current) ECT system has been employed for sensing dielectric medium level of urea, ash and water in the permittivity distribution. The system presented radiation-free, less expensive, non-dangerous and non-
contact level measurements and further measurement of level with high temperature is looked forward [4]. Charge discharge measurement method of ECT system has been evaluated. Evaluation of fast active differentiator method to overcome the drawback of the results of method tested here is the future prospect of this paper [5]. AC ECT system implemented for detecting temperature of solid and liquid. The paper further requires investigation of high accuracy measurement for various medium [6]. Image reconstruction is done using MATLAB [4-5], and LABVIEW [7], [15].

Monitoring systems using various methods and the overall effects on the imaging process in both the medical and industrial sector have been discussed. ECT system sections and composition and specifications of ECT sensor are discussed [8]. Operation principles and calibration methods of ECT system are discussed. LBP and Yang’s method based on Landweber’s iteration method algorithms are discussed [9]. Possibility of flow measurement by an ECT sensor with electrodes is discussed [10]. Principle of ECT, constitution of a typical ECT system, ECT sensor design and specifications, image reconstruction algorithms like forward problem and inverse problem in which non-iterative algorithm linear-back projection, iterative algorithm Landweber iteration algorithm and Model-based image reconstruction algorithm are discussed [12]. ECT sensor with a high excitation frequency in order to image the dielectric/conductive gas/liquid distributions was implemented and used in Petroleum industries [13]. Design of ECT system choosing external electrodes was focussed, sensor modelling using COMSOL multiphysics was done and explained in detail and electric potential distribution is imaged. 2D and 3D geometries of ECT sensors were generated [14]. Model of an 8 electrode ECT for imaging of bone was implemented and concluded to be used for imaging of human tissues [15]. A model-based image reconstruction algorithm for the ECT system to derive WLR and the thickness of liquid layer of oil-continuous annular flows has been implemented whose accuracy needs further validation [16].

2. Block diagram
An ECT system has 3 main blocks as shown in Figure 1. ECT sensor will measure the permittivity of the material to be imaged in terms of an electrical quantity. For every pair of excited electrodes, ECT sensor will give an electrical output. Based on number of electrodes, the number of electrical outputs given by the sensor will vary accordingly. Data acquisition system converts the electrical quantity measured by the sensor into a form which can be given for image reconstruction. Therefore the electrical quantity is converted to digital voltage values. These are given for image reconstruction of the object to be imaged.

![Figure 1 Block diagram of ECT system](image-url)

Figure 1 Block diagram of ECT system

3. ECT Sensor
The development process for modelling an ECT sensor using ANSYS is based on the relationship between capacitance and dielectric properties as different dielectric properties between the conductors will create different capacitance values. The sensors usually consist of electrode plates and the material to be imaged is introduced into the dielectric medium. The measurement is determined as given in Equation (1).
\[ C = \frac{\varepsilon_0 \varepsilon_r A}{d} \]  

(1)

Where \( C \) is the capacitance to be measured, \( \varepsilon_0 \) is the permittivity of free space, \( \varepsilon_r \) is the permittivity of the dielectric, \( A \) is area of the plate, \( d \) is the distance between the pair of electrodes across which the measurement is made. A 12-electrode ECT sensor model is developed by creating the shape of outline of PVC pipe which is circular for this application. The Copper electrodes are mounted on the PVC tube. The electrodes are identical and symmetrically mounted. Bone structure is introduced in the hollow circular portion of the sensor. For calibration purpose air and water which have their relative permittivity as 1 and 80 respectively are created in the hollow portion.

![ECT sensor](image)

**Figure 2** ECT sensor

The source electrodes are excited with 20V and detector electrodes are grounded in sequence as mentioned in Table 1 for measuring capacitance. The outputs obtained are 66 values of capacitances and 66 plots of potential distribution for 12-electrode ECT sensor according to Equation (2)

\[ M = \frac{n(n-1)}{2} \]  

(2)

| Electrode excited | Capacitance measured |
|-------------------|----------------------|
| 1                 | \( C_{12}, C_{13}, C_{14}, C_{15}, C_{16}, C_{17}, C_{18}, C_{19}, C_{110}, C_{111}, C_{112} \) |
| 2                 | \( C_{23}, C_{24}, C_{25}, C_{26}, C_{27}, C_{28}, C_{29}, C_{210}, C_{211}, C_{212} \) |
| 3                 | \( C_{34}, C_{35}, C_{36}, C_{37}, C_{38}, C_{39}, C_{310}, C_{311}, C_{312} \) |
| 4                 | \( C_{45}, C_{46}, C_{47}, C_{48}, C_{49}, C_{410}, C_{411}, C_{412} \) |
| 5                 | \( C_{56}, C_{57}, C_{58}, C_{59}, C_{510}, C_{511}, C_{512} \) |
| 6                 | \( C_{67}, C_{68}, C_{69}, C_{610}, C_{611}, C_{612} \) |
| 7                 | \( C_{78}, C_{79}, C_{710}, C_{711}, C_{712} \) |
| 8                 | \( C_{89}, C_{810}, C_{811}, C_{812} \) |
| 9                 | \( C_{910}, C_{911}, C_{912} \) |
4. Modelling of Electrical Capacitance Sensor using ANSYS

ANSYS is a general purpose software package based on Finite Element Analysis which is used to build 2-D and 3-D models of real world scenarios without compromising on geometrical details. Table 2 provides the specifications of ECT sensor used in ANSYS.

Table 2 Specifications of ECT sensor

| No | Item                                      | Parameter     |
|----|-------------------------------------------|---------------|
| 1  | Number of electrode plates                | 12            |
| 2  | Outer diameter of PVC tube                | 71.5mm        |
| 3  | Inner diameter of PVC tube                | 70mm          |
| 4  | Electrode length                          | 14.9754mm     |
| 5  | Spacing between electrodes                | 3.7439mm      |

4.1. Pre-processing

Preferences is selected as electric. The pre-processor is entered to initiate model-building session. Model is built using solid modelling procedures. The dimension of the model is 2D. Working plane is established. By default, when mechanical APDL session is initiated, a working plane is located on the global Cartesian X-Y plane, with its x and y axes collinear with the global X and Y axes which is used. It can be changed if needed. Create tables of element attributes (element types, real constants, material properties). Set element attributes pointers. Element type is selected as electrostatic for the application of our project. Relative permittivity for the material model is defined. Three elements of electrostatic type for dielectric (air), PVC tube, Copper electrodes and their relative permittivity are defined.

4.2. Geometry Modelling

Inspite of robustness issues of the solid modelling features of Mechanical APDL the model required for analysis can be successfully created with planning and alternative strategies. Areas are required if you wish to use area elements or if you wish to create volumes from areas. A circle of diameter 70mm is drawn for the dielectric. An annular circle for PVC tube is drawn with inner diameter 70mm and outer diameter 71.5mm. An electrode of length 14.9754mm and width 0.5mm is placed around PVC tube. The coordinate system is changed to cylindrical and the electrode placement angle is calculated to be 24°.11 such electrodes are duplicated and equidistantly placed with angle of spacing between electrodes as 6°. Boolean operators or number controls are used to join separate solid model regions together as suitable. All the areas are glued. After gluing the entities maintain their individuality but they become connected at their intersection. Overlapping is done after gluing. The overlap commands will join two or more entities to create three or more new entities that encompass all parts of the originals. After gluing and overlapping, the three regions become 1 complete structure after which the entire structure can be meshed. Areas are numbered to know the number of each electrode as shown in Figure 3.
Meshing

Meshing is used for getting finite elements which defines the accuracy obtained. Meshing is discretization which is the process of dividing the model into elements consisting of nodes. The processing phase solves equations for these nodes and obtains results. Meshing is the initial step in doing analysis of any geometry. The process for generating a mesh of nodes and elements is:

(a) Set the element attributes: By setting element attribute pointers, the element attributes to the solid model entities are allocated.
(b) Set mesh controls: A large number of mesh controls are available from which to choose from which SmartSize was used.
(c) Meshing the model

The meshed structure is as shown in Figure 4.

Solution

Simultaneous set of equations are solved that the finite element method generates for the model. The results of the solution are: nodal degree of freedom values which forms the primary solution and derived values which form the element solution. The nodal degree of freedom is used in this paper. The model is solved by applying loads by defining loads as electric boundary voltage on areas. The source electrode is supplied 20V and subsequent electrodes are detector electrodes and are given 0V one after another and results are plotted in post processing. Considering, electrode 1 is source electrode and electrode 2 is detector as shown in Figure 5, the model is solved by calculating the solution. After solving, the electrodes on which loads are applied are highlighted.
Post processing are tools that review the results of an analysis. After building the model and obtaining the solution, post processors help to find out whether the design really works when put to use. Two postprocessors are available in ANSYS: the general postprocessor and the time-history postprocessor. General postprocessor is used in this paper.

4.6. ECT sensor for bone

In order to model an ECT sensor with a bone suspended in it surrounded by air, a PVC tube was first generated and then nodes were plotted with respect to the origin. The plotted nodes were joined by lines to get straight continuity and arcs with certain radius to get the desired curvature. Doing this an outline of bone is created. Now 12 identical electrodes are equidistantly mounted outside the PVC tube. Areas are generated for the bone by filling in the outline and for air surrounding the bone by filling the space between bone and inner lining of ECT sensor as shown in Figure 6.

Now to assign the mesh attributes we need to assign element types, real constants, material properties for every area. Since we need potential distribution as output, we go for electrostatic type element i.e. 2D quad 121. For different areas we need to give different material properties as desired. For bone the material properties given are structural and electromagnetics. In structural, the properties are: Elastic modulus-20GPa, Poisson’s ratio-0.3, Density-3.88. In electromagnetics, the properties are: Real part of permittivity-7.3, Imaginary part of permittivity-19.91, Relative permittivity-21.21, Conductivity-0.03, Resistivity-33.33. For air, PVC and Copper plates, the properties defined are density in structural and relative permittivity in electromagnetics. For air the properties are, Density-1.225, Relative permittivity-1. For PVC the properties are Density-1.38, Relative permittivity-3. For Copper the properties are Density-8.96, Relative permittivity-6. These are defined in pre-processor before modelling. After modelling before meshing we need to assign each set of values of a particular material to the respective area in mesh attributes. After assigning mesh attributes, meshing is done. For meshing smart size with size 1 for fine meshing is chosen. With this the finite element generated is fine and enables more uniform distribution of load thereby increasing the accuracy. Voltage of 20V is
applied to source electrode and 0V to detector electrode. After applying voltage to the electrodes 2 yellow pointers point to the electrodes to which the voltages were applied. The entire model is then solved.

5. Calibration of ECT sensor

Twenty known capacitances are used instead of sensor and the current output is checked. Based on this an iterative algorithm is generated. Hence, twenty voltages for twenty capacitances are acquired. These twenty voltages are put in a table and given to the iteration method thereby deriving a formula as given in Equation (3).

\[ C = (K_1V_n) + (K_2V_{n-1}) + \cdots + (K_nV_0) \]  \hspace{1cm} (3)

Based on the known set of capacitors a multiple regression formula is derived using which an unknown capacitance measurement of sensor can be accomplished by connecting the sensor instead of capacitors. The sensor is calibrated in ANSYS using materials of known permittivity viz. air and water with relative permittivity 1 and 80 respectively. For material with lowest permittivity viz. air the voltage distribution should be not hindered and highly penetrative on contrast with highest permittivity material viz. water.

6. Fabrication of Electrical Capacitance Tomography Sensor

ECT sensors are usually built with metallic electrodes evenly mounted around the outer face of a pipe or vessel wall. For the configuration in which electrodes are mounted outside, the pipe must be non-conducting for which PVC tube is used. For fixation of metallic plates on PVC tubes Araldite is used. Araldite is a synthetic resin adhesive for bonding metals, glass, porcelain, china and other materials. It sets by the interaction of a resin with a hardener. Warming helps in reducing the curing time and improving the strength of the bond. The adhesive needs to be applied on both the surfaces viz. the copper plates and the tube and then firmly press the 2 surfaces. In consequence of this type of electrode mounting, ECT with external electrodes becomes a non-invasive and nonintrusive imaging technique. The determination of the number of electrodes in ECT is a trade-off between speed of capacitance measurement and resolution of the reconstructed image. The pipe structure should be such that it is comfortable and easy for the patient to insert his hand or leg for measurement. Every electrode is soldered with a wire so that connections can be made to every electrode as a source or a detector. Model femur bone for hardware is sculpted based on the 3D model step file as used in ANSYS. The next set of current measurements of the sensor is taken by placing the model bone in the sensor. The sensor, bone and sensor with bon inside are shown in sequence in Figure 7.
Source of 20V, 20kHz square wave signal with 50% duty cycle is given by function generator to the source electrode. The current flow is measured using a multimeter by connecting it to the detector electrode. The negative terminals of function generator and multimeter are connected together thereby completing the circuit. The setup is show in Figure 8.

7. Results and Discussion

Nodal solution in contour plot is used to plot the electric potential distribution. The results obtained are as follows in the Table 3 and Table 4 shown below.

Table 3: Electric potential variation between electrode 1 and 2 for air medium

Table 4: Electric potential variation between electrode 1 and 2 for water medium
Table 5: Electric potential variation between electrodes 1 and 2 for bone in air

The outputs in the Table 3, Table 4 and Table 5 above represent the electric potential distribution when a pair of electrodes is given the potential. Table 3 shows the outputs when the dielectric medium is air inside the pipe. Table 4 shows the outputs when the dielectric medium is water. These two tables represent the outputs for calibration purpose. Based on these outputs the sensor is calibrated for implementation with bone as medium. Table 5 shows the outputs when the dielectric medium is bone suspended in air. Because of its low permittivity the voltage distribution is spread over the entire region inside the pipe for air while for bone in air, potential distribution is evenly spread in air but deviates as it encounters the bone thereby indicating the presence of bone. The ANSYS output graph for capacitances in pF for air and bone is shown in Fig 9.

![Capacitance plot for air and bone](image)

**Figure.9** Capacitance plot for air and bone

The hardware output graph for current in μA for air and bone is shown in Fig 10.

![Current plot for air and bone](image)

**Figure.10** Current plot for air and bone
8. Conclusions

Conventional imaging techniques are radio-active and hence inhibit its use on humans. Electrical capacitance tomography is a technique which overcomes this major drawback and hence can be extensively and safely used thereby contributing to medical field and benefitting the society. ECT sensor is the sensing element which is the initial part of the ECT system. It gives output values as capacitance proportional to the permittivity change within. In order to design such an ECT sensor for bone imaging practically calibration is required, for which ANSYS APDL is used in which media of known permittivity are used as dielectric media in this paper. Using ANSYS, the sensor is modelled virtually using actual dimensions. Media used are air and water with permittivity 1 and 80. From the observations, for air, the potential distribution is uniform and evenly spread since it is the material with lowest permittivity while for water due to its high permittivity has restricted voltage distribution thereby indicating the variation in permittivity. It is concluded that a sensor which gives diverse potential distribution with change in permittivity. Voltage plot for bone surrounded by air is plotted and the detection of bone is visible in the variation of voltage distribution. Capacitances for air and bone are calculated using ANSYS and the capacitances values for electrode 1 as reference are plotted as a graph. Capacitance plots for air and bone imply that since the air has lower permittivity its graph is lower than that of bone. Capacitance plot for air is smoother than that of bone. Graph with current magnitude variations from fabricated sensor tallies with capacitance plot giving a similar plot but with less difference between two graphs. Therefore it is concluded that the fabricated sensor can be used for image reconstruction.

REFERENCES

[1] M. Ambika and S. Selvakumar “Modeling and Calibration of Electrical Capacitance Tomography Sensor for Medical Imaging,” presented at the 8th Int. Conf. on Engineering and advancement in technology, Coimbatore, India, 2018.

[2] S. Mohammad, S. Ahmad and D. Ruslizam. “Analysis of Crack Propagation in Human Long Bone by Using Finite Element Modeling.” AIP Conference Proceedings, pp. 100014-1—100014-5, 2017.

[3] K. Prasob, N. Praveen Kumar, T. B. Isha, "Inter-turn short circuit fault analysis of PWM inverter fed three-phase induction motor using Finite Element Method", Circuit Power and Computing Technologies (ICCPCT) 2017 International Conference on, pp. 1-6, 2017.

[4] K. Manikandan and S. Sathiyamoorthy. “Level Measurement of ASH Handling System Using AC ECT.” World Applied Sciences Journal, vol. 34, pp. 1338-1342, 2016.

[5] K. Manikandan and S. Sathiyamoorthy. “Performance Analysis of AC-DC Electrical Capacitance Tomography.” International Journal of Innovation and Scientific Research, vol. 25, pp. 540-544, 2016.

[6] K. Manikandan and S. Sathiyamoorthy. “Temperature Measurement of Various Permittivity Medium by AC ECT.” International Journal of Scientific Engineering and Applied Science, vol. 2, pp. 2395-3470, 2016.

[7] K. Manikandan and S. Sathiyamoorthy. “Modeling and Implementation of AC Electrical Capacitance Tomography.” Circuits and Systems, vol. 7, pp. 3818-3830, 2016.

[8] Ruzairi Hj. Abdul Rahim et al. “A Review: Tomography Systems in Medical and Industrial Processes.” Jurnal Teknologi, vol. 73, pp. 1–11, 2015.

[9] M. S. Soji, K. Manikandan and S. Sathiyamoorthy. “Electrical Capacitance Tomography System.” International Research Journal of Emerging Trends in Multidisciplinary, vol.1, pp. 2395-4434, 2015.

[10] J. Sun and W. Yang. “A dual-modality electrical tomography sensor for measurement of gas–oil–water stratified flows.” Measurement, vol.66, pp. 150-160, 2015.
[11] Aa Rajiv, Nathan, Va, Ashwanth, Aa, Rajan, Sa, and Dr. Sindhu Thampatty K.C., “Modelling and analysis of rotor bearing fault in a three phase squirrel cage induction motor using ANSYS® Maxwell2D”, International Journal of Applied Engineering Research, vol. 10, pp. 3612-3616, 2015.
[12] Z. Ren. “Exploration of medical applications of electrical capacitance tomography.” Ph.D. thesis, University of Manchester, 2015.
[13] Y.Li and M.Soleimani. “Imaging conductive materials with high frequency electrical capacitance tomography.” Measurement, vol. 46, pp. 3355–3361, 2013.
[14] M.A. Zimam, E.J. Mohamad, R.A. Rahim, L.P Ling, “Sensor Modeling For An Electrical Capacitance Tomography System Using Comsol Multiphysics.” Jurnal Teknologi, vol.55, pp. 33-47, 2012
[15] B.B.Abraham and G. Anitha. “Designing of Lab View Based Electrical Capacitance Tomography System for the Imaging of Bone Using NI ELVIS and NI USB DAQ 6009,” in Bonfring International Journal of Power Systems and Integrated Circuits, vol. 2, pp. 2277 – 5072, 2012
[16] Y. Li, W.Yang, Z.Wu and D.Tsamakis. “Gas/oil/water Flow Measurement by Electrical Capacitance Tomography,” in Proc. IEEE-IST, 2012, pp. 1558-2809.