Influence of design parameters of ECT sensors on the quality of reconstructed images

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Abstract. The configuration of electrodes and guards, as well as the shielding arrangement, determines the resolution and sensing field of an ECT sensor. In this work, a full study of the response of a 12-electrode sensor is carried out by means of 2D and 3D Finite Element Method based simulations, and the influence of the design parameters on the sensitivity and quality of the reconstructed images is stated.

Keywords: Electrical Capacitance Tomography sensor, Finite Element Method, image reconstruction

1. Introduction

Electrical Capacitance Tomography (ECT) was developed to image industrial processes containing dielectric materials, such as the gas-solid mixtures found in fluidized bed boilers [1, 2], or the gas-oil flow in pipelines [3, 4].

An ECT system measures capacitance changes between pairs of electrodes distributed around the cross-section of a pipe containing the multi-phase flow to be imaged. The data thereby obtained, related to permittivity distribution inside the sensor and, therefore, to phases concentration, are processed using image-reconstruction techniques in order to estimate the instantaneous multi-phase distribution inside the pipe.

The sensor array under study here consists of 12 measurement electrodes, with two sets of driven guard electrodes and an exterior earthed screen to prevent external noise and to confine the electric field lines within the pipe. Grounded radial guards have also been added between every set of driven guards and measuring electrode, as shown in Figure 1. The inner and outer radii of the pipe are 6.00 cm and 6.5 cm, respectively. The pipe wall is assumed to have a relative permittivity of 3.

Measurement sensitivity of an ECT system depends upon sensor configuration [5]. Finite Element Method (FEM) based simulations have proven to be useful tools for studying the sensitivity of ECT sensors [6, 7] and can therefore be applied to obtain optimum designs.
FEM is used to solve the boundary value problem that describes the electric field in an ECT sensor:

\[
\begin{align*}
\nabla (\varepsilon (x, y, z) \nabla \phi (x, y, z)) &= 0 \\
\phi (S_k) &= V_k
\end{align*}
\]

where $\varepsilon(x,y,z)$ is the permittivity distribution inside the pipe, $\phi(x,y,z)$ is the potential distribution and $S_k$ is the surface at fixed potential $V_k$ (electrodes, screen, etc.).

Figure 2 shows the mesh used to perform the two-dimensional simulation. The 3D mesh is obtained by repeating the 2D mesh along the Z axis.

2. Image Reconstruction

To study the overall effect of the design parameters, simulated image reconstructions have been carried out using the algorithm known as Linear Back-Projection (LBP) [8].

In Figure 3, three permittivity distributions have been reconstructed using a non-shielded sensor, that is a sensor with no radial guards, and using a shielded sensor. The relative image error is given by Equation (2) [8]:

\[
\text{Image error} = \frac{\|g^* - g\|}{\|g\|}
\]

where $(g)$ is the original permittivity distribution and $(g^*)$ is that obtained using the LBP algorithm.

The image error for the reconstructed images in Figure 3 is indicated below every illustration. As can be seen, the presence of radial guards improve the quality of the reconstructed images [9].
Figure 3: Simulated permittivity distributions and reconstructed images using a non-shielded sensor and a shielded sensor.

The effect of the electrode broadness has been evaluated by reconstructing the permittivity distributions shown in Figure 4 with sensors of different measurement electrodes covering ratio \([10]\) (30, 60 and 90\%). It is plain to see that, the higher the covering ratio, the lower the reconstruction error.
Figure 4: Simulated permittivity distributions and reconstructed images using sensors with different electrodes covering ratio

The permittivity distribution in Figure 5 (a) has been used for the reconstruction of a phantom at different heights along the axis of the sensor. This phantom has been simulated at the middle part of the electrode cross-section ($z=0$) and at the middle part of the upper driven guard cross-section ($z=h$), as shown in Figure 5 (b) and (c). The image reconstructions were carried out for three different ratios between electrode axial and longitudinal sizes, $r=1/4$, $r=1$ and $r=2$. The results are shown in Figure 6, together with the reconstruction error, for the plane $z=0$. As can be seen, the image obtained is more intense and presents lower relative error for short electrodes. The influence of the phantom outside the electrode region on the reconstruction can be quantified as the ratio between the norms of the reconstructed images at $z=h$ and at $z=0$ [10]:

$$\text{Phantom Influence} = \frac{\| \hat{g}_{z=h} \|}{\| \hat{g}_{z=0} \|}$$

This parameter takes the values of 0.8862, 0.7992 and 0.6711 for $r=1/4$, $r=1$ and $r=2$, respectively. Thus, measurement and imaging at the electrode cross-section is less distorted by elements outside the electrode region for larger electrodes.
Figure 5: (a) Permittivity distribution in the cross section. (b)-(c) Heights at which the phantom is simulated

Figure 6: Reconstructed images using sensors with different ratios between electrode axial and longitudinal length

Finally, Figure 7 depicts reconstructed images of the distribution in Figure 5 (a) at $z=0$ for the ratios between the driven guard axial length and electrode axial size $q=1/2$, $q=2$ and $q=4$. As happened when enlarging the electrodes, the image becomes distorted and less intense when larger driven guards are used.
3. Conclusions
Simulations based on the Finite Element Method in two and three dimensions were carried out to study the influence of the design parameters on the quality of the image reconstruction.

Image reconstruction of different phantoms has been carried out for several values of the design parameters, confirming that broader electrodes provide enhanced images. In addition, better images are obtained when using shorter electrodes, whereas longer electrodes are less sensitive to elements far from the electrode cross-section (z=0). The presence of shielding axial tracks also enhances the quality of the reconstructed images.

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