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Evaluation of fringe effect of electrical resistance tomography sensor

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ABSTRACT

A conventional electrical resistance tomography (ERT) sensor uses pin electrodes for current injection, and the electric field spreads far beyond the electrode plane, as a result of "soft field" nature. This phenomenon is referred to as "fringe effect" and would cause measurement errors and image distortion. The impact of fringe effect on measurement and reconstructed images depends on the object distributions, the conductivity contrast and others. It is not trivial to evaluate the fringe effect of an ERT sensor and its impact on the measurement and the reconstructed images. In this paper the fringe effect of an ERT sensor is evaluated for central core and off-central core distributions at different axial positions and with different axial dimensions and conductivity contrasts. Then, how to compensate for the fringe effect of the ERT sensor is discussed and a method proposed for improving the measurement accuracy and image reconstruction. Finally, the findings and methodology is verified by experiment.

1. Introduction

Electrical resistance tomography (ERT), often referred to as electrical impedance tomography (EIT), has been developed since 1980s. Its applications have been extended from medical imaging to industrial monitoring and measurement, e.g. multi-phase flows with conductive medium inside cylindrical pipes or vessels. To measure a multi-phase flow, 2D or 3D images may be reconstructed. While some researchers worked on 3D image reconstruction, realistically, 2D image reconstruction is preferred because it is much simpler and faster than 3D image reconstruction. To obtain a 2D image for a cylindrical pipe or vessel, a certain number of electrodes (say 16) are normally mounted evenly around its inner surface to form a single-plane ERT sensor. To obtain 3D images, a multi-plane ERT sensor, i.e. multiple single-plane ERT sensors at different axial layers, is needed. While the current-injection and voltage-measurement strategy is usually adopted for ERT measurement, different protocols can be applied for data acquisition, e.g. adjacent, opposite and diagonal with non-conductive boundary for 2D ERT imaging [6]. Among those protocols, the adjacent strategy is the most popular and used for data acquisition in this paper.

Since the material distribution of a multi-phase flow in industry and the electric field of an Electrical Tomography (ET) sensor are essentially 3D, a great effort has been dedicated to 3D imaging with ERT and electrical capacitance tomography (ECT) [2,3,4,5,12,16,17,19,22,21,28,29]. Even though the achieved 3D imaging results seem promising, more effort is needed to improve the image quality. Firstly, most of them are implemented with incomplete measurement data because the electrodes on both the bottom and top sides of the true 3D sensor are normally removed for flow measurement [22]. The one with complete measurement data should be similar to true 3D ECT imaging proposed by Li [12] and Soleimani et al. [22]. It means that they are only approximated 3D imaging. Secondly, the condition number of the sensitivity matrix of a

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3D ET sensor is much larger than that of a 2D sensor due to the increased number of unknowns, as compared by Li [12] between 2D and true 3D ECT sensors. A much larger condition number means that 3D ET imaging presents a more severely ill-posed and ill-conditioned problem and would be tolerant to very small errors caused by the measurement noises or simulation errors [22]. This brings high demands on sensor fabrication and measurement electronics. A fast reconstruction algorithm was implemented by Pinheiro et al. [19] to reduce the condition number of 3D ERT imaging but led to deteriorated image resolution. Thirdly, 3D imaging with a reasonable resolution takes a much longer time than 2D imaging [12,19,22] because it normally needs to obtain the approximated inverse of a very large sensitivity matrix for image reconstruction, as indicated by the large number of independent measurements and voxels for imaging. This would limit its application in situations with high commands on the real-time performance. Even though 3D imaging by a single-plane ET sensor was attempted, either the position or the shape of the object cannot be correctly reconstructed [4,22]. More geometry parameters in a 3D ET sensor also makes the sensor design more difficult than a 2D ET sensor since the approximated 3D imaging is an "open-field" as described by Li [12]. In view of the above points, 2D ET imaging is preferred in most cases.

As discussed by Sun and Yang [23], the fringe effect would occur with 2D ET imaging because certain conditions should be satisfied to make it permissible that the 3D reconstruction can be simplified to 2D with tolerate errors. The first condition is that the electric field should be confined inside an ERT sensor and axially homogeneous. This can guarantee a 3D electric field to be represented by the corresponding 2D one. The second one is that the material distribution should be axially homogeneous. This would guarantee the 3D material distribution to be simplified into a 2D distribution. If any one of those two conditions is not satisfied, severe fringe effect may occur.

Up to now the fringe effect of ERT sensors for 2D imaging has not been investigated systematically. The fringe effect was illustrated qualitatively and avoided by using voltage excitation and long strip electrodes (not pin electrodes) as described by Li and Yang [13]. It was investigated quantitatively by comparing the simulation results of a 3D ERT sensor with the corresponding 2D analysis when the fringe effect was ignored [15], or with the corresponding experimental results [8]. However, the comparison was made quantitatively only for simulated or measured potential differences before normalization, which may be referred to as "absolute" fringe effect. The image-forming mechanism of an EIT system was described by using equi-current perturbation hypothesis and axially extending an object from the sensor plane to a distant position, aiming at investigating the fringe effect with different electrode pairs [20]. It was concluded that where the disturbed equi-current surface with the largest current density intersects the cross-section of the EIT sensor is where the largest change in the reconstructed image would take place. The image reconstructed for the extended objects covering the whole cross section would be circular, but for the extended objects not covering the whole cross section, the situation would be more complicated. Wang [27] also conducted research into the fringe effect in EIT with experimental, simulation and analytical models. One of the findings was that the axial 3D attenuation range (3/4 attenuation) regarding the EIT sensor plane would be one third of the vessel's diameter. Another phenomenon discovered was that the image reconstructed for a small object in the halfway between the center and the pipe wall and moving away from the sensor plane would move towards the center of the sensor cross section. But these two findings did not account for the influences of the object length on the fringe effect since only a small non-conductive ball was taken as a test object in the experiment. Sun and Yang [23] found that similar fringe effect exists in ECT and ERT sensors if both of them are excited by a voltage signal, and increasing the electrode length and grounded end guards would reduce the fringe effect in both cases. But the fringe effect of the conventional ERT sensors with the current injection strategy was not investigated, e.g. the normalized potential differences or resistance. Therefore, it is worthwhile evaluating the fringe effect of single-plane ERT sensors with the current injection strategy, especially with the normalized measurements, which are actually used for image reconstruction.

ERT may be applied to various industrial processes, e.g. multi-phase flow imaging and measurement, which normally involves a conductive fluid as the continuous phase and non-conductive material as the dispersed phase, e.g. in a bubble column [7,9,25,11,26]. The dispersed phase is usually measured and imaged, with the distribution being axially non-homogeneous. In this case there would exist severe fringe effect. This brings the necessity to study the fringe effect with axially non-homogeneous distribution. Because of many possible distributions, a specified ERT sensor with a typical distribution, i.e. core distribution, is investigated, aiming to compensate the fringe effect in 2D imaging. This involves examining whether the above two conditions are satisfied with different measurement strategies, evaluating how large the fringe effect is with objects of different lengths and conductivities and what the influence is when the objects are placed at different axial and cross-sectional positions. Thus a method is proposed on the basis of phenomenon discovered during future investigations to compensate for the fringe effect of the ERT sensor in different situations. Experimental verification of the findings and the proposed methodology is then presented.

2. Image reconstruction and ERT sensor

2.1. Linear back projection (LBP) and evaluation

Before numerical simulation, it is necessary to introduce a popular image reconstruction algorithm, linear back-projection (LBP). It is a simple single step method, which is used for both ERT and ECT. Two crucial aspects in LBP for ERT need to be considered: the sensitivity maps and the normalized resistance. The element in a 2D sensitivity map, e.g. the sensitivity of electrode pairs $i - j$ (i for excitation and j for measurement) to the conductivity