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Image reconstruction algorithm for capacitively coupled electrical resistance tomography

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ABSTRACT

Capacitively Coupled Electrical Resistance Tomography (CCERT), which is on the basis of Capacitively Coupled Contactless Conductivity Detection (C^4D), is a novel electrical tomography technique. As a developing technique, more research work should be undertaken. This work focuses on the study of image reconstruction algorithm of CCERT. Combining Tikhonov regularization principle and Simultaneous Iterative Reconstruction Technique (SIRT), a new hybrid image reconstruction algorithm is proposed. Tikhonov regularization is introduced to obtain the initial reconstructed image. SIRT is used to obtain the final reconstructed image. With a 12-electrode CCERT prototype, image reconstruction experiments are carried out. Experimental results show that the images reconstructed by the proposed image reconstruction algorithm are satisfactory and are in accord with the actual distributions of two-phase flows. The research work also indicates that the proposed image reconstruction algorithm is more suitable for image reconstruction of CCERT, comparing with the conventional image reconstruction algorithms of Electrical Capacitance Tomography (ECT) and Electrical Resistance Tomography (ERT).

1. Introduction

Electrical Resistance Tomography (ERT) can implement the parameter measurement of conductive two-phase flows by providing cross-sectional images and has broad application prospects in many industrial fields, such as petroleum, chemical engineering, environment protection, etc. [1–4]. However, the conventional ERT systems are on the basis of contact conductivity detection technique, the electrodes are directly in contact with the conductive fluid, that may result in electrochemical erosion effect and polarization effect of the electrodes. Meanwhile, unpredictable measurement errors will arise, if the electrodes are contaminated. These drawbacks limit the practical applications of the conventional ERT systems.

Capacitively Coupled Contactless Conductivity Detection (C^4D) was proposed by Zemann et al. [5] and da Silva and do Lago [6] independently in 1998. Its measurement principle is shown in Fig. 1. A typical C^4D sensor consists of an insulating pipe, two metal electrodes (an excitation electrode and a detection electrode) placed cylindrically around the outer surface of the insulating pipe, an AC source and an AC current pick-up unit, as shown in Fig. 1(a). The electrodes, the insulating pipe and the conductive fluid can form two coupling capacitances C_1 and C_2, and the conductive fluid between the two electrodes can be equivalent to a resistor R, that forms an alternating current path. Fig. 1(b) shows the equivalent circuit of the C^4D sensor. If an AC voltage is applied to the excitation electrode, an AC current which contains the information of the conductivity of the fluid can be obtained from the detection electrode.

Obviously, C^4D is a contactless conductivity detection technique and can avoid the electrochemical erosion effect and the polarization effect. So, C^4D has received great attention of scientific researchers since it appeared. Unfortunately, C^4D is still a developing technique. Up to date, it is mainly studied and used in the research field of analytical chemistry for ion concentration or conductivity detection [7–9]. Few research works concerning the application of C^4D in process tomography are reported.

Currently, by introducing C^4D into the research field of process tomography, our research group has proposed a novel electrical tomography, Capacitively Coupled Electrical Resistance Tomography (CCERT). Based on a mathematical model of CCERT, the sensitivity fields have been obtained by Finite Element Method (FEM) simulation. A 12-electrode CCERT prototype has been developed with its data acquisition system designed on the basis of the Phase-Sensitive Demodulation (PSD) method. With the prototype, the feasibility of CCERT has been verified by Linear-Back Projection (LBP) algorithm [10]. The influence of three main parameters (the angle of the electrodes, the permittivity and the thickness of the pipe wall) on the measurement performance of CCERT sensor has been studied and an optimized CCERT sensor has been designed [11]. However, compared with Electrical

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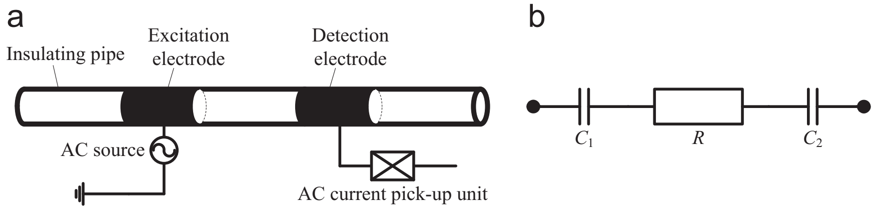

Fig. 1. Measurement principle of C^4D. (a) Construction of typical C^4D sensor and (b) simplified equivalent circuit of the C^4D sensor.

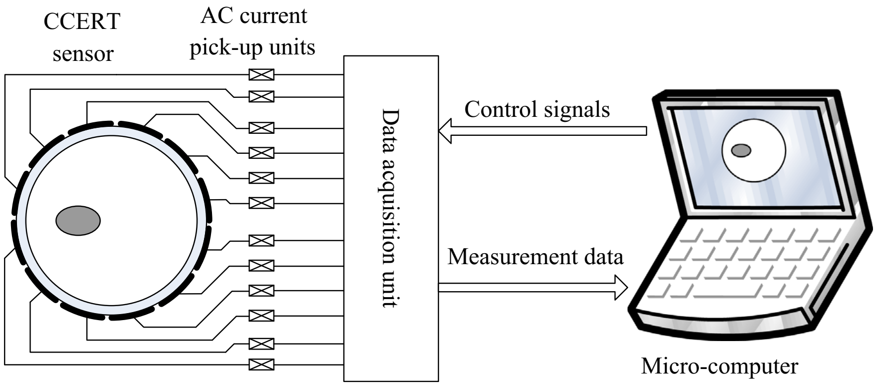

Fig. 2. Construction of the 12-electrode CCERT prototype.

Capacitance Tomography (ECT) and Electrical Resistance Tomography (ERT) [1–4,12–16], our knowledge and experience concerning CCERT are very limited. More research work should be undertaken. Up to date, only the LBP algorithm is reported concerning image reconstruction of CCERT. Although the LBP algorithm is widely used because of its simplicity and rapidity, the image quality should be improved.

This work aims to seek a new image reconstruction algorithm which is suitable for CCERT. Combining Tikhonov regularization principle and Simultaneous Iterative Reconstruction Technique (SIRT), a new hybrid image reconstruction algorithm is proposed. Meanwhile, with the 12-electrode CCERT prototype, image reconstruction experiments are carried out to investigate the effectiveness of the proposed algorithm.

2. 12-Electrode CCERT prototype

Fig. 2 shows the construction of the 12-electrode CCERT prototype, including a 12-electrode CCERT sensor, 12 AC current pick-up units (each electrode is connected with an AC current pick-up unit), a data acquisition unit and a micro-computer.

As shown in Fig. 3(a), the electrodes of the 12-electrode CCERT sensor are mounted symmetrically around the outer surface of an insulating pipe. Fig. 3(b) shows the cross-sectional view of the CCERT sensor with electrodes numbered from 1 to 12. The insulating pipe is made of polyvinyl chloride (PVC). The inner diameter d_0 and the thickness δ of the insulating pipe are 110 mm and 2 mm, respectively. The length L_e and the angle θ_e of the electrodes are 150 mm and 25°, respectively. The detailed information concerning the prototype is available in Refs. [10,11].

Any two electrodes (one is the excitation electrode and the other is the detection electrode) form an electrode pair. The equivalent circuit of each electrode pair can be simplified as a resistance in series with two capacitances, as shown in Fig. 3(c).

For each independent measurement, an electrode pair is firstly selected as the measurement electrode pair. Then, AC voltage source is applied to the excitation electrode. The detection electrode is kept at zero potential and the rest electrodes are kept at floating potential. Finally, by the AC current pick-up unit, a current measurement which reflects the conductivity distribution of the fluid can be obtained.

For a complete measurement cycle, electrode 1 is firstly excited, the electrodes 2–12 are used as the detection electrode to form the electrode pairs respectively and the AC currents are measured. Next, electrode 2 is excited, electrodes 3–12 are used as the detection electrode to form the electrode pairs and the AC currents are measured. The measurement cycle continues until electrode 11 is excited and electrode 12 is used as the detection electrode. Therefore, total 66 independent current measurement data can be obtained. The 66 current measurement data are transmitted to the micro-computer to reconstruct the cross-sectional image of the conductivity distribution.

3. Image reconstruction algorithm

The aim of image reconstruction of CCERT is to determine the conductivity distribution from the current measurement data (projections). It can be attributed to solve the following matrix equation:

$$P = WF \tag{1}$$

where, p_i is the ith current measurement, $i=1, 2, \ldots, M$. M is the number of independent current measurement data and $M=66$. $P=[p_1, p_2, \ldots, p_M]^T$ is the projection vector. f_j is the equivalent conductivity of the jth pixel, $j=1, 2, \ldots, N$. N is the number of pixels. $F=[f_1, f_2, \ldots, f_N]^T$ is the vector of equivalent conductivity. $W=[w_{i,j}]$ is the weight coefficient matrix, whose entries are $w_{i,j}$. $w_{i,j}$ is the weight coefficient of the jth pixel to p_i. The values of $w_{i,j}$ are predetermined by Finite Element Method (FEM) simulation.

CCERT is a new kind of electrical tomography technique. Its measurement principle is different from that of the conventional ERT. Meanwhile, compared with the conventional ERT, the weight coefficient matrix (corresponding to the sensitivity distributions) of CCERT is also different, that may cause different image reconstruction challenges. Mathematically, the image reconstruction of CCERT is similar to that of the conventional ERT. It is also a typical ill-posed inverse problem. To develop a suitable image