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Image reconstruction algorithm for electrical capacitance tomography based on data correlation analysis☆

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ABSTRACT

In order to acquire improved ECT reconstruction method that can increase spatial resolution and reduce the image errors, this study proposes an ECT imaging method based on data correlation analysis, instead of using conventional sensitivity maps. This method first collected the capacitance values when each micro element in the sensor is assigned in turn by a high dielectric constant, and then compared the simulated capacitance values with the true capacitance. Then a correlation coefficient can be obtained between them. Images can be reconstructed according to the correlation coefficient and the re-calculated capacitances. The simulation results show that the quality of the image reconstruction is improved, and the algorithm does not need to be iterative, but when combined with iterative method the image quality can be further improved. Also this new algorithm can be adapted to the situations when there are already materials in the sensor, and the materials, such as water, with high dielectric constant can also be imaged.

1. Introduction

There are a large number of two-phase flow systems in the fields of power generation industry, petroleum and refinery industry, chemical industry, metallurgy industry etc. At the present stage, the two-phase flow pattern recognition is mainly used as an observation or a measurement method, according to flow pattern change criterion or flow chart to determine the flow mode with the flow parameters. However, due to the complex flow mechanism of two-phase flows, the use of traditional detection technology can hardly match the large variety of the flow conditions.

Electrical capacitance tomography, ECT for short, is a process tomography technique developed for the industrial multiphase flow measurement since the 1980s. Various media have different dielectric constants. This technique can calculate the spatial distribution of the dielectric constant inside and deduce the distribution of the working medium in the sensing zone by measuring the capacitance values between the electrodes, usually placed on the insulating surface. Because ECT does not interfere the flow field, and with the merits of fast response, economical, non-radioactive and other advantages, it is rapidly becoming an indispensable tool in research and industrial practices, such as multiphase flow [1] and flame analysis [2].

With all the success of ECT, one of the areas remaining much improvement is the relatively low spatial resolution, and this more pronounced on the pixels further away from the electrodes. This problem is closely related to the soft-field nature of the electric field.

When an image is reconstructed, most algorithms use a matrix called sensitivity map in the inverse process, or in both the forward and inverse steps for an iterative algorithm, such as the well-known Landweber method [3]. Recently, a pre-iteration method was developed that iteratively updates the sensitivity maps instead of the image, and then use the final sensitivity map in real time ECT measurement [4]. This method offers fast image reconstruction speed while maintaining the same image quality as the Landweber algorithm does. However, as reflected in the literature, practically the sensitivity maps are generated as the inner product of the electrode fields that are usually calculated by solving the Poisson equations for electric fields. The soft-field nature may thus be inherited during the generation of the sensitivity map. Furthermore, as the strength of electrical field diminishes for the locations further away from the electrodes, the sensitivity reduces correspondingly. To alleviate such a weakness, researchers have proposed different approaches, such as the expanded sensitivity map [5], in which the elements in the sensitivity map can be constructed based on a set of blocks of different sizes. The stability and image quality can be improved with the suitably designed extended sensitivity maps.

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There are also other considerations on proper division of the image elements in the measurement domain, such as proposed by Teniou, and Meribout [6], where a hierarchical mesh algorithm was proposed for ECT image reconstruction by locating progressively the boundaries by refining the mesh. At each step of the hierarchy the image was obtained using Gauss–Newton algorithm (GN) or Hierarchical Mesh Regularized Constrained Gauss–Newton algorithm (HM-RCGN). The algorithm gives two advantages: the speed of image reconstruction is significantly accelerated and the spatial resolution of the reconstructed images is enhanced. In addition, Teniou and Meribout used a basis constraint method, in which the basis support vectors are extracted that can significantly reduce the number of unknowns and hence the inverse problem can be more stable. The author also proposed an algorithm that makes use of the edge gradient information to estimate the possible motion of an object, which reduces the computing cost while enhances local spatial resolution [7]. In terms of reconstruction accuracy, Firdaus and Meribout compared the accuracy of three algorithms, i.e. LBP, Landweber, and a Modified Landweber, which provided a good basis for algorithm evaluation [8].

From the above, it can be seen properties of the sensitivity maps and the relationship between the pixel values and the capacitance measured on the electrodes play an important role in determining the quality of the images. In this study, we would like to propose an alternative approach that will not use the conventional sensitivity maps generated on the electromagnetic principles. Instead, we wish to explore the direct correlations between the pixel permittivity values and the capacitances measured by the electrodes. The method will be built on the principle of statistics that can cover a broad range of disciplines [9]. In doing this we hope the nature of the soft-field problem can be alleviated and the quality of the images can be improved.

2. The theoretical basis

2.1. The basic principles of electrical capacitance tomography system

Electrical capacitance tomography system is composed of three parts: sensing system, data acquisition system, data analysis system and imaging reconstruction system, as shown in Fig. 1, where 1 is the working medium, 2 is the insulation frame, 3 is the electrodes, 4 is the measurement data, 5 is the control signal, and 6 is the reconstructed image [10]. When the distribution of the medium in the sensing zone changes, the value of capacitances between the sensor electrodes will change, this can be measured according to the actual capacitance between the electrodes to calculate the distribution of working medium within the sensing zone.

Assuming that the volume of two phase flow composed of discrete phase and continuous phase is respectively sum V_2 and V_1, dielectric constant is ε_2 and ε_1, we can get the dielectric constant equivalent to the original permittivity distribution as follows:

$$\varepsilon = \frac{V_1}{V}\varepsilon_1 + \frac{V_2}{V}\varepsilon_2 = \frac{V_1}{V}\varepsilon_1 + \frac{V - V_1}{V}\varepsilon_2 = \varepsilon_2 + \frac{V_1}{V}(\varepsilon_1 - \varepsilon_2) \tag{1}$$

For an 8-electrode sensor, 28 pairs of independent electrode combinations can be made. When the multiphase flow remains static and the distribution of the dielectric constant does not change, the capacitance between the $i - j$ electrode pairs can be expressed as:

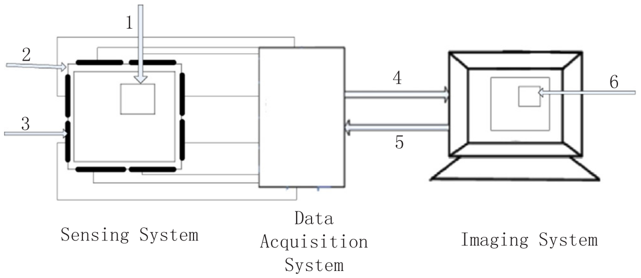

Fig. 1. Sketch of an ECT system.

$$C_{ij} = \iint^{D} \varepsilon(x,y)S_{ij}(x,y)dxdy \tag{2}$$

where C_{ij} is the capacitance between the electrode i and the electrode j, ε (x, y) is the distribution function of the dielectric constant in the sensing zone and S_{ij} is the sensitivity of the electrode pair i and j for a medium at the location (x, y).

When the cross section of the sensing zone is divided into E microelements, and assuming that the sensitivity of each micro element can be regarded as a constant value, i.e. the average value over the element, formula (2) can be simplified as:

$$C_{ij} \approx \sum_{i=1}^{E} \varepsilon(\xi_i,\quad \eta_i)\cdot S_{ij}(\xi_i,\quad \eta_i)\cdot\delta_i = \sum_{i=1}^{E} \varepsilon(i)\cdot S_{ij}(i)\cdot\delta_i \tag{3}$$

where $S_{ij}(i)$ represents the average sensitivity of the i-th micro element and δ is the area of the element.

When the dielectric constant in the k-th micro element of the sensing zone is ε_2 and the dielectric constant in the other micro element is ε_1, the capacitance is written as $C_{ij}(k)$, and the capacitance change is:

$$\Delta C = C_{ij}\mathrm{k} - C_{ij}^1 \approx \sum_{i=1}^{E} \varepsilon(i)\cdot S_{ij}(i)\cdot\delta_i - \sum_{i=1}^{E} \varepsilon_1\cdot S_{ij}(i)\cdot\delta_i = (\varepsilon_2 - \varepsilon_1)\cdot S_{ij}(k)\cdot\delta_k \tag{4}$$

$$C_{ij}(\mathrm{k}) = (\varepsilon_2 - \varepsilon_1)\cdot S_{ij}(k)\cdot\delta_k + C_{ij}^1 \tag{5}$$

By normalizing, the capacitive and sensitive fields can be written as:

$$C_{ij}(\mathrm{k}) = (\varepsilon_2 - \varepsilon_1)\cdot(C_{ij}^2 - C_{ij}^1)\cdot S_{ij}(k)\cdot\delta_k + C_{ij}^1 \tag{6}$$

where δ_k represents the correction factor associated with the k-th cell area in the sensing zone, since the sensitivity map is divided into the same area, it can be ignored.

Conventionally, the sensitivity map for a pair of electrodes i and j can be made by alternatively assigning an excitation voltage to electrode i or j, then calculating the corresponding field of electric potential, and finally acquiring the inner product of the two fields, i.e.:

$$S_{ij(x,y)} = -\int_{p(x,y)} \frac{E_i(x,y)}{V_i} \times \frac{E_j(x,y)}{V_j} dxdy \tag{7}$$

where $E_i(x,y)$ is the electric field when electrode i is excited with a voltage V_i, $p(x,y)$ is the area of the pixel centered at the point (x, y). This is then carried out for all the electrode pairs.

After obtaining the sensitivity map by simulation method, we can obtain the capacitance values using Eq. (6) when the dielectric constant is ε_2 in the k-th element and the dielectric constant in the other micro element are ε_1 [11,12].

2.2. Calculation of correlation coefficient

In general, the relationship between x and y is used in our model:

$$y = a + bx + \eta \tag{8}$$

When Eq. (6) is compared with Eq. (8), because $G = C_w S$(G is the pixel gray value),

$$C_{ij}(k) = (\varepsilon_2 - \varepsilon_1)\cdot(C_{ij}^2 - C_{ij}^1)\cdot {C_w}^T\cdot G\cdot\delta_k + C_{ij}^1 \tag{9}$$

we can simplify Eq. (6) as $C(k) = AG\bullet {C_w}^T + C_{ij}^1 + \eta$, where $A = (\varepsilon_2 - \varepsilon_1)\bullet(C_{ij}^2 - C_{ij}^1)\bullet\delta_k$ is constant, $b = G$, and η is a variable error.

It is usually considered that $\eta \sim \mathrm{N}(0,\sigma^2)$ and suppose σ^2 has no relationship with x. Substituting the observed data $(x_i, y_i)(i = 1,\ldots,\mathrm{n})$ into Eq. (8), and note that the sample is a simple random sample, we obtain: