Image Reconstruction Performance of A 12-electrode CCERT Sensor Under Five Different Excitation Patterns

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ABSTRACT
To obtain useful knowledge and experience of CCERT under different excitation patterns, the image reconstruction performance of a 12-electrode CCERT sensor under five different excitation patterns (1-electrode excitation pattern, 2-electrode excitation pattern, 3-electrode excitation pattern, 4-electrode excitation pattern and 5-electrode excitation pattern) are investigated and compared. A 12-electrode CCERT prototype, which can implement different excitation patterns, is developed to obtain the practical experiment data. Four typical image reconstruction algorithms (Linear Back Projection (LBP) algorithm, Landweber’s iteration algorithm, Algebraic Reconstruction Technique (ART) algorithm and Simultaneous Iterative Reconstruction Technique (SIRT) algorithm) are introduced to investigate and compare the image reconstruction performance with the experiment data obtained from the CCERT prototype. Research results show that the 1-electrode excitation pattern and the 2-electrode excitation pattern have better global image reconstruction performance. These two excitation patterns are better choices, while the 3-electrode excitation pattern, the 4-electrode excitation pattern and the 5-electrode excitation pattern are not recommended.

INDEX TERMS
Process tomography, electrical resistance tomography, excitation pattern, image reconstruction

I. INTRODUCTION
Electrical tomography (ET) has got much attention since it was proposed [1-19]. Studying the image reconstruction performance under different measurement strategies (excitation patterns) is an important aspect of electrical tomography (ET). In the past decades, a lot of research works have been reported and significant achievements have been obtained, e.g., electrical capacitance tomography (ECT) [6-10], electrical resistance tomography (ERT) [5, 20-25] and electromagnetic tomography (EMT) [26-28].
Capacitively coupled electrical resistance tomography (CCERT) was proposed as a contactless electrical resistance tomography (ERT) [1, 29-30]. The electrodes of a CCERT sensor are not in contact with the fluid and can avoid the drawback of conventional ERT (electrochemical erosion effect and polarization effect). Therefore, the proposed CCERT may have more broad applications in future.
However, as a new kind of ERT, the research works on the image reconstruction performance of CCERT under different excitation patterns are very limited and few research works are published [1, 29-32]. Therefore, to obtain more knowledge and experience of CCERT under different excitation patterns, further research works should be undertaken.

The aim of this paper is to study the image reconstruction performance of CCERT under different excitation patterns. Five excitation patterns will be investigated (including 1-electrode excitation pattern, 2-electrode excitation pattern, 3-electrode excitation pattern, 4-electrode excitation pattern and 5-electrode excitation pattern). A 12-electrode CCERT prototype, which can realize the different multi-electrode excitation patterns, will be developed to obtain the practical experiment data. With the obtained experiment data, four typical image reconstruction algorithms (including Linear Back Projection (LBP) algorithm, Landweber’s iteration algorithm, Algebraic Reconstruction Technique (ART) algorithm and Simultaneous Iterative Reconstruction Technique (SIRT) algorithm) will be introduced to investigate the image reconstruction performance.

II. EXCITATION PATTERNS OF CCERT
Figure 1 shows the construction of a 12-electrode CCERT sensor and the equivalent circuit of a measurement electrode pair. As can be seen from Figure 1(a), the electrodes of the CCERT sensor are mounted symmetrically around the outer periphery of an insulating pipe. When the pipe is filled with conductive liquid, for each measurement electrode pair, the electrodes, the insulating pipe and the liquid can form two coupling capacitors, and the liquid can
be equivalent to a resistor. Therefore the equivalent circuit of each measurement electrode pair can be simplified as two coupling capacitors in series with one resistor, as shown in Figure 1(b).

![Figure 1](image1.png)

**FIGURE 1. Construction of CCERT sensor and equivalent circuit of a measurement electrode pair.**

The conventional excitation pattern of CCERT is the 1-electrode excitation pattern as shown in Figure 1(a)). The CCERT array sensor is a 12-electrode array sensor, i.e., the total number of electrodes \( H=12 \) and the electrodes are numbered from 1 to \( H \). One electrode is selected as the excitation electrode and one of the other electrodes is selected as the detection electrode. That forms a measurement electrode pair. From the measurement electrode pair, a corresponding independent measurement (projection) can be obtained. For the 1-electrode excitation pattern, it can be known that the total number of the independent projections \( N=H(H-1)/2=66 \) independent projections, where \( N \) is the total number of the independent projections, \( p_n \) is the \( n \)th projection. The 66 independent projections are corresponding to their measurement electrode pairs: 1-2, 1-3, …, 1-12, 2-3, 2-4, …, 11-12, i.e., \( p_1 \) corresponding to the measurement electrode pair 1-2, \( p_2 \) corresponding to the measurement electrode pair 1-3, ……, and so on.

![Figure 2](image2.png)

**FIGURE 2. Four multi-electrode excitation patterns.**

Besides the 1-electrode excitation pattern, four new excitation patterns of CCERT will also be investigated in this work. For the 2-electrode excitation pattern as shown in Figure 2 (a), two adjacent electrodes are selected as the excitation electrodes and one of the other electrodes is selected as the detection electrode. That forms a measurement electrode pair. From the measurement electrode pair, a corresponding independent measurement (projection) can be obtained. In the 2-electrode excitation pattern, it can be known that the total number of the independent projections \( N=H(H-2)/2=120 \), \( p_n \), \( n=1, 2, \ldots, N \). The corresponding measurement electrode pairs are: 1&2-3 (1 and 2 are the excitation electrodes, 3 is the detection electrode), 1&2-4, …, 1&2-12, 2&3-4, 2&3-5, …, 2&3-11, …, 12&1-11. For the 3-electrode excitation pattern as shown in Figure 2 (b), three adjacent electrodes are selected as the excitation electrodes and one of the other electrodes is selected as the detection electrode, it can be known that the total number of the independent projections \( N=H(H-3)/6=108 \), \( p_n \), \( n=1, 2, \ldots, N \). The corresponding measurement electrode pairs are: 1&2&3-4 (1, 2 and 3 are the excitation electrodes, 4 is the detection electrode), 1&2&3-5, …, 1&2&3-12, 2&3&4-5, 2&3&4-6, …, 2&3&4-11, 12&1&2-11. For the 4-electrode excitation pattern as shown in Figure 2 (c), four adjacent electrodes are selected as the excitation electrodes and one of the other electrodes is selected as the detection electrode, it can be known that the total number of the independent projections \( N=H(H-4)/24=84 \), \( p_n \), \( n=1, 2, \ldots, N \). The corresponding measurement electrode pairs are: 1&2&3&4-5, 1&2&3&4-6, …, 1&2&3&4-12, 2&3&4&5-6, 2&3&4&5-7, …, 2&3&4&5-11, 12&1&2&3-11. For the 5-electrode excitation pattern as shown in Figure 2 (d), five adjacent electrodes are selected as the excitation electrodes and one of the other electrodes is selected as the detection electrode, it can be known that the total number of the independent projections \( N=H(H-5)/120=56 \), \( p_n \), \( n=1, 2, \ldots, N \). The corresponding measurement electrode pairs are: 1&2&3&4&5-6, 1&2&3&4&5-7, …, 1&2&3&4&5-12, 2&3&4&5&6-7, 2&3&4&5&6-8, …, 2&3&4&5&6-12, …, 12&1&2&3&4-11.

For all of the five excitation patterns, the excitation electrode(s) are connected with the AC voltage source(s). The detection electrode is kept at the ground potential and the measured current signal can be obtained on the detection electrode. The rest electrodes are kept at the floating condition.

Besides, it is necessary to indicate that owing to the property of symmetry, the sensitivity distributions of measurement electrode pairs with a same form are the same. The sensitivity distributions of measurement electrode pairs with the same form can be attributed to one typical sensitivity distribution. Only one of them needs calculating and the rest of them can be obtained by simple rotation transformation. Using the 2-electrode excitation pattern as an example, the measurement electrode pairs 1&2-3,
1&2-12, 2&3-4, 2&3-1, ..., 12&1-2, 12&1-11 have a same form. The sensitivity distributions of these measurement electrode pairs can be attributed to one typical sensitivity distribution and the sensitivity distributions of measurement electrode pairs 1&2-12, 2&3-4, 2&3-1, ..., 12&1-2, 12&1-11 can be obtained by rotating that of measurement electrode pair 1&2-3 around the center of the pipe.

Table I lists the total number of independent measurements (projections) \( N \) and the total number of typical sensitivity distributions \( L \) of CCERT under the five excitation patterns.

### III. SENSITIVITY DISTRIBUTION

In this work, the sensitivity distributions of the 12-electrode CCERT sensor under the five excitation patterns are obtained by simulation [1, 4, 12, 25, 28, 33-36]. The softwares are COMSOL Multiphysics and MATLAB. The mathematical model of CCERT can be described as [4, 33]:

\[
\begin{align*}
\nabla \cdot \left( \left( \sigma(x, y) + j\omega \epsilon(x, y) \right) \nabla \phi(x, y) \right) &= 0 \quad (x, y) \subseteq \Omega \\
\phi_a(x, y) &= V_0 \quad (x, y) \subseteq \Gamma_a \\
\phi_b(x, y) &= 0 \quad (x, y) \subseteq \Gamma_b \\
\frac{\partial \phi(x, y)}{\partial n} &= 0 \quad (x, y) \subseteq \Gamma_c \quad (c \neq a, b)
\end{align*}
\]

Where, \( \sigma(x, y) \) is the spatial conductivity distribution. \( \epsilon(x, y) \) is the permittivity distribution. \( \phi(x, y) \) is the spatial potential distribution. \( \omega \) is the angular frequency of the AC voltage source. \( \Gamma_a \) represents the excitation electrode(s), \( \Gamma_b \) represents the detection electrode, \( \Gamma_c \) represents each remaining floating electrode.

For an independent projection \( p_n \), the sensitivity of the \( m \)th element (pixel) in the sensitivity matrix \( S \) is defined as [5, 13, 33]:

\[
s_{nm} = \frac{R_{nm} - R_{n0}}{R_{n0} \Delta \sigma}
\]

(2)

Where, \( m = 1, 2, ..., M, n = 1, 2, ..., N \). \( M \) is the total number of elements, in this work, \( M = 864 \). \( R_{n0} \) is the equivalent resistance of the \( n \)th measurement electrode pair when the pipe is filled with the conductive liquid (its conductivity is \( \sigma_1 \)). \( \sigma_2 \) is the conductivity of gas. \( R_{nm} \) is the equivalent resistance of the fluid of the \( n \)th measurement electrode pair when the \( m \)th element’s conductivity becomes \( \sigma_2 \) and the conductivities of the rest elements remain at \( \sigma_1 \). \( \Delta \sigma = \sigma_1 - \sigma_2 \).

The average sensitivity \( \bar{s} \) and the average uniformity coefficient \( \bar{q} \) are introduced to analyze the sensitivity distributions.

The definition of \( \bar{s} \) is:

\[
\bar{s} = \frac{1}{L} \sum_{i=1}^{L} s_{i}^{m}
\]

(3)

Where, \( s_{i}^{m} \) is the sensitivity value of the \( m \)th element of the \( i \)th typical sensitivity distribution under a certain excitation pattern.

The definition of \( \bar{q} \) is:

\[
\bar{q} = \frac{1}{L} \sum_{i=1}^{L} \frac{s_{i}^{\max}}{s_{i}^{\min}}
\]

(4)

Where, \( s_{i}^{\max} \) and \( s_{i}^{\min} \) are the sum of the maximum 50 sensitivities and the sum of the minimum 50 sensitivities of the \( i \)th typical sensitivity distribution respectively.

Figure 3–7 show the sensitivity distributions under the five excitation patterns. Table II shows the information concerning the sensitivity distributions of CCERT under different excitation patterns.

### TABLE I

**INFORMATION OF THE FIVE EXCITATION PATTERNS**

<table>
<thead>
<tr>
<th>Excitation patterns</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation of total number of independent measurements</td>
<td>H(H-1)/2</td>
<td>H(H-2)</td>
<td>H(H-3)</td>
<td>H(H-4)</td>
<td>H(H-5)</td>
</tr>
<tr>
<td>Total number of independent measurements (H=12)</td>
<td>66</td>
<td>120</td>
<td>108</td>
<td>96</td>
<td>84</td>
</tr>
<tr>
<td>Total number of typical sensitivity distributions (H=12)</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

### TABLE II

**INFORMATION CONCERNING THE SENSITIVITY DISTRIBUTION OF CCERT UNDER DIFFERENT EXCITATION PATTERNS**

<table>
<thead>
<tr>
<th>Excitation patterns</th>
<th>1-electrode</th>
<th>2-electrode</th>
<th>3-electrode</th>
<th>4-electrode</th>
<th>5-electrode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of sensitivity matrix</td>
<td>66×812</td>
<td>120×812</td>
<td>108×812</td>
<td>96×812</td>
<td>84×812</td>
</tr>
<tr>
<td>Average sensitivity</td>
<td>0.2070</td>
<td>0.2135</td>
<td>0.2193</td>
<td>0.2102</td>
<td>0.2136</td>
</tr>
<tr>
<td>Average uniformity coefficient</td>
<td>1605.4373</td>
<td>827.6804</td>
<td>379.0583</td>
<td>206.6207</td>
<td></td>
</tr>
</tbody>
</table>

**FIGURE 3.** 6 typical sensitivity distributions of CCERT under 1-electrode excitation pattern.
From Figure 3–7 and Table II, it can be found that: 1) All the five excitation patterns have no negative sensitivity region and are not uniform. For all the sensitivity distributions, the sensitivities near the excitation and detection electrodes are much higher than those near the central area. 2) Except the 1-electrode excitation pattern, for all the multi-electrode excitation patterns, the sensitivities near the detection electrode are much higher than those near the excitation electrodes. All the average sensitivities of the multi-electrode excitation patterns are higher than that of the 1-electrode excitation pattern. 3) When the number of excitation electrodes increases, the uniformity of the sensitivity distributions increases simultaneously.

IV. CCERT PROTOTYPE

A 12-electrode CCERT prototype which can implement multi-electrode excitation is developed to obtain the practical experiment data in this work.

Figure 8 shows the construction of the 12-electrode CCERT prototype, including a 12-electrode CCERT array sensor, a data acquisition unit and a computer. Figure 9 is a photo of the 12-electrode CCERT prototype. The CCERT sensor consists of an insulating pipe and an electrode array which includes 12 electrodes. Each electrode is made of a rectangular copper foil with the length of 125 mm and the electrode angle is 25°. Each electrode is connected with an excitation and detection unit. The insulating pipe is a PVC pipe and its inner diameter and wall thickness are 110 mm and 2 mm respectively. Figure 10 shows the data acquisition unit. The data acquisition unit is designed on the basis of DSP, FPGA and other digital/analog chips. The DSP is used to control the whole system. The FPGA is used to generate the channel control signal and excitation signal, and implement data storage. The 12 excitation and detection units are designed by CPLD (Complex Programmable Logic Device), electronic switches and an analog amplifier circuit. The CPLD is controlled by the DSP. Each CPLD decodes the 8 signals from the DSP together with the 4 signals of each excitation and detection unit to control the status of each electrode (excitation electrode, detection electrode or floating electrode). Different excitation patterns have different logics. The voltage signals which contain the resistance information can be obtained and transmitted to the computer by USB. With the obtained measurement data, the computer reconstructs the cross-sectional images.
Where, the gain factor $\lambda$ should satisfy:

$$0 < \alpha < \frac{2}{\lambda}$$

The main iteration equation of Landweber’s iteration algorithm can be described as [1, 4, 38, 39]:

$$f_m^{(k)} = f_m^{(k-1)} + \alpha \sum_{n=1}^{N} w_{nm} (p_n \sum_{m=1}^{M} w_{nm} f_m^{(k-1)})$$

(9)

Where, the gain factor $\alpha$ should satisfy:

$$0 < \alpha < \frac{2}{\lambda}$$

(10)

$\lambda$ is the maximum eigenvalue of the matrix $WW^T$. $f_m^{(k)}$ and $f_m^{(k-1)}$ are the gray levels of the $m$th element after the $k$th and $(k-1)$th iteration respectively.

The main iteration equation of ART algorithm can be described as [13, 38, 39, 40]:

$$f_m^{(k)} = f_m^{(k-1)} + \frac{R_n - R_{n0}}{\sum_{m=1}^{M} w_{nm} f_m^{(k-1)}} \sum_{m=1}^{M} w_{nm} f_m^{(k-1)}$$

(11)

The main iteration equation of SIRT algorithm can be described as [38, 39, 40]:

$$f_m^{(k)} = f_m^{(k-1)} + \frac{R_n - R_{n0}}{\sum_{m=1}^{M} w_{nm} f_m^{(k-1)}} \sum_{m=1}^{M} w_{nm} f_m^{(k-1)}$$

(12)
\[ f_m^{(k)} = f_m^{(k-1)} + \frac{1}{N} \sum_{n=1}^{N} \left( \sum_{m=1}^{M} w_{nm} f_m^{(k-1)} \right) w_{nm} \]  
\[ (12) \]

For the three iteration algorithms, the iteration procedure goes on until:

\[ |f_m^{(k)} - f_m^{(k-1)}| \leq \xi \]  
\[ (13) \]

Where, \( \xi \) is chosen as \( 1 \times 10^{-6} \) S/m.

VI. IMAGE RECONSTRUCTION

In our previous work [31], the image reconstruction performance by LBP algorithm with simulation data under two excitation patterns (the 1-electrode excitation pattern and the 3-electrode excitation pattern) has been investigated. This work aims to investigate the image reconstruction performance of CCERT under the five excitation patterns by the four image reconstruction algorithms with experiment data. Therefore, the research works have two parts: 1) To investigate the image reconstruction performance by LBP algorithm with simulation data and experiment data to find out whether the simulation results are different from the experiment results or not. 2) To investigate the image reconstruction performance of CCERT under the five excitation patterns by three iteration algorithms with experiment data.

A. EXPERIMENT SETUP AND PHASE DISTRIBUTIONS

Experiments were carried out with the developed CCERT prototype. The experiment materials were tap water (as the continuous phase) and plastic rods with diameters of 34.5 mm and 20 mm to simulate the conductivity distributions of gas-liquid two-phase flows. Figure 10 shows the four tested conductivity distributions. Distribution-1 represents one rod with diameter of 34.5 mm at the central area, distribution-2 represents one rod with diameter of 20 mm at the edge, distribution-3 represents two rods with diameter of 20 mm at the edge and distribution-4 represents three rods with diameter of 20 mm at the edge. The red area represents the water and the blue area represents the rods.
Figure 12 shows the image reconstruction results obtained by LBP algorithm with simulation data under the five excitation patterns. Figure 13 shows the image reconstruction results obtained by LBP algorithm with experiment data under the five excitation patterns. Table III presents the relative image error $e$ by LBP algorithm.

![Image of 5-electrode excitation pattern](image1)

![Image of 4-electrode excitation pattern](image2)

![Image of 3-electrode excitation pattern](image3)

![Image of 2-electrode excitation pattern](image4)

![Image of 1-electrode excitation pattern](image5)

**FIGURE 12.** Image reconstruction results obtained by LBP algorithm with simulation data.

**FIGURE 13.** Image reconstruction results obtained by LBP algorithm with experiment data.

**TABLE III**

<table>
<thead>
<tr>
<th>Excitation patterns</th>
<th>With simulation data</th>
<th>With experiment data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1-electrode</td>
<td>0.509</td>
<td>0.217</td>
</tr>
<tr>
<td>2-electrode</td>
<td>0.475</td>
<td>0.235</td>
</tr>
<tr>
<td>3-electrode</td>
<td>0.474</td>
<td>0.220</td>
</tr>
<tr>
<td>4-electrode</td>
<td>0.494</td>
<td>0.208</td>
</tr>
<tr>
<td>5-electrode</td>
<td>0.537</td>
<td>0.208</td>
</tr>
</tbody>
</table>

Figure 12 shows the image reconstruction results obtained by LBP algorithm with simulation data under the five excitation patterns. Figure 13 shows the image reconstruction results obtained by LBP algorithm with experiment data under the five excitation patterns. Table III provides the relative image error $e$ for each excitation pattern under both simulation and experiment data conditions.
lists the relative image error $e$ of the reconstructed images by LBP algorithm. From Figure 12, 13 and Table III, it can be found that the image reconstruction results with simulation data are different from the results with experiment data. As we know, considering the practical application, the practical experiment data are more convincing than the simulation data. Therefore, in this work, the evaluation of image reconstruction performance is on the basis of the image reconstruction results with experiment data. Thus, from Figure 13 and Table III, with experiment data, among the five excitation patterns, the 1-electrode excitation pattern, the 2-electrode excitation pattern and the 3-electrode excitation pattern have better global image reconstruction performance by LBP algorithm.

C. IMAGE RECONSTRUCTION PERFORMANCE BY THE THREE ITERATION ALGORITHMS WITH EXPERIMENT DATA

![Image reconstruction results obtained by Landweber's iteration algorithm with experiment data.](image)

**TABLE IV**

<table>
<thead>
<tr>
<th>Excitation patterns</th>
<th>Tested conductivity distributions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1-electrode</td>
<td>0.178</td>
</tr>
<tr>
<td>2-electrode</td>
<td>0.224</td>
</tr>
<tr>
<td>3-electrode</td>
<td>0.227</td>
</tr>
<tr>
<td>4-electrode</td>
<td>0.233</td>
</tr>
<tr>
<td>5-electrode</td>
<td>0.234</td>
</tr>
</tbody>
</table>

Figure 14 shows the image reconstruction results obtained by Landweber’s iteration algorithm under the five excitation patterns. Table IV lists the relative image error $e$...
of the reconstructed images by Landweber’s iteration algorithm. Combining Figure 14 and Table IV, it is obvious that the 1-electrode excitation pattern and the 2-electrode excitation pattern have better image reconstruction performance. While the image reconstruction results under the 3-electrode excitation pattern, the 4-electrode excitation pattern and the 5-electrode excitation pattern are not satisfactory in some cases.

Figure 15 shows the image reconstruction results by ART algorithm under the five excitation patterns. Table V lists the relative image error $e$ of the reconstructed images by ART algorithm. According to Figure 15, it can be found that the 4-electrode excitation pattern has the worst image reconstruction results, while the image reconstruction results under the other four excitation patterns are all in accordance with the practical conductivity distributions. According to Table V, the 1-electrode excitation pattern and the 2-electrode excitation pattern have better accuracy globally. Meanwhile, the image reconstruction performance of the 2-electrode excitation pattern is slightly better than that of the 1-electrode excitation pattern.
Figure 16 shows the image reconstruction results by SIRT algorithm under the five excitation patterns. Table VI lists the relative image error $e$ of the reconstructed images by SIRT algorithm. According to Table VI, the 1-electrode excitation pattern, the 2-electrode excitation pattern and the 3-electrode excitation pattern have better accuracy globally. Considering the image reconstruction results in Figure 16, the 1-electrode excitation pattern and the 2-electrode excitation pattern have better global image reconstruction performance. Meanwhile, same as the image reconstruction results by ART algorithm, the 2-electrode excitation pattern has slightly better global image reconstruction performance than the 1-electrode excitation pattern.

In general, according to the above image reconstruction results, for all the four image reconstruction algorithms (the LBP algorithm and three iteration algorithms), the 1-electrode excitation pattern and the 2-electrode excitation pattern have better global image reconstruction performance, while the 3-electrode excitation pattern, the 4-electrode excitation pattern and the 5-electrode excitation pattern have relatively poor global image reconstruction performance although they all have more independent projections than the 1-electrode excitation pattern. Furthermore, taking the complexity of the CCERT hardware system under different excitation patterns into consideration, the 1-electrode excitation pattern and the 2-electrode excitation pattern are better choices and recommended.

VII. CONCLUSION
This work focuses on the investigation of image reconstruction performance of a 12-electrode CCERT sensor under five different excitation patterns, the 1-electrode excitation pattern, the 2-electrode excitation pattern, the 3-electrode excitation pattern, the 4-electrode excitation pattern and the 5-electrode excitation pattern.

The sensitivity distributions of CCERT under the five excitation patterns are investigated by simulation. The research results indicate that all the sensitivity distributions of the five excitation patterns have no negative sensitivity region and there are no uniform sensitivity distributions under the five excitation patterns. The average sensitivities of all the multi-electrode excitation patterns are higher than that of the 1-electrode excitation pattern. The sensitivity distributions become more uniform simultaneously as the number of excitation electrodes increases.

A 12-electrode CCERT prototype which can implement the different excitation patterns is developed to obtain the practical experiment data.

With the practical experiment data obtained by the 12-electrode CCERT prototype, four image reconstruction algorithms (the LBP algorithm, the Landweber’s iteration algorithm, the ART algorithm and the SIRT algorithm) are introduced to investigate the image reconstruction performance. Practical image reconstruction experiments are carried out. The experiment results show that the 1-electrode excitation pattern and the 2-electrode excitation pattern have better global image reconstruction performance, while the global image reconstruction performance of the 3-electrode excitation pattern, the 4-electrode excitation pattern and the 5-electrode excitation pattern is not satisfactory. Furthermore, considering the complexity of the CCERT hardware system under different excitation patterns, it is concluded that the 1-electrode excitation pattern and the 2-electrode excitation pattern are better choices and recommended.

Useful knowledge and experience have been obtained. This work can provide a good reference for further research on CCERT. However, due to the complexity of CCERT technique, more research works should be undertaken in the future, such as the influence of different excitation patterns on the spatial resolution of CCERT system and the image reconstruction performance of CCERT system under more difficult and complicated flow patterns (or distributions).

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REFERENCES


