The design of a sensor with flexible circuit excitation in electromagnetic tomography system

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Abstract. A novel sensor structure of electromagnetic tomography system is presented in this paper. Flexible circuit straps are used in the excitation layer of the sensor and current of each strip can be controlled independently according to the excitation protocol matrix. In the sensor three kinds of excitation protocols: parallel, quasi-parallel and coil pair can be generated. Furthermore excitation field simulation and image reconstruction experiments have been done for analyzing the performance of the different excitation protocols.

1. Introduction
Electromagnetic Tomography (EMT) is one of electrical tomography technologies that combine the electromagnetic theory with the computerized tomography technology [1]. The sensor of EMT can generate electromagnetic excitation field in the measured space and acquire the boundary magnetic induction around the measured space [2]. EMT system can reconstruct spatiotemporal distributions of the conductive and/or ferromagnetic materials. Furthermore the sensor of EMT system has the advantages of non-invasive, non-contacting and non-hazardous. So EMT has the potential to be used in fields of industrial multi-phase flow measurement, chemical abstraction, foreign material monitoring, geologic exploration and biomedical research [3][4].

This paper focus on the design and realization of a sensor using flexible circuit strips as its excitation sub-system. Three kinds of excitation protocols can be produced in the system. And three kinds of electromagnetic fields are simulated by infinite element method. The excitation circuit design and excitation method are introduced. For analyzing the performances of the excitation protocols image reconstruction experiments have been done and the images reconstructed by liner back projection based field sensitivity algorithm are demonstrated and analyzed.

2. The EMT sensor with flexible circuit strips

2.1. The structure of the EMT system
The structure of the EMT system is shown in figure 1. The system consists of image reconstruction and information extraction computer [5], excitation signal generator, excitation control circuit, sensor and data acquisition and signal processing unit.
2.2. The structure of the sensor

The EMT sensor with flexible circuit strips is designed and its cross section is shown in figure 2. The sensor consists of pipe wall, detection layer, excitation layer and electromagnetic shielded layer. The material of the pipe is organic glasses. Electromagnetic shield layer is made up of ferrite rings and permalloy cylinder. So the shielded layer can improve the system's electromagnetic compatibility and reduce the disturbance from the environment. Compared with the parallel excitation implementation using two orthogonal excitation coils, the advantage of the sensor with flexible circuit strips is the excitation layer’s current distribution can be controlled freely. So different excitation protocols can be realized and studied in this experimental EMT system. But the disadvantage of this sensor structure is the complexity of the excitation current’s distribution control.

As shown in figure 2, the detection layer consists of eight magnetic detector coils. The excitation layer is made up of a flexible circuit board which consists of 32 copper strips on it. The 3D structure of the sensor is shown in figure 3. The diameter of the inner pipe wall is 70 mm. The diameter of the detection layer is 76.8 mm. The diameter of the excitation layer is 110 mm.

2.3. Excitation control of the sensor

The advantage of the flexible circuit excitation system is able to produce different excitation field without changing the system’s hardware structure. 32 excitation strips around the excitation layer are connected as shown in figure 4. The strips are grouped as 16 coils and the current on each coil can be controlled independently. So the sensor can generate 16 excitation projections. The block diagram of current control circuit is shown as figure 5. In the figure, the current on each coil is controlled by the signal select and drive module which consists of excitation source signal multiplexer, voltage controlled current source (VCCS) and current direction control circuit. Excitation signal array generator generates 8 sine wave with different amplitude according sine signal in the range from 0 to \( \pi / 4 \) by direct digital synthesizer (DDS) signal generator. Control data of multiplexer and current direction control circuit are stored in the EEPROM. Control data of 16 excitation coils and 16 projections compose a excitation protocol matrix. So different exciation protocol can be realized by changing the matrix in the EEPROM array.
Based on the excitation control structure, parallel excitation [6] can be produce by control the current of excitation strips according sine signal distribution. Furthermore, considering independent projections and central sensitive of the excitation field, an excitation protocol named quasi-parallel excitation is designed to improve the sensor performance. And if let only one coil be excited, the sensor also can simulate the single coil excitation. But the difference between this kink of single coil excitation and the mature single coil excitations [2] is this sensor’s excitation coil across the diameter of the measured pipe. So in this EMT system three kinds of protocols can be realized for study the excitation mode. Three kinds of current distributions are implemented as following.

- **Coil-pair excitation**
  In every projection, excitation current flows into one excitation strip \( m \) and flow out from another excitation strip \( m+16 \), the range of \( m \) is 0 to \( N/2 \). \( N \) is the number of total excitation strips, \( N \) is equal to 32. In the same time the current on other strips are zero. Variation of \( m \) from 1 to \( N \) brings out \( N/2 \) independent projections. For the projection \( p \), the current on each strip can be discribed as (2.1).

\[
I_m = \begin{cases} 
I \sin \omega t & \text{when } m = p \\
-I \sin \omega t & \text{when } m = p + N/2 \\
0 & \text{otherwise}
\end{cases} \quad \text{where } (m = 1, 2, \ldots, N; \ p = 1, 2, \ldots, N/2)
\]  

(2.1)

Where, \( I \) is the current on excitation strip \( m \), and \( I \sin \omega t \) is the excitation current with maximum amplitude.

- **Parallel excitation**
  In parallel excitation protocol, for the \( p \)-th projection, the current distribution of excitation strip \( m \) is as following.

\[
I_m = I \sin \omega t \cdot \sin(\phi_m - p\phi) \quad (m = 1, 2, \ldots, N; \ p = 0,1,2,\ldots,\ N/2)
\]

\[
\phi_0 = 2\pi / N, \quad \phi_m = 2\pi m / N
\]

Where, \( \phi_m \) is spatial angle of the excitation strip \( m \).

- **Quasi-parallel excitation**
  The aim of this excitation is to increase the independent excitation projections. Its current distribution is as following.

\[
I_m = \begin{cases} 
I \sin \omega t \cdot \left[ c_p + \sin(\phi_m - p\phi) \right] & \text{when } m = p \\
I \sin \omega t \cdot \left[ -c_p + \sin(\phi_m - p\phi) \right] & \text{when } m = p + N/2 \\
I \sin \omega t \cdot \sin(\phi_m - p\phi) & \text{Otherwise}
\end{cases} \quad (m = 1, 2, \ldots, N; \ p = 1, 2, \ldots, N/2)
\]  

(2.3)

Where, \( c_p \) is the additional current added into a pair of excitation strips. As shown in (2.3), the excitation current distribution in quasi-parallel excitation can be regarded as the combination of the parallel excitation and the coil-pair excitation.

2.4. **Compare of excitation field between analytical and simulation**
For analyzing the difference of excitation field between ideal continuous excitation sensor and noncontinuous one, analytical solution and finite element method are used. For the continuous sensor, if suppose that: a) the magnetic sensing field can be considered as a two-dimension steady-state field and the magnetic potential vector has only the axial part; b) the object is linear and isotropic; c) the field is sinusoidal, the magnetic field in the measured pipe can be described as (2.4).

\[
\frac{1}{\rho} \frac{\partial^2}{\partial \rho^2} \left( \frac{1}{\rho} \frac{\partial A}{\partial \rho} \right) + \frac{1}{\rho^2} \frac{\partial^2 A}{\partial \phi^2} + \frac{1}{\rho} \frac{\partial}{\partial \phi} \left( j \omega \sigma \rho \sigma \rho \phi \mu \rho \rho \mu \phi \right) = 0
\]

(2.4)

Where, \(\rho\) and \(\sigma\) are polar coordinates, \(A\) is magnetic potential vector, \(\omega\) is angular frequency of the excitation signal, \(\mu\) and \(\sigma\) represent the magnetic permeability and conductivity of object in the measured pipe. \(R\) is the radius of circular with excitation strips array and \(I(\phi)\) is the excitation current distribution. \(I(\phi)\) should satisfies (2.5) to make the excitation system spatially independent.

\[
\int_{0}^{2\pi} I(\phi) d\phi = 0
\]

(2.5)

If the excitation current satisfies (2.6) and the measured pipe is empty then the magnetic flux density will be as (2.7).

\[
I(\phi) = I \sin \omega t \cdot \sin \phi
\]

(2.6)

\[
B = \mu I \cdot i_x
\]

(2.7)

Where, \(i_x\) is the unit vector of X axis. Equation (2.7) shows that flux density \(B\) of the excitation field is parallel and even.

As shown in figure 2, the current distribution along excitation layer is not continuous. So in the real sensor bias error will generate because the strips can not be fixed infinitely. For analyzing the excitation sensing field of the nonideal excitation structure, magnetic flux density distribution is simulated by using finite element method based on the actual structure. The maximum current of the strips is 10 mA. In the simulation model, the magnetic vector potential of shield layer is constrained as equal to emulate the condition of actual structure. Under these conditions, the simulated magnetic flux lines distribution and the flux density distribution of the empty measured pipe are as shown in figure 6 and figure 7.

Figure 6. Simulated distribution of flux lines
Figure 7. Simulated distribution of \(B\)

The simulated magnetic flux lines of coil-pair excitation and quasi-parallel excitation are also shown in figure 8(a) and figure 8(b).
3. Image reconstruction experiments

In order to compare the performances of three excitation protocols, some copper poles, which diameters are 15mm, are inserted into the pipe vertically at different position as the test objects. The image reconstruction algorithm used in the experiments is the linear back projection algorithm based on field sensitivity. The cross section of the pipe is divided into 1024 elements. Experimental results are listed in Table 1.

### Table 1. Images reconstructed by different excitation protocols

| Position of test objects | Parallel excitation | Coil-pair excitation | Quasi-parallel excitation |
|--------------------------|---------------------|----------------------|--------------------------|
| Cu 15mm                  | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png)     |
| Cu 15mm                  | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png)     |
| Cu 15mm                  | ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png)     |

The image reconstruction result indicates that the quality of the image reconstructed by the quasi-parallel excitation protocol is better than that of the other two. The quasi-parallel excitation mode can approximately reconstruct the profile of one to three poles while the definition of images reconstructed by using parallel excitation mode and coil-pair mode is blurred. Of course, this result is not universal because it is only got from the special sensor structure described in this paper.

For analyzing the excitation efficient of these three excitation protocols a kind of current sensitivity is defined by the authors as (3.1).
\[
S_i = \frac{\sum_{p=1}^{P} \sqrt{\sum_{d=1}^{D} \left(U(p,d) - U_{emp}(p,d)\right)^2}}{\sum_{p=1}^{P} \sum_{n=1}^{N} |I(p,n)|}
\]

(3.1)

Where, \( p \) is the sequence number of excitation projection. \( d \) is sequence number of detector. \( U(p,d) \) is the induced potential on detector numbered \( d \) in \( p \)-th projection, and \( U_{emp}(p,d) \) is the value in empty field. \( I(p,n) \) is the excitation current on \( n \)-th excitation strip in the \( p \)-th projection. \( n \) is the sequence number of excitation strip. So \( S_i \) can denote the current sensitivity. Table 2 shows the current sensitivities of different excitation with a copper pole which diameter is 15mm in the center of the pipe.

Table 2. Comparison of \( S_i \) with different excitation protocols

| Excitation protocol       | \( S_i \)       |
|---------------------------|-----------------|
| Parallel excitation       | 4.9088×10^{-4}  |
| Quasi-parallel excitation | 4.3706×10^{-4}  |
| Coil-pair excitation      | 1.8028×10^{-4}  |

The table shows the current sensitivity of parallel excitation is higher than the others. The current sensitivity of quasi-parallel is similar with that of parallel excitation.

4. Conclusion and discussion

A novel sensor of EMT system is designed by using flexible circuit as excitation layer. In the sensor, three kinds of excitation protocols can be realized by changing the data of excitation control matrix. Simulation of the excitation fields show the sensor can generate qualified excitation field for the image reconstruction. Image reconstruction result shows that the performance of quasi-parallel excitation is better than that of the others by using the same basic reconstruction algorithm. So quasi-parallel combines the advantage of parallel and coil-pair excitation. It has better central current sensitivity and more independent projections. However this result is only base on the sensor structure and test conditions mentioned in this paper.

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