3D EFT imaging with planar electrode array: numerical simulation

T. Tuykin and A. Korjenevsky
Kotel'nikov Institute of Radio-engineering and Electronics of the RAS, Moscow, Russia
E-mails: tt@cplire.ru and korjenevsky@cplire.ru

Abstract. Electric field tomography (EFT) is the new modality of the quasistatic electromagnetic sounding of conductive media recently investigated theoretically and realized experimentally. The demonstrated results pertain to 2D imaging with circular or linear arrays of electrodes (and the linear array provides quite poor quality of imaging). In many applications 3D imaging is essential or can increase value of the investigation significantly. In this report we present the first results of numerical simulation of the EFT imaging system with planar array of electrodes which allows 3D visualization of the subsurface conductivity distribution. The geometry of the system is similar to the geometry of our EIT breast imaging system providing 3D conductivity imaging in form of cross-sections set with different depth from the surface. The EFT principle of operation and reconstruction approach differs from the EIT system significantly. So the results of numerical simulation are important to estimate if comparable quality of imaging is possible with the new contactless method. The EFT forward problem is solved using finite difference time domain (FDTD) method for the 8x8 square electrodes array. The calculated results of measurements are used then to reconstruct conductivity distributions by the filtered backprojections along electric field lines. The reconstructed images of the simple test objects are presented.

1. Introduction

Electric Field Tomography (EFT) is new imaging technique which enables contact-less visualization of spatial distribution of electrical properties inside conductive object. The object is investigated by alternating quasistatic electric field, with wavelength much longer then object size. Due to finite conductivity free charge carriers of object media can not redistribute immediately to compensate external field (Maxwell-Wagner relaxation [1, 2]) and produce weak secondary electric field, which depends on conductivity, permittivity, geometry of the object and frequency of sounding field. This secondary field is in quadrature with the primary field, so measuring of phase shift between perturbed and primary field using spatially distributed receiving and transmitting electrodes in conjunction with appropriate reconstruction algorithm enables to reconstruct spatial distribution of media electrical properties. In common case visualization combines both electrical characteristics (permittivity and conductivity), shows spatial distribution of object phase shift ability. But when frequency of investigation field is equals to relaxation frequency of media (\( \omega = 1/\varepsilon \rho \)), where \( \varepsilon \) is permittivity of the medium, \( \rho \) is specific resistance of the medium, the phase shift is maximal and its value do
not depend on conductivity of media, and depend only on permittivity, geometry of media [1, 2]. And there is theoretical possibility to detach spatial distribution of conductivity and permittivity.

In contrast to electrical capacitance tomography [3] the EFT is intended for imaging of conductive medium, such as biological tissues and visualizes not only permittivity. Just as for magnetic induction tomography (MIT) [4], the EFT potential application areas include medicine and industrial process control, and due to contact-less operation it can be used for brain imaging and in security systems. In previous paper [5] experimental visualization of the test objects by electric field tomography method was shown at first time. The results of numerical simulation and comparison of 2D EFT system with different electrodes organization (round and linear) was presented in the paper [6]. It was shown that system with round electrodes organization provides image suitable for further visual analysis, but system with planar electrodes organization reconstructs image with worse quality, sufficient only for detection purposes. The main cause is a lack of field lines registered by planar electrodes system after interaction with object. Planar electrodes array geometry for measuring system more convenient in use for certain application then system with round electrodes array organization: there is no need to surround investigated objects by system for measurements and planar system can be easily mounted or hidden in wall, floor or cell. Clinical application experience of electrical impedance tomography system [7] with 2D flat electrode system for 3D visualization shown practical possibility to collect sufficient data set for visualization with further quantities analysis by planar electrodes array. This paper describes numerical experiment for 2D planar electrodes system for 3D EFT visualization.

2. Methods and materials

2.1. FEM and FDTD simulation

For the description of an electric field in an inhomogeneous conducting medium in the quasi-static approximation (the wavelength of sounding field is greater than system size), it is possible to use combination of the Poisson equation and the continuity equation (conservation law of charge) [1]:

\[
\begin{align*}
\nabla \cdot (\varepsilon \nabla \phi) &= -4\pi \rho, \\
\nabla \cdot (\sigma \nabla \phi) &= \partial \rho / \partial t,
\end{align*}
\]

(1)

where \( \phi \) is the potential of an electric field, \( \rho \) is the density of free charges and \( \varepsilon \) and \( \sigma \) are the permittivity and conductivity of a medium, respectively. Considering processes at angular frequency \( \omega \) and eliminating the density of free charges \( \rho \) from system (1), we obtain a homogeneous equation with complex permittivity:

\[
\nabla \cdot ((\varepsilon - i4\pi \sigma / \omega) \nabla \phi) = 0.
\]

(2)

This equation (2), with the corresponding boundary conditions, including the grounded shield and the active electrode with a given potential, describes the behavior of the electric field inside and outside the object and can be used for simulation a system [1]. The finite element method implementation to (2) is a common way to simulate a quasi-static electromagnetic tomography system. Description of simulated system is given in the chapter 2.4.

Other way to simulate system is to solve Maxwell equations:

\[
\begin{align*}
\text{rot}(\mathbf{H}) &= \partial \mathbf{D} / \partial t + \mathbf{J}, \\
\text{rot}(\mathbf{E}) &= -\partial \mathbf{B} / \partial t,
\end{align*}
\]

(3)

where \( \mathbf{E} \) is electric field intensity, \( \mathbf{H} \) is magnetic field intensity, \( \mathbf{D} \) is electric flux density, \( \mathbf{B} \) is magnetic flux density. If the medium is linear and dispersionless we have \( \mathbf{D} = \varepsilon \varepsilon_0 \mathbf{E}, \mathbf{B} = \mu \mu_0 \mathbf{H}, \mathbf{J} = \sigma \mathbf{E}, \) where \( \varepsilon, \mu, \) and \( \sigma \) are permittivity, permeability and conductivity of the medium. It is rather difficult task to FEM method. Usually it can be solved by finite-difference time-domain method. This method need more time to calculate, but suitable not only for quasi-static. And the results obtained trough the method taking into account wave propagation effects. Also the method enables to simulate
wideband frequency result in one simulation run for further spectral analysis. The FDTD method has been used in the previous paper [6].

2.2. FEM model description
The model consists of 2D flat electrode array (8x8 electrodes) and cylinder of fat-like tissue with conductivity 0.03 Sm/m and permittivity 10, see figure 1. Data simulation has been done for frequency 10 MHz.

2.3. Image reconstruction by weighted back projection along electric field line
The vector of values of medium phase shift ability \( \mathbf{R} \) in nodes of cubic grid is calculated through symbolic expression: \( \mathbf{R} = -\hat{B}\hat{F}\tilde{\Delta} \), where \( \hat{B} \) is operator of weighted back projection along non-perturbed electric field lines, \( \hat{F} \) is filter operator (standard Ramachandran-Lakshminarayanan filter is used), \( \tilde{\Delta} \) is vector of measured (simulated) phase shifts for all combination of transmitting and receiving electrodes [1]. Operator \( \hat{B} \), in addition to proper backprojection, provides correction of sensitivity non-uniformity inside the measuring system through multiplying projected data by the corresponding geometrical weighting factor.

3. Results
Images have been successfully reconstructed from simulated data set. The 3D distribution of conductivity is presented as the set of four 2D cross-sectional images with increasing depth. The cross-section planes are parallel to the electrode array. The resulting images are presented on figure 2. The cylinder object shown on the figure 1 is clearly identifiable on the images (darker shadows correspond to larger phase shift). The axis of the cylinder object is on the depth of 2 in units of the figure 2, so the cross-section planes 2 and 3 (depth 1.5 and 2.5 units) contain the object (dark area). The white area in the plane 1 and grey spots in the plane 4 are reconstruction artefacts.

4. Conclusions
EFT system with planar array for 3D subsurface imaging has been simulated. Images representing 3D spatial distribution of electrical properties have been reconstructed with proper object size and position.

In further research more electrodes in the system should be used to obtain images with higher quality. We consider using 16x16 electrodes array for experimental measuring system. This will enable spatial resolution similar to the resolution enabled by existing breast imaging EIT system. Contactless operation provided by the EFT method will extend fields of application significantly.
Figure 2. Reconstructed images from FEM simulated data set corresponding to geometry shown on fig. 1: 1 is cross-section parallel to the electrode array at depth equal to 0.5 units (the unit is step between electrodes), 2 – 1.5 units, 3 – 2.5 units and 4 – 3.5 units depth.

Acknowledgment
The work was partially supported by the Russian Foundation for Basic Research, Grant No 09-02-12222.

References
[1] Korjenevsky A V 2004 Electric field tomography for contactless imaging of resistivity in biomedical applications Physiol. Meas. 25 391
[2] Korjenevsky A V 2005 Maxwell-Wagner relaxation in electrical imaging Physiol. Meas. 26 S101
[3] Huang S M, Plaskowski A, Xie C G and Beck M S 1988 Capacitance-based tomographic flow imaging system Electron. Lett. 24 418
[4] Korjenevsky A, Cherepenin V and Sapetsky S 2000 Magnetic induction tomography: experimental realization Physiol. Meas. 21 89
[5] Korjenevsky A and Tuykin T 2009 Experimental demonstration of the electric field tomography Proc. 10th Int. Conf. Biomedical Applications of Electrical Impedance Tomography (EIT2009) (Manchester)
[6] Korjenevsky A V and Tuykin T S 2008 Phase measurement for electric field tomography Physiol. Meas. 29 S151
[7] Cherepenin V, Karpov A, Korjenevsky A, Kornienko V, Kultiasov Y, Ochapkin M, Trochanova O and Meister D 2002 Three-dimensional EIT imaging of breast tissues: system design and clinical testing IEEE Trans. Medical Imaging 21 662