Properties of CMT studies by means of FEM and Spice model

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Abstract— **A joint capacitive and magnetic tomography (CMT) is considered. Current flow in a semi-infinite 3D medium is induced by application of current between electrodes located distantly from an examined medium. These electrodes are also used to measure potential distribution at a border of the medium. Current distribution inside the medium contributes to magnetic flux measured by coils, also located distantly from the medium. A finite element model for forward problem has been developed. It is a sphere of a radius appropriately chosen. It is filled in a half with air and in a half with examined medium. Each half is described by complex conductivity. Electrodes and coils are immersed in the half containing air. A surface of the sphere is connected to ground potential. This model has been used to calculated potential distribution inside the examined medium. Aside from FE model an equivalent circuit containing resistances and capacitances, both frequency dependent and independent, has been developed and used to examine properties of the proposed technique in the frequency domain (PSpice software). It follows from the study that the potential distribution and thus the sensitivity decreases rapidly with the distance from matrix of sensors. Optimal measurement frequency for a given set of material parameters which assures the highest value of current flowing into the medium thus has been found to be dependent on all characteristic values of model.**

Keywords— **Electrical Capacitance Tomography, imaging methods.**

I. INTRODUCTION

Electrical Capacitance Tomography (ECT) is a useful tool for imaging from 1986 [1]. It aims to image dielectric permittivity distribution inside an examined medium using an array of sensors for capacitance measurements. ECT systems have widespread applications in research and industry. It is commonly implemented for imaging of non-conductive and with low level of moisture mediums [2]. The most important advantages of ECT technique are low cost and high speed of the reconstruction process. In many applications of crucial importance is its non-invasiveness, remote measurement process [3]. The essential weaknesses of this method is poor spatial resolution and low accuracy which are closely connected with a low sensitivity of boundary capacitance to inner permittivity perturbations, and also with practical problems, e.g. with electrodes which allow for only a limited number of boundary capacitance measurements. An improvement of inaccurate low spatial resolution images yield by conventional ECT still is a challenge for engineers.

One of the possible approaches for improving a quality of a reconstructed image relies on increasing of data set by using extra measurement technique in a reconstruction process [4,5,6]. In the latest scientific publications there are some proposals based on combination of different measurements techniques which have proved advantage of a such attempt [7,8]. A new remote imaging method called Capacitive and Magnetic Tomography (CMT) has been proposed to provide a better quality of images using potential and magnetic flux density measurements. In CMT a number of electric potential measurements is augmented by additional measurements of the exterior magnetic field induced by a current flowing in the examined medium.

II. METHODS

A. Model of a problem

Method of examination utilizes electrodes capacitively coupled to the medium and magnetic coils (Fig. 1). Electrodes are used, both, to introduce current into the examined object and to measure potential distribution. Additionally, coils are used to measure current distribution inside the object. A current excitation of a low frequency used in examination. Thus, magnetic and electrical problems are treated separately and edge current effect could be omitted.

Thus, an associated mathematical problem can be considered as a quasi-static one. It means that electric and magnetic problems are treated separately. The forward problem of electric excitations and measurements involves solution

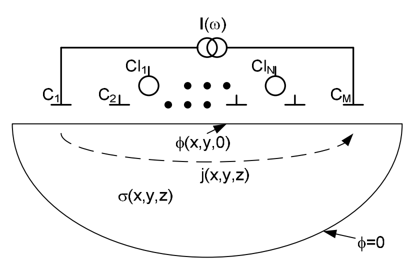

Fig.1 Model of the examined problem

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of a Laplace equation

$$\nabla \cdot \left(\tilde{\sigma}(\omega)\nabla \phi\right) = 0, \tag{1}$$

where:

$$\tilde{\sigma}(\omega) = j\omega\tilde{\varepsilon}(\omega). \tag{2}$$

ω is angular frequency, $\tilde{\varepsilon}(\omega)$ is a dielectric permittivity which is a complex function with ε' and ε'' - real and imaginary components, respectively and is defined as $\tilde{\varepsilon}(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega)$.

On the assumption that the current flows through examined medium is a quasi-static, the divergence of the current density vanishes

$$\nabla \cdot \mathbf{J} = 0, \tag{3}$$

where J is current density. Thus for calculation of magnetic field generated outside of the considered conductor Biot-Savart law can be used

$$\mathbf{B} = \frac{\mu_0}{4\pi}\int \frac{I \times \mathbf{R}}{R^3} dV, \tag{4}$$

where: μ_0 – permeability of free space, R – distance between the source point in the conductive medium to the field point, I – current density and V represents the conductive medium volume.

As a model for the frequency dependence of the permittivity y of the soil a Debye relaxation equation is used. This model for the complex permittivity may be expressed as

$$\varepsilon(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega) = \varepsilon_\infty + \frac{\varepsilon_S - \varepsilon_\infty}{1 + j\omega\tau_\varepsilon} \tag{5}$$

where: ε_∞ – permittivity at infinite frequency, ε_s – static permittivity (d.c.), τ_ε – permittivity relaxation time, ω - angular frequency.

B. Spice Model

An equivalent scheme of a measurement system and examined soil is presented in Figure 2. Capacitors C1 and C2 represent capacitive electrodes introducing current into the examined medium (soil). Cs is a coupling stray capacitance between capacitive electrodes, resistance Rg and capacitance Cg simulate examined soil.

A more detailed model is presented in Figure 3.

A value of capacitance of a capacitor used to inject current or measure potential may be represented as a sum of geometric and boundary capacitances: C_g and C_b, respectively

$$C = C_g + C_b \tag{6}$$

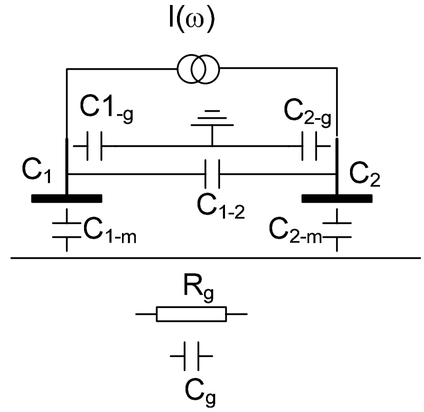

Fig.2 PSpice model of the examined problem

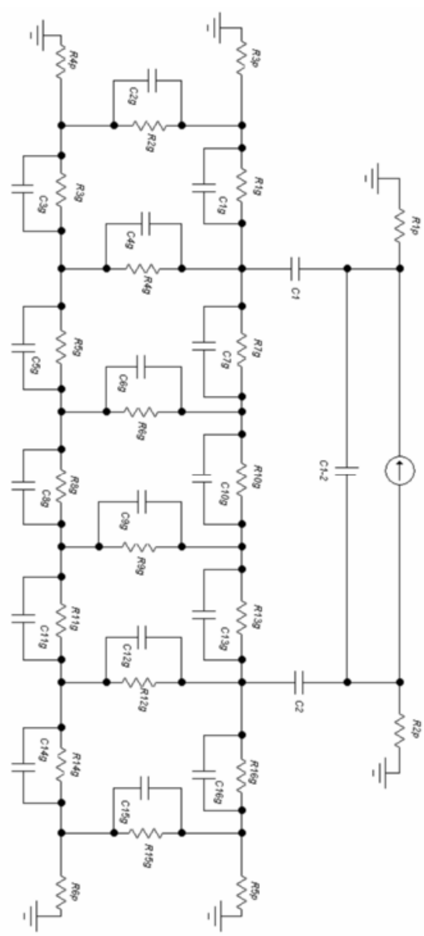

Fig.3 A detailed PSpice model of the examined problem

C_g is connected to a part of electric field which is characterized by geometric regularity while the second one is related to complicated filed distribution “outside” the volume enclosed by electrode and the medium surface. For capacitance used in simulations both components C_g and C_b are expressed as [9]

$$C_g = 0{,}0695 \frac{\varepsilon_r \varepsilon_0 D^2}{d}, \tag{7}$$

$$C_b = 0{,}077 \lg\left(\frac{3{,}8}{d} + 0{,}0185\right) \varepsilon_r \varepsilon_0 P, \tag{8}$$

where: ε_0 – permittivity of free space, ε_r – relative permittivity of material placed between electrode and medium (typically air), d – distance between electrode and medium border, D – diameter of the electrode, P – circumference of the electrode.

Resistance and capacitance which mimic electrical soil properties follow from relationship (5) however, it is enhanced with a static conductivity component. This conductivity arises, among others, from ionic conductance of the soil.

C. FEM Model

Model FEM has significant influence on the reconstruction results [4]. Taking into account complexity of the reconstruction process identification of the region of interest (ROI) is crucial. A finite element model of forward problem is presented in the Figure 4. It is a sphere of a radius r which describes the region of current density greater than assumed value $p|I_{max}|$, where p is a percentage value of the maximal current density in the examined object (on a border surface). Value of r may be evaluated using the following equation [10]

$$r = \frac{3}{2} a \sqrt{\left(\frac{1}{p}\right)^{\frac{3}{2}} - 1}, \tag{9}$$

where: a is a distance between transmitting and receiving current electrode, in the model equals 0,3 m, and p is a coefficient stating an assumed limiting value of the current density equals 5% of I_{max}.

Spherical mesh is filled in a half with an air and in a half with the examined medium (soil). Both parts of the model are described by complex conductivity. Electrodes and coils are immersed in the half containing air. They are located in the model as shown in Figure 4b. The external shell also shown in Figure 4 has a very small conductivity equals 10^{-10} [S/m]. It simulates infinite character of the examined medium. An outer surface of the model is connected to ground potential.

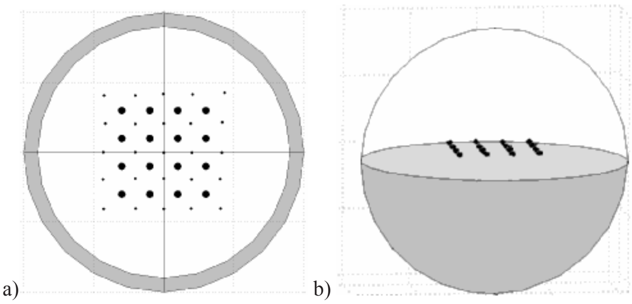

Fig.4 A 3D model of considered problem, dots stand for electrodes while circles for coils locations

III. Results

Potential distribution between two application electrodes calculations for the excitation current frequency ranged from 1 Hz to 10 MHz were carried out using PSpice model. Electrical soil properties were modelled according to the relationship (5) enhanced with a dc conductivity. Exemplary electromagnetic properties of the soil were taken from [11]. It is easy to observe in the Fig. 5 that optimal measurement frequency for a given set of material parameters is in range of 10^2 and is precisely equal 240 Hz. For this frequency sensitivity to conductivity changes in the medium would be the greatest.

Variation of the potential between two measurements electrodes on the assumption that conductivity and capacity are steady for current frequency from 1 Hz to 10 MHz carried out using PSpice model is illustrated in the Figure 6. Conductivity and permittivity values for frequency equals 10Hz and 100Hz. In the figure may be observed rapid decrease variation of the potential with increase of frequency. It is readily see that only for frequency in range from 1Hz – 1kHz changes of the potential can be detected.

The potential distribution on surface of the medium is presented in the Figure 7. It follows from the study that the potential distribution and thus the sensitivity decreases rapidly with the distance from sensors.

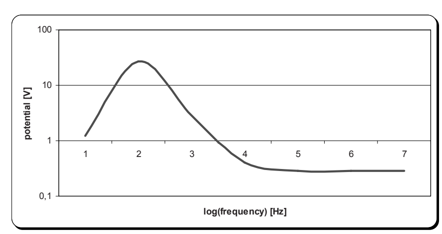

Fig.5 Variation of the potential between two measurements electrodes with adjustment of conductivity and capacity dependence on injected current frequency

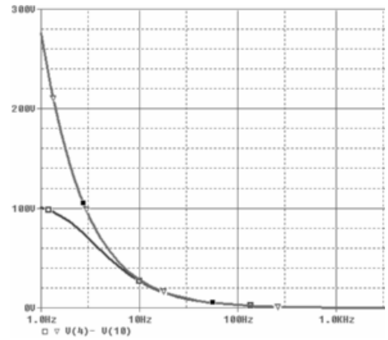

Fig.6 Dependence of voltage as measured by two electrodes on the frequency assuming different, but constant, properties of soil (soil parameters are described by numbers not by relationship (5))

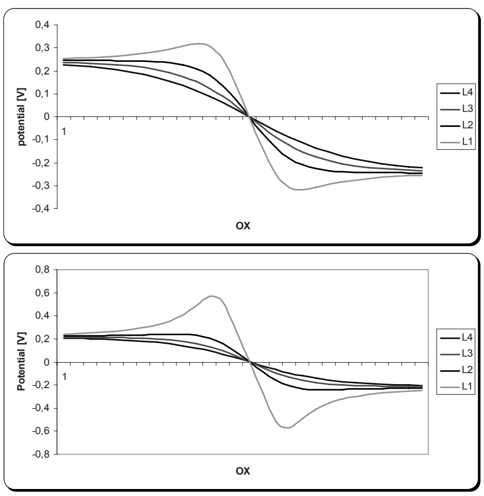

Fig.7 Potential distribution on surface layer of the FEM model for two different distances of excitation electrodes, upper figure – bigger distance between electrode and medium, lower figure – a smaller distance

IV. Conclusions

Calculated results show that proposed in the paper technique should work effectively (theoretically) in a low frequency range. Complex conductivity dependence on frequency has significant influence on measurements, thus it should be taken into account for generating more accurate and real results of a reconstruction process.

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